APPLICATION OF MULTI-ATTRIBUTE UTILITY ANALYSIS TO PROBLEMS IN MATERIALS SELECTION

by

FRANK REMSEN FIELD, III

SB, Nuclear Engineering, Massachusetts Institute of Technology
(1978)

SM, Nuclear Engineering, Massachusetts Institute of Technology
(1981)

SM, Technology and Policy, Massachusetts Institute of Technology
(1981)

SUBMITTED TO THE DEPARTMENT OF
MATERIALS SCIENCE AND ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN THE FIELD OF
MATERIALS SYSTEMS ANALYSIS

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June, 1985

Signature of Author ....
Department of Materials Science and Engineering
May 3, 1985

Certified by ....
Professor Joel P. Clark
Thesis Supervisor

Accepted by ....
Professor Joel P. Clark
Chairman, Interdepartmental Doctoral Committee

Accepted by ....
Professor Bernhardt J. Wuensch
Chairman, Departmental Graduate Committee

APPLICATION OF MULTI-ATTRIBUTE UTILITY ANALYSIS TO PROBLEMS IN MATERIALS SELECTION

by

FRANK REMSEN FIELD, III

Submitted to the Department of Materials Science and
Engineering on May 3, 1985 in partial fulfillment of
the requirements for the Degree of Doctor of Philosophy in
the field of Materials Systems Analysis

ABSTRACT

An investigation into the application of multi-attribute utility analysis to the problem of materials selection was undertaken. This investigation was predicated upon the hypothesis that materials selection is based on the performance characteristics of a fabricated, assembled product, rather than upon any instrinsic worth of a material. While this hypothesis is commonly accepted, none of the available materials selection techniques currently employed adequately take this perception of the problem into account, limiting the reliability and utility of their results.

The application of multi-attribute utility analysis affords a disciplined approach to the analysis of materials selection problems. At the expense of increased effort, utility analysis yields a normative, quantitative measure of a decision maker's preferences for incommensurable characteristics and places them on a commensurate scale. The resulting utility function captures the decision-maker's preferences for competing material selection objectives and enables the estimation not only of the relative ranking of material alternatives, but also of the ways in which the characteristics of the alternatives are balanced against each other.

Two materials selection problems in the automobile industry were treated: deck lids and bumpers. In each case, the engineering, cost, and utility analyses employed to rank material alternatives are outlined. Additionally, the application of utility curves in identifying the degree to which one alternative surpasses or lags the others is described.

The results of this work suggest that treating the multiple objective materials selection problem through a combination of engineering, cost, and utility analysis can yield insights into the problem unavailable with other techniques. While this technique requires somewhat more effort than traditional ones, it not only enables the analyst to rank material alternatives, but also makes it possible to identify the degree to which a material's characteristics contribute to or detract from its desirability for a particular application.

Thesis Supervisor: Dr. Joel P. Clark
Title: Associate Professor of Materials Systems

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ACKNOWLEDGEMENTS

This thesis is the culmination of a lengthy and enjoyable matriculation and, in this small space, I would like to extend my gratitude to those who have made the process memorable.

First, I would like to thank my thesis advisor, Professor Joel P. Clark. Since meeting Professor Clark during my sophomore year at MIT, he has enriched my academic career. He encouraged me to pursue a graduate career at MIT and his support of my work has been both unflagging and rewarding.

I also would like to thank the other members of my interdepartmental doctoral committee: Professor Richard de Neufville, for his guidance and instruction in the theory and practice of utility analysis and for his valuable critical readings of this thesis; and Professor J. Daniel Nyhart, whose critiques and perspectives helped to sharpen the arguments presented in this thesis.

My work was aided and enhanced by the contributions and encouragement of my co-workers in the Materials Systems Laboratory. I would especially like to thank Elaine Rothman and Joonchul Park, who developed some of the metal forming models employed in the cost estimations presented in this thesis. John Busch developed the plastics fabrication cost model and helped me with the assembly and finishing cost model. I owe an extra share of thanks to John Busch, who managed to endure innumerable trips to Detroit in my company and proved particularly skilled at extracting otherwise unobtainable cost information from reticent engineers. He also was particularly skilled at identifying weak points in both my writing and my arguments, to the improvement of both.

I also would like to thank the people in the automobile industry and in their supplier industries who aided my work. In particular, I would like to thank Daniel Kelley of Chrysler Corporation, who was unfailingly helpful throughout the past year and a half.

The actual production of this document was greatly aided by John Maglio of the East Campus Computing Facility, who helped me to use the IBM 4341 there and who guided me through the vagaries and subtleties of the IBM 6670, QPRINT, SCRIPT/VS, and GML.

Finally, I would like to thank my family for their support; my aunt, uncle, and cousins in Lincoln who were always willing to provide diversion from academia when the need arose; my brother and sisters, who were always sure I could do it even when I wasn't; and my mother, who seems to have lost her bet that the Last Trump would sound before I finished. The Mormons better be there!

This thesis is dedicated to the memory of my father, Frank R. Field, Jr.

INTRODUCTION

This thesis addresses the topic of materials selection from among many alternatives. This topic is one of growing importance today. From its beginnings at the start of this century, the field of materials science has shepherded rapid growth in the number and types of engineering materials available. This growth continues apace.

With this materials explosion, a new class of problems have arisen. The methods used by designers to select appropriate materials for applications are inadequate to the task of balancing the myriad of materials available today. Additionally, systematic analyses of the properties of these materials, with a view towards expanding their applicability, have been unavailable.

For example, today's automobile engineer, by and large, makes his product out of the same class of materials that have been used since the inception of the industry, steel. The selection of steel was based upon a variety of properties, notably the strength of the material, the ease with which it could be formed, and its low price.

In the past, there were no materials which could offer this combination of properties. Today, however, the situation has changed. Steel now finds competition for most applications from a variety of souces, most notably plastics. Furthermore, new and different materials are being developed almost daily.

Given the rapidly expanding universe of material alternatives, how can an engineer assess the applicability and desirability of new materials in the components that he designs? There has been a notable lack of systematic techniques which adequately address the full scope of the materials selection problem. In particular, most materials selection decisions have been based on the strategy of supplying adequate performance at a minimum of cost. This approach assumes that the non-cost performance characteristics are valuable only insofar as they effect the cost of the component. Several characteristics of engineering design lead to the conclusion that is view is too narrow to completely describe the materials selection decision.

In this thesis, an approach to the problem of materials selection which takes this objection into account is developed. This technique employs multi-attribute utility analysis to assess the value of a material in an application on the basis of both its performance and its cost. Furthermore, this technique enables the analyst to assess the relative importance of performance characteristics and to estimate the value of improved performance.

This thesis is composed of 7 chapters. In chapter 2, the problem of materials selection is presented and the complexities of the problem are outlined. Chapter 3 summarizes the techniques available to treat the materials problem and describes how these techniques have been applied in the field to treat materials selection. The advantages and disadvantages of these techniques are outlined and multiple attribute utility analysis is introduced. Chapter 4 describes in detail the application of multi-attribute utility analysis, in conjunction with engineering cost models and design analysis, to the problem of materials selection. Chapter 5 then presents the results of the analysis of materials selection for two automobile components, the automobile deck lid and the automobile bumper. In Chapter 6, the results obtained in the bumper case are compared with those which could be obtained using the conventional materials selection techniques and the advantages of the multi-attribute utility technique are described. The results of the present work is then summarized in Chapter 7, which also outlines areas for further development of the technique.

THE MATERIALS SELECTION PROBLEM

The selection of a material for an engineering application is one of the central issues of the engineering design process. No engineering design is complete without a material specification, and the success or failure of an engineering concept can hinge upon the material chosen by the designer to implement his design. The material selected for production may ultimately determine both the success and the profitability of an engineering product. The development of some products (such as steam turbines and jet engines) has been largely determined by advances in materials technology while the advent of readily and inexpensively processed materials (such as plastics) has led to the development of economical consumer goods. [131]

Because of the influence of the constituent material upon the performance of an engineering application, materials selection is a critical part of the design process. A material selection must reflect the designer's knowledge not only of the material, but also of the performance required of the application being designed. As such, engineering design is frequently a synergistic process, as designs evolve according to the advantages and shortcomings of the materials under consideration.

The influence of material on the design of an application is a function of the properties of the material. While many of these are intrinsic to the material, a significant fraction of material properties are also affected by the processes employed in the production of the material and the manufacture of the application. For example, the strength of a steel component is a function of the steel alloy composition, the process by which the steel was produced, and the process by which the steel component was made.

In the past the procedures employed in engineering materials selection were predicated upon the assumption that the designer was familiar with the properties and capabilities of the candidate materials [33,36,109]. Because the set of engineering materials was limited, the problem of materials selection could be readily reduced to a problem in engineering analysis. The limited materials set enabled designers to concentrate on a small number of materials without sacrificing flexibility. In most cases, materials selection (if consciously treated at all) was performed as an engineering satisficing problem, hoping to minimize cost. However, for many applications, there was really only one material available which could meet the requirements set by the designer.

Under these conditions, materials selection reduced to the problem of finding a material which was feasible in a particular application. Engineers were able to develop a feel for the capabilities of all the materials available to them, and were able to select materials based on their own experience. Furthermore, manufacturing firms were able to establish standard procedures for materials selection, based upon past experience [e.g., the auto industry]. As long as there were only a few new materials introduced, it was fairly straightforward to include them in this sort of materials selection procedure.

However, the rate of growth in the number of materials available for manufacturing has undergone a dramatic change in the past half-century

[32,64,102,138]. With this growth of the field of materials science and engineering has come a concomitant growth in the number of materials available for applications, as well as new manufacturing and materials processing techniques. While as little as forty years ago an engineer had at most twenty candidate materials for an application, today's engineers frequently must choose from among many times that number [12,123,132].

While the growth in the set of available materials has made better materials available for engineering applications, the size of the materials set available has introduced its own problems. It has become more and more difficult for engineers to keep up with the volume of developments in the materials fields. This difficulty is compounded by the fact that the objectives of engineering design have grown to include ecomomic and regulatory considerations [54,109,144]. Furthermore, materials science has increased the amount of information available to characterize a material, and thus, the number of engineering constraints which must be met [59]. As a result, many engineers have been forced to restrict the scope of their materials knowledge, focusing on a limited set of materials and assuming that this reduced materials set will provide satisfactory solutions to their materials problems [59,109].

However, few (if any) engineers look upon this narrowing of scope as a satisfactory solution to this problem. Missed material opportunities can be extremely costly and and engineering firms failing to capitalize upon the potential of new materials will likely lose their competitive position [109]. Rather than restrict the scope of the materials selection problem, new ways to treat the materials selection problem must be developed and implemented.

In response to this situations, materials engineers have proposed and developed a number of systematic approaches to the problem of materials selection. Twenty years ago, these materials screening techniques were proposed as ways to enable the materials designer to perform materials selection on his own [33]. Recently, these techniques have been cited as appropriate algorithms for computerized materials selection [36,41,53,57,59]. In either incarnation, these techniques suffer from limitations which restrict their application to to a limited number of problems.

Before turning to a discussion of these techniques in the next chapter, it is instructive to express formally the materials selection problem in its two most commonly stated forms. The most common form of the materials selection problem is:

> Given a set of materials $\underline{X}$, each possessing properties $\underline{x}$, select the material X_i which, when used in application Y gives the minimum cost and satisfies a set of required physical characteristics $\underline{Z}$

This statement, which can be found in most of the literature of materials selection, can be simply paraphrased as 'choose the cheapest material which meets the minimum performance requirements of the application.' This philosophy of materials selection finds its most complete expression (where variations in design are also considered) in the area of engineering analysis known as value engineering [33,120].

This approach is also at the root of a number of cost versus performance index techniques [5,33], which also seek to achieve the minimum cost solution to the materials selection problem by reducing the performance requirements to a single requirement and then determining the least cost material which supplies the requisite properties.

However, the cost minimizing approach to materials selection is a particularly limiting way of looking at the materials selection problem. In particular, the cost minimizing approach requires that the limiting performance constraints be specified at the outset of the materials selection process. These constraints must be satisfied; there is no way in which an improved level of performance in one area could compensate for a reduced level in another area. In order to consider an alternative design, the constraints must be completely respecified and the sole basis for material/design selection is the cost of the final solution.

This limitation is a consequence of the limited size, particularly in the past, of the materials set available to the designer. Because the designer already had a good idea of the material he wanted, his design was sufficiently specific to enable the setting of these performance constraints, and the materials selection techniques were employed to select, from a very restricted set, the cheapest material for the application. Because of the relationship between material and design, the designer was compelled to make a general materials selection before the materials selection problem could be completely expressed.

With the increase in the size of the materials set, as well as an increase in the number of performance criteria brought to bear on materials selection [54,124,144], another formulation of the materials selection problem is frequently considered. Because of the scope of the alternatives, the decision maker cannot necessarily specify the necessary levels of design performance in advance of the selection of the appropriate material. Depending upon the material selected, the design of the application may be completely different, and the required performance of the material will critically depend upon that design.

The basic elements of this formulation of the problem of selecting a material for a particular application can be stated as follows:

> Given a set of materials $\underline{X}$, each possessing properties $\underline{x}$, select the material X_i which, when used in application Y, gives <u>the best set of characteristics $Z^*(x)$</u>

This formulation of the materials selection problem is a considerably more comprehensive approach to the problem. In this formulation, the problem is constrained by the properties of the available materials and the necessary function of the application being examined. The solution to the problem when formulated this way is no longer limited to a particular design, only to a particular type of functionality. However, this added flexibility comes at the expense of a new kind of problem to solve.

In particular, the materials selection problem now divides into two segments. The first segment treates the problem of relating the material properties $\underline{x}$ to the performance characteristics of the application $Z(\underline{x})$. This portion of the problem is the basic engineering problem which had to be solved for the first problem before it could be framed. Here it is included in the objective. Furthermore, cost, which above was the sole objective, is now one of many performance criteria.

The second segment of the problem, concerned with identifying the best set of characteristics, $Z^*(\underline{x})$, takes the problem of materials selection outside the scope of basic engineering science, because there is no objective way in which the best set of characteristics can be established. It has become necessary for materials engineers to treat materials selection as a problem in determining how performance characteristics are traded-off against both each other and the objectives of the decision maker.

A few techniques have been applied to this sort of problem in the materials area. These techniques will be discussed in the following chapter. They are limited in their ability to answer important questions about the ways in which varying levels of performance are balanced against the engineering objectives of the materials decision maker. This thesis presents a new technique for selecting a material from a large set of alternatives and demonstrates its use in two cases.

TECHNIQUES FOR ASSESSING MATERIAL ALTERNATIVES

In this chapter, the analytical techniques which are may be used to select between material alternatives will be discussed. This chapter will focus on the techniques available to solve the second formulation of the materials selection problem presented in the preceding chapter.

For each technique, the basic characteristics of the technique will be outlined and the advantages and disadvantages of each technique will be discussed. Where possible, references will be made to discussions and applications of each technique in the materials engineering literature. Finally, these techniques will be compared with the technique developed in the course of this work and the advantages of multi-attribute utility analysis in this area will be described.

THE MULTIPLE OBJECTIVE MATERIALS SELECTION PROBLEM

As stated in the preceding chapter, one of the common formulations of the materials selection problem is:

> Given a set of materials $\underline{X}$, each possessing properties $\underline{x}$, select the material X_i which, when used in application Y, gives the application the best set of characteristics $Z^*(\underline{x})$.

In spite of the ease with which this problem can be stated, its solution cannot be computed so simply. The problem naturally divides into two segments. The first segment treates the problem of relating the material properties $\underline{x}$ to the performance characteristics of the application $Z(\underline{x})$. This portion of the problem may be treated through a variety of engineering and economic analyses. While it may presently not be possible to characterize every performance characteristic of an application in terms of its constituent material, it is safe to state that, in general, this portion of the problem may be satisfactorily addressed through the application of engineering science.

The second segment of the problem, however, cannot be addressed so easily. While engineering science is a remarkably complete tool for estimating the performance of an application as a function of its component material properties, it is ill-equipped to treat the major aspect of the second segment of the problem, the determination of the best set of characteristics $Z^*(\underline{x})$.

This problem can be grouped with a large class of decision analysis problems called 'multi-objective problems'. These problems are characterized by the requirement that several objectives (or criteria) must be attained through a single course of action. In the case of the material selection problem, the selection of material X must lead to a best set of component performance characteristics, satisfying a potentially wide range of objectives.

The critical feature of this problem (and multi-objective problems in general) is that explicit consideration of the values of the decision maker must be incorporated into the decision calculus. Only under extremely peculiar (and somewhat uninteresting) situations can the 'best' selection be made in the absence of an explicit treatment of the preference structure of the decision maker.

The importance of considering the preferences of the decision maker can best be demonstrated by example. Suppose that there are three alternative materials which may be employed to make an automobile body panel. A panel made of material A would cost $10 to make and would weigh 5 pounds. A panel made of material B would cost $8 to make and would weigh 8 pounds. A panel made of material C would cost $9 and would weigh 8 pounds. If the objective of materials selection is to reduce cost and weight, which panel material should be used?

A careful examination of the alternatives reveals, first, that material C should never be used. Assuming that it is always better to reduce cost and weight, any panel made of material C could be made for less cost and at the same weight using material B. In the language of multi-objective problems, material C is said to represent a 'dominated solution' to the problem; i.e., there are solutions to the problem which are unqualifiedly better.

However, the remaining two alternatives cannot be so easily treated. Material A offers low weight at high cost, while material B offers low cost at high weight. These alternatives are said to constitute the set of 'non-dominated solutions' to the decision problem, which is defined to include all solutions to the decision problem such that there exists no solution to the decision problem which, when compared to a member of the non-dominated set, possesses characteristics at least as good and, further, possesses at least one characteristic which is better.

```
            $10 +    A
                |
 Panel       $9 +               C
                |
 Cost        $8 +               B
                |
             $7 +
                |
             $6 +----+----+----+----+----+
                4    5    6    7    8    9

                    Panel Weight (lbs)
```

To select from the members of the non-dominated set, it is no longer sufficient to consider the characteristics of the alternatives alone. A strategy for selection must be employed, since there is no objective way to distinguish a 'better' solution from a 'worse' one.

While a variety of frivolous techniques (such as flipping a coin) can be employed, the most common approach is to devise a selection strategy which takes explicit consideration of the preference structure of the decision maker. If cost is more important than weight, material B may offer the best set of performance characteristics. Alternatively, for other preference structures, material A may supply the best set of performance characteristics. Or, the decision maker may be indifferent between the alternatives. Regardless of the outcome, it is compelling to consider that the selection of the best alternative can only be made on the basis of the decision maker's attitudes toward varying levels of performance.

In addition to the specification of the 'best' material alternative, the solution of the materials selection problem may afford a number of attractive features. Note that the determination of the best alternative is based upon the performance of the application, itself a function of the physical properties of the material selection. Therefore, a solution to the problem should allow the analyst to characterize the value of material properties to a material decisionmaker. In order to solve the problem, it is necessary to trade-off one characteristic for another, based upon the preference structure of the decision maker. The nature and form of these trade-offs could also be a valuable product of the analysis.

A number of techniques have been developed to treat the multi-objective decision problem. However, each is marked by critical deficiencies when applied to materials selection problems. In the following sections, these techniques will be described and their limitations outlined.

The techniques available for analyzing material alternatives may be grouped into 4 basic classes. These are:

- Sorting
- Optimization
- Regression
- Decision Analysis

SORTING TECHNIQUES

Sorting techniques rely upon the ability of the decision maker to rank the characteristic consequences of a decision on the basis of their importance. These techniques are also able to treat constraints imposed on the level of each of these characteristics. The three major classes of sorting techniques are:

- Exclusionary Screening,
- Conjunctive Sorting, and
- Lexicographic Sorting.

EXCLUSIONARY SCREENING

The simplest sorting technique is exclusionary screening. This technique requires the decision maker to specify minimum acceptable performance standards for each performance characteristic being considered. Non-dominated solutions failing to meet these criteria are then eliminated from consideration.

For example, consider the following table which describes six alternative combinations of cost and weight.

Table 1. Example Alternatives

System	cost	weight
A	30	6
B	32	8
C	32	5
D	35	6
E	36	8
F	38	5

If exclusionary criteria as set such that cost must be no more than 37 and weight must be no more than 7, the set of alternatives is reduced as shown in the following table.

Table 2. Alternatives After Exclusionary Screening

System	cost	weight
A	30	6
C	32	5
D	35	6

While the simplicity of this technique is attractive, it is severely limited. First, this technique implicitly assumes that all non-dominated solutions meeting the minimum performance criteria are equally acceptable. Therefore, if a sufficiently large number of solutions survive this screening, the decision maker is still confronted with a large set of alternatives which must be further limited. For example, in the above case, three alternatives survive the exclusionary screening, A, C and D. Of these, A dominates D, leaving A and C as the set of non-dominated alternatives. Clearly, the screening has not resolved the question of which alternative is the best.

Second, while exclusionary screening can establish the preferred level of performance, it fails to reveal the structure of the preferences or the degree to which one characteristic can be sacrificed to improve another. Third, while this technique can be reasonably applied when the number of alternatives and characteristics is small, it becomes increasingly difficult to apply consistently as the size and scope of the problem expands.

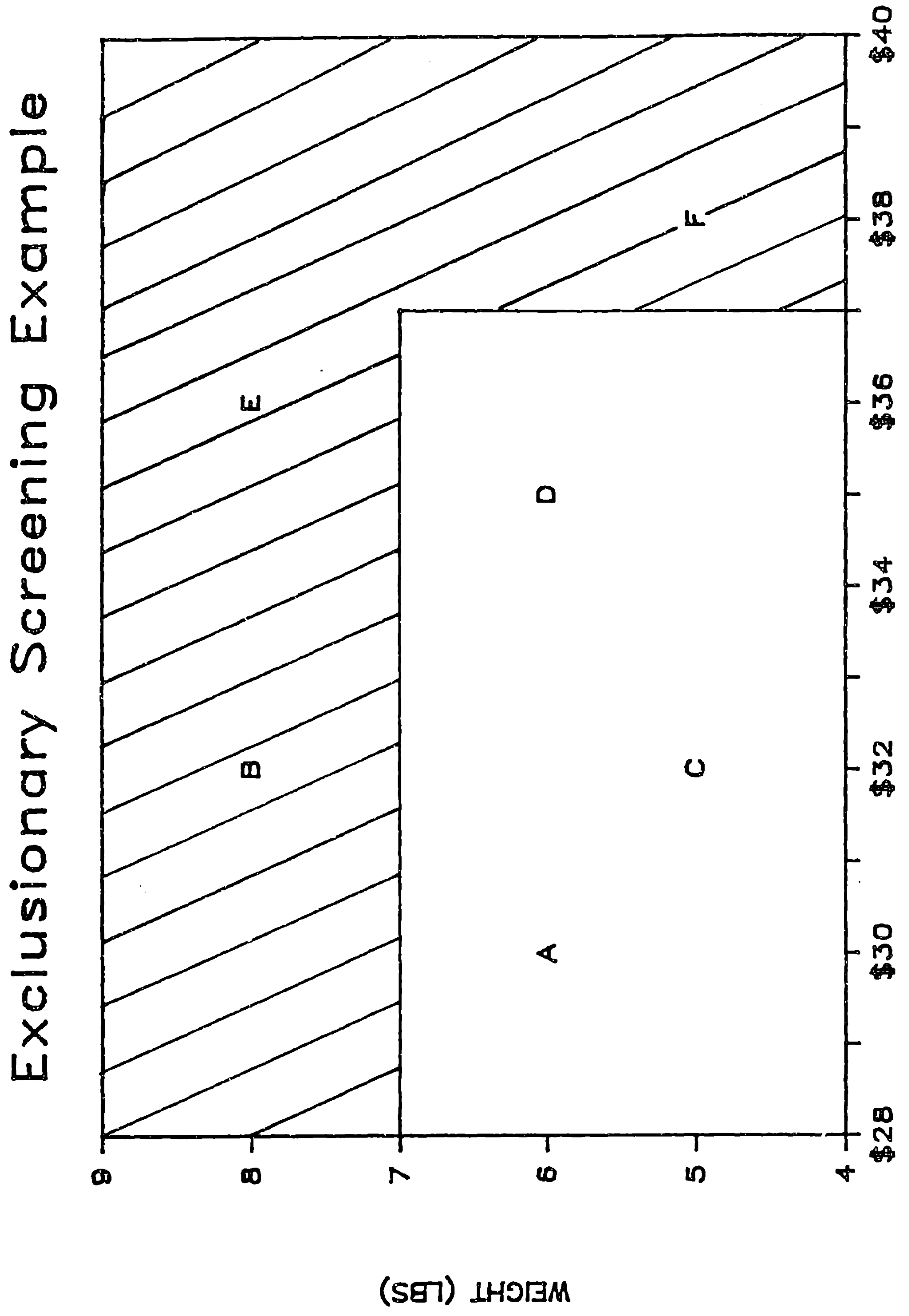


Figure 1. Exclusionary Screening Example

CONJUNCTIVE SORTING

A conjunctive sorting of the alternatives goes exclusionary screening one better. Employed following an exclusionary screening, a conjunctive sort requires that the decision maker define one of the performance characteristics as the most important. Using this characteristic as a guide, the remaining non-dominated solutions are ordered according to the level of performance displayed for the selected characteristic.

Again, consider the six cases presented above. In the following table, the alternatives are sorted according to cost or weight, assuming that the least cost or least weight alternative is the most preferable.

Table 3. Conjunctive Sorting of Alternatives

Sorted by Cost

System	cost	weight
A	30	6
B	32	8
C	32	5
D	35	6
E	36	8
F	38	5

Sorted by Weight

System	cost	weight
C	32	5
F	38	5
D	35	6
A	30	6
E	36	8
B	32	8

This technique is an improvement over the exclusionary screening process in that it does choose a best alternative from the remaining alternatives. However, the technique reduces the decision process to a single dimension, seeking only to maximize the level of performance in a single area. The importance of other characteristics in the decision process is ignored.

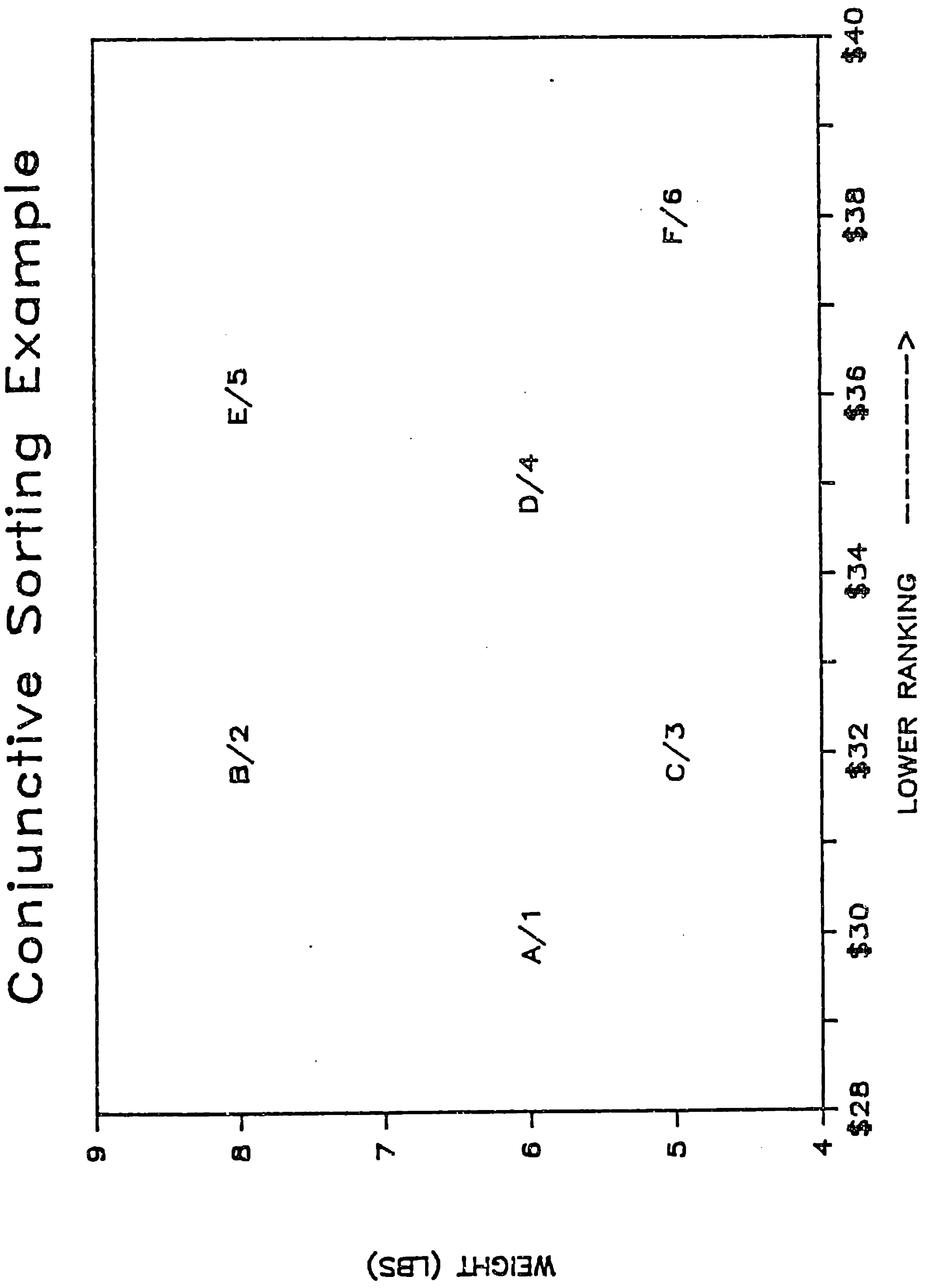


Figure 2. Conjunctive Sorting Example

LEXICOGRAPHIC SORTING

A lexicographic sort attempts to overcome the limitations of conjunctive sorting by asking the decision maker to rank the performance characteristics of the alternatives on the basis of their importance. Using this ranking, the alternatives are sorted in a fashion directly analagous to alphabetizing. Alternatives are sorted according to the most important characteristic. Within each level of the most important characteristic, alternatives are then sorted according to the second ranked characteristic. This sequence is repeated until all characteristics have been treated, resulting in a lexicographically sorted list of the alternatives.

Again, the following tables show the results of two lexicographic sortings of the six cases treated in the above sections. In the first table, the alternatives are sorted assuming that low cost is more important than low weight; in the second, low weight is assumed more important than low cost.

Table 4. Lexicographic Sorting of Alternatives

Sorted by Cost,Weight

System	cost	weight
A	30	6
C	32	5
B	32	8
D	35	6
E	36	8
F	38	5

Sorted by Weight,Cost

System	cost	weight
C	32	5
F	38	5
A	30	6
D	35	6
B	32	8
E	36	8

Again, this technique results in the naming of a best or a small set of best alternative solutions. Further, it considers all of the characteristics when ordering the alternatives according to the decision maker's ranking of their importance. However, this ranking of the characteristics results in a particularly rigid structure for decision making. In particular, there is no way that extremely good performance in a low ranking characteristic can compensate for poor performance in a high ranking characteristic. This rigid decision structure is uncharacteristic of materials selection situations, where very good performance in one area can compensate for reduced performance in other areas.

APPLICATIONS OF SORTING TECHNIQUES

There are a number of features of sorting techniques that are common to all of its incarnations. The most important of these is that they are best suited to the treatment of problems for which there is a discrete set of alternatives. In addition, the performance of each of these alternatives must also be completely determined. Finally, none of these techniques explicitly treat the way in which the level of performance in one area is traded-off against other characteristics. In sorting techniques, no trade-off is possible; alternatives are solely ranked according to their performance levels.

In spite of these limitations, sorting techniques are the most commonly used method of materials selection. The literature of materials selection is dominated by this technique. In particular, most materials selection guides are nothing more than a complete listing of each of the exclusionary criteria which must be considered for an engineering application, followed by a listing of materials which meet these criteria. Typical examples can be found in [79,83,118,130].

The materials selection literature also contains numerous examples of the conjunctive sorting technique. In most cases, the characteristic used to order the alternatives is the cost of the application, reducing the multiple objective materials selection problem to a cost minimizing formulation. As noted in the preceding chapter, the engineering technique known as value analysis explicitly states its objectives in these terms. In particular "value engineering or value analysis is an organized method of finding the least expensive way to make a product without compromising quality or reliability" [33]. In value engineering, the set of material alternatives is first subjected to an exclusionary screening, to select those materials which provide the necessary level of performance. Following this step, the remaining alternatives are ranked according to their cost, with the least cost alternative being the solution to the problem [120].

Another form of conjunctive sorting is the use of cost versus performance indices or engineering performance indices. [33,99] In both cases, the alternatives which fail to meet the limiting criteria are removed from the set of alternatives and the remaining alternatives are ranked according to the appropriate index. This approach has received considerable attention in the past and the indices employed are known by a variety of names, including specific names such as strength to weight ratios, strength to density ratios, and cost per unit strength, and general names such as materials selection factors or figures of merit [99].

These techniques are the most prevalent primarily because of the simplicity of the concept, not because they are simple to apply. The choice of characteristics to be considered, the weightings to be placed on these characteristics, and the relevance of these characteristics to the final design complicate the application of these techniques. Recognizing that capturing all of this information in a single figure is perhaps asking too much, engineers often use more than one such measure, thereby reintroducing the multiple objective problem which they were attempting to circumvent.

These techniques are most effective when the number of material alternatives has already been extensively limited, usually to a single material class [33]. Under those conditions, it is legitimate to ignore many selection criteria, because the remaining materials are practically identical in all but a few areas.

OPTIMIZATION TECHNIQUES

Optimization techniques revolve around the maximization (or minimization) of an individual or a set of objective functions, subject to a number of constraints. These techniques may be linked with interviews or consultations with decision makers to further refine the selection process. Several of these techniques will be described below.

LINEAR PROGRAMMING

Perhaps the most generally established of these techniques is linear programming. Under this method, a single linear objective is optimized subject to a set of linear constraints. This technique yields not only an optimized value of the objective function, but also the effect of a change in the constraints on the optimum value.

This technique is applied to multi-objective problems in three ways. Most commonly, linear programming is used to identify, from among a large number of alternatives, the set of non-dominated solutions to a multiple objective problem. By identifying the solution or set of solutions which optimize each of the objectives singly, the set of non-dominated solutions can be quickly identified, narrowing the multiple objective problem to a selection from among a considerably narrowed set. However, this application, by definition, cannot identify the 'best' solution to the multi-objective problem.

In another application of this technique, the multiobjective problem must be reduced to a satisficing problem for all but one objective. The objectives to be satisficed are then expressed as constraints upon the objective to be optimized. Because the technique can reveal the effects of changes in these constraints upon the optimal solution (called the 'shadow price' of the constraint), the technique does yield insight into the value of a characteristic, in terms of another. However, it relies upon the assumption that the problem can be reduced to a single objective problem.

In the third, the objective function is constructed as a linear combination of one or more objectives, thereby averaging the objectives according to a fixed weighting. In this case, the value of the characteristics (the weights) must be assessed in advance of the optimization process.

The application of this technique to materials selection problems is limited, however. First, the functional form of the constraints and the objective is restricted to linear forms (although quadratic forms can also be treated). This severely limits the scope of the analysis, since only a limited number of engineering performance characteristics can be expressed as linear functions of a single physical parameter. Second, the shadow prices of the constraints are defined only within the vicinity of the optimal solution. Outside of these ranges, their values can only be approximated. Third, linear programming, like many optimization techniques, exhibits what is called 'flip-flop' behavior [103]. That is, for very slight changes in the objective function or the constraints, the optimal solution can change dramatically. Because of this behavior, this technique is not well-suited to identifying the second-best solution without re-solving the problem with the optimal solution removed. Further, even though the second-best (or third, or fourth, etc.) solution can be found, the technique cannot identify the reason for this ranking. However, for problems which fall within these requirements, linear programming is a very powerful tool for analysis.

REFINEMENTS OF LINEAR PROGRAMMING

The most obvious limitation of linear programming techniques is the restriction that the constraints and the objective must be expressed as linear functions of the decision variables. A variety of nonlinear programming techniques do exist and have seen considerable application [101,110,111].

However, this improvement does not address the limitations of the solutions derived when the problem must be reduced to optimizing a single objective subject to satisficing the other objectives. While there are techniques which may solve a multiple objective linear problem, these techniques can only specify the set of non-dominated solutions; they cannot reveal the 'best' solution without treating the decision maker's attitudes.

GOAL PROGRAMMING

Given the limitations of linear and nonlinear programming techniques, an alternative technique, called goal programming, may be applied. Goal programming takes many forms and relies to varying degrees upon the degree of consultation with the decision maker.

The basic assumption of goal programming is that a decision maker can state his desired levels of performance for each objective being pursued. Given these goals, a non-linear optimization process can reveal the solution to the problem which minimizes the difference between available alternatives and the decision maker's goals.

There are a wide range of goal programming techniques. Each represents a way to avoid the major limitation of the technique; given a too restrictive set of goals, the technique may select a dominated solution. Most of these techniques rely upon a number of interactions with the decision maker following each optimization step. Based upon the solution provided, the decision maker is invited to revise his goals. When the decision maker is satisfied with the result, the optimal solution has been determined [59,60].

Goal programming is of limited applicability in materials selection situations. The potential for selecting dominated solutions in the absence of interaction with the decision maker severely limits the applicability of the technique to treat situations when materials are added to the set of alternatives. Further, the setting of goals, while removing the computational limitations of other optimization techniques, fails to characterize the relative importance of these goals. The importance of each goal relative to another is fixed at the outset of the problem, similar to the situation described above when a linear programming objective function is expressed as a weighted average of the objectives. The technique fails to capture the degree to which the relative importance of each goal may change as a goal is achieved.

SEQUENTIAL OPTIMIZATION TECHNIQUES

Given the limiting structure of the objective function used in goal programming, other optimization technique have been developed. These include the step method (STEM), the method of Geoffrion, the sequential multiobjective problems solving method (SEMOPS), and others. While each of these techinques structure the objective and the constraints differently, each relies upon a similar algorithm, which may be summarized as follows:

1. Identify the objectives of the problem.
2. Construct these objectives into a set of objective functions.
3. Combine the objective functions into a single objective or construct a multiple objective linear program.
4. Determine a non-dominated solution from the solution set.
5. Ask the decision maker if the solution is satisfactory.

6. If the solution is satisfactory, terminate the procedure.

7. If the solution is not satisfactory, determine, based upon the comments of the decision maker, how the objective function should be changed.

8. Compute a new solution based upon the decision maker's comments and the objective(s).

9. Go to step 5.

How each of these techniques accomplish these steps is beyond the scope of this review. Interested readers are referred to several texts on multi-objective programming [51,69].

Again, these techniques suffer from many of the same limitations of the preceding optimization techniques. First, they are critially dependent upon access to the decision maker. Without the progressive articulation of his preferences (steps 5 and 7), these techniques cannot be applied. Furthermore, the solution to the problem can yield only local information about the decision maker's trade-offs between properties. The addition of new alternatives to the decision set would require a complete reassessment of the problem.

APPLICATION OF OPTIMIZATION TECHNIQUES

Those systematic techniques applied to materials selection problems in the materials engineering literature which are not screening techniques can be grouped into optimization techniques, although very few actually make use of the mathematical formalisms described above.

While optimization techniques are not often described or completely applied to materials selection problems, several of basic features of the optimization problem can be found. In particular, the formulation of the objective function is usually the only aspect of the technique presented. The most commonly used objective function is an weighted average of the characteristics of interest. In this technique (known as the weighted characteristics [5] or the geometric approach [59]), each characteristic is normalized by dividing its value by the highest value found from among the alternatives. The normalized values then are weighed according to their relative importance and averaged. The material yielding the highest average value is the optimal material.

This technique enables the materials decisionmaker to set the relative importance of the alternatives and can be sequentially modified to allow the decision maker to refine these weightings. This technique has many proponents, particularly among those researchers and designers developing computerized materials selection techniques.

However, the reliability of this technique relies heavily upon the selection of the normalizing factor. If an outlying solution with a particularly high value for a characteristic is used as a normalizing factor, the technique can yield misleading results.

For example, the following figure describes five alternative combinations of cost and weight. Of these five, the fifth (Alternative F) has far and away the highest cost of all the alternatives. This alternative would certainly never be chosen, but if it is included in the weighted average technique, the technique will yield an ordering of alternatives different from that which would result if the alternative were not included.

The results of the weighted average technique are presented in the following table. The weightings assumed for the characteristics are (1 * weight index) + (3 * cost index). Notice that the order of the alternatives changes between the two sets of results. This change in ordering is a direct result of the inclusion or exclusion of Alternative F, a so-called 'irrelevant alternative'. It is this sensitivity to such alternatives that critically limits this technique.

Table 5. Weighted Index Ranking Including Irrelevant Alternatives

Alternative	Cost	Weight	Normalized Cost	Normalized Weight	Weighted Average
A	5	6	0.25	1.00	0.44
B	3	6	0.15	1.00	0.36
C	5	5	0.25	0.83	0.40
D	6	4	0.30	0.67	0.39
F	20	6	1.00	1.00	1.00

Resulting ordering (B,D,C,A,F)

Table 6. Weighted Index Ranking Without Irrelevant Alternatives

Alternative	Cost	Weight	Normalized Cost	Normalized Weight	Average
A	5	6	0.83	1.00	0.88
B	3	6	0.50	1.00	0.63
C	5	5	0.83	0.83	0.83
D	6	4	1.00	0.67	0.92

Resulting ordering (B,C,A,D)

Goal programming techniques have also been used to treat materials selection problems. Known as the algebraic approach, the objective function is:

$$\text{Minimize the sum of } a_i \left| \frac{(X_i - Y_i)}{Y_i} \right| \text{ for all } i$$

where:

X_i = the ith characteristic of a material

Y_i = the targeted level of the ith characteristic

a_i = the weighting placed on the ith characteristic

Frequently, this analysis is presented in graphical form, in which the targeted levels of each characteristic are used to form rays, which are connected to form a complex polygon [59]. The attributes of each candidate material are also used to form a polygon, and the polygon most similar to the target polygon is then the optimal material for the application. The graphical presentation and the ability to rapidly apprise the user of the influences of changes in the goals set by the decisionmaker makes this technique particularly attractive to proponents of computerized materials selection systems.

Another form of goal-oriented programming has been employed in the selection of material fabrication processes and is readily applicable to materials selection problems [92]. In this technique, a target achievement level for each characteristic of interest is set, and a number of points is assigned to that level of achievement. This point assignment corresponds to the degree of importance of that performance to the decision maker. Similarly, a number of points is assigned to each candidate process, based upon performance in each of the areas of interest. The points for each target are then combined with the points for each candidate, resulting in a single index measuring the suitability of the candidate against the targeted performance.

REGRESSION TECHNIQUES

The regression techniques most applicable to the treatment of a materials selection problem have been developed by economists studying price indexing [38,55,127] and by market analysts [84,112,118]. In both cases, these groups have developed the theory of 'hedonic pricing', a direct outgrowth of the work of Kelvin Lancaster [85]. While these regression techniques have not been directly applied to materials selection problems, the problems to which they have been applied are analagous to the materials selection problem.

In hedonic price analyses, commodities are viewed as being valued on the basis of their performance characteristics. Given this assumption, it follows that the market price of a commodity must be a direct function of these characteristics and that, further, the value of each of these characteristics (the hedonic price) can be estimated from market information.

To compute the hedonic price of the characteristics of a commodity, the price of the commodity is regressed against the levels of its characteristic performance. The resulting regression coefficients express the value of a unit of the characteristic in terms of the price of the commodity.

While most of the analyses have treated the relationship between the characteristics and the price as a linear one (i.e., $p = a + \Sigma b_i x_i$), recent work has explored the implications of non-linear relationships. Using a relationship of this form allows the analyst to estimate not only the hedonic price of the characteristic, but also a market demand curve for the characteristic [119].

Because the hedonic technique focuses on the market value of a commodity, its application to the materials selection problem is very limited. Very few commodities can be considered to be a single materials application; most are combinations of such applications. As such, it is impossible to estimate the price of any one application.

The hedonic technique is also limited by the use of regression to estimate the parameters of the price equation. Regression techniques are limited to the treatment of historical data and therefore can only illuminate past behavior. This limitation is particularly acute when considering issues of prospective behavior, such as the attractiveness of a new material.

Hedonic techniques, in effect, treat the entire market as the decision maker. Successful producers are those which recognize the preferences of the market and respond accordingly. While such a view is very compelling, it is difficult to accept that market preferences are sufficiently developed to resolve the performance trade-offs inherent in a materials decision. In particular, it is extremely unlikely that consumers have enough information to assess the materials selection decision adequately. This view can be supported by examining the performance criteria which are used in practice to treat these problems.

For example, typical hedonic analyses of automotive demand [4,55,127] parameterize the automobile according to its such characteristics as

- Horsepower (engine displacement),
- Interior space,
- Passing speed,
- Volume of luggage space,
- Size (wheel base),
- Weight, and
- A variety of features (V-8 engine, hardtop, number of doors)

While these characteristics may be sufficient to estimate the attractiveness of an automobile car line, few of these characteristics could be considered as meaningful indicators of the preferability of one material over another.

DECISION ANALYSIS TECHNIQUES

The final class of techniques to be discussed are decision analysis techniques, most notably, multi-attribute utility analysis. MAUA is based upon the assumption that it is possible to assign an ordered metric to various combinations of characteristics which reflect the desireability of each set of characteristics. This metric is called 'utility' and the relationship between the value of a set of characteristics and the utility of that set is called the 'utility function.' By estimating a decisionmaker's utility function, an analyst can gain new insights into the criteria employed by the decisionmaker and can make predictions regarding the decisionmaker's actions under certain conditions.

Utility analysis is based upon the assumption that there exits a function (the utility function) such that;

- for every A which the decision maker prefers to B, U(A) > U(B),
- for every A which the decision maker is indifferent to B, U(A) = U(B), and
- if A is preferred to B, then the difference between U(A) and U(B) indicates the degree to which A is preferred to B.

This utility function describes the decision maker's preferences and expresses the level of preference in terms of a commensurable metric. The function is analytic and may be used as the objective function of an optimization technique. However, the form of the function itself also has significance and can be used to estimate the value of trade-offs between competing objectives or characteristics.

Six axioms of individual behavior lie at the heart of utility analysis. It is these axioms which enable the analyst to estimate and construct an individual utility function. Each of these axioms are briefly summarized below:

1. Complete Preorder - For each possible pair of consequences, an individual will either prefer one to the other or will find them to be equally preferable. This axiom basically states that individuals can make choices between alternatives, which reveal their preferences.

2. Transitivity - If an individual prefers A to B and also prefers B to C, then he prefers A to C. This axiom is reasonable for individuals, but may not hold for groups with different sets of preferences.

3. <u>Monotonicity</u> - Individuals always prefer more of a good thing to less of a good thing. Again, this assumption is reasonable in many cases, although there are situations in which it is not true.

4. <u>Existence of Probabilities</u> - In uncertain situations, where the resulting consequences are uncertain, the probability of each possible consequence exists and can be quantified. While the quantification of such probabilities can be quite difficult, the proposition that such quantification is possible is reasonable.

5. <u>Monotonicity of Probability</u> - Individuals prefer a greater chance of achieving a good outcome than a lesser chance. This axiom is similar to the above monotonicity axiom, again stating the usually reasonable assumption that more is better.

6. <u>Substitution</u> - This axiom basically implies that individuals have linear preferences with respect to probability. For example, if an individual prefers A to B, then a 50:50 chance between A and some other alternative C is preferred to a 50:50 chance between B and C.

The consequence of these axioms is that utility can be treated as a cardinal scaling function for levels of characteristics and its value can be treated analytically. Furthermore, individual preferences can be assessed using probability to measure an individual's intensity of preference for varying levels of a characteristic.

There are a wide range of techniques for estimating the utility function of a decision maker. The most commonly employed technique is the Keeney-Raiffa interview technique. This technique revolves around the administration of a questionnaire to the decision maker. In this questionnaire, the decision maker's preferences are revealed based upon his preferences between certain and uncertain outcomes. The questionnaire is designed to represent decision situations similar to the problem being studied.

One of the great advantages of MAUA is that it transforms incommeasurable characteristics (like dollars and pounds per square inch) into a commensurable metric (utility), thus allowing the analyst, in effect, to compare apples and oranges. For materials selection problems, this advantage is particularly attractive. Since the utility function is designed to capture the decision maker's preferences in an analytic form, the function itself can be examined to reveal the rate at which one characteristic may be traded-off against another. Additionally, since the function is estimated without explicit treatment of the set of alternatives, new alternatives may be treated without requiring a re-estimation of the function.

The technique does have some disadvantages. The Keeney-Raiffa estimation technique can be time-consuming and requires that the analyst be well-acquainted with the decision process being modeled. However, while the interview process is potentially lengthy, the number of questions necessary can be reduced through a number of structural assumptions. Under these conditions, an interview of only an hour's duration is needed to estimate a six-dimensional utility function.

Recent experiments [93,94] have suggested an explanation for some features of the Keeney-Raiffa estimation technique (as well as any other techniques based upon certainty equivalence) which have been presented in the past, including the so-called Allais Paradox. In particular, recent investigations indicate that the utility function of the interviewee is a function of the probabilities employed to probe the subject's preferences. The effect is particularly noticeable when the probability of one of the uncertain outcomes presented in the questionnaire is close to one. This dependence is traceable to the use of certainty equivalents to measure utility functions. A new technique, using probability equivalents instead of certainty equivalents, has been proposed and currently is under development.

While utility analysis has been the subject of a certain amount of controversy, it has been successfully employed to treat a wide range of multi-objective problems, including airport siting [105], power plant siting [78], building code selection [104], and water management problems [76]. Because the technique focuses on characteristics and the preference structure of individuals making choices on the basis of these characteristics, this technique is particularly suited to a treatment of materials selection on the basis of materials performance. However, it has not been applied to this problem in the past.

SUMMARY

The following table summarizes the major features of the materials selection techniques reviewed in this section. As the table indicates, none of these techniques adequately addresses the problem of materials selection.

The sorting, optimization, and regression approaches to this multiple objective problem each bears critical limitations when applied to the problem of materials selection. The sorting techniques, while simple to apply, depend critically upon the availability of a materials decision maker to guide the setting of the sorting parameters. While this feature makes sorting techniques attractive for computer-aided materials selection, analyses of materials selection by individuals not actively involved in the materials selection cannot be performed with this technique.

The optimization techniques are limited by the need to state an appropriate, analytical objective function for the materials selection problem. Again, the construction of such an objective function depends heavily upon access to a materials decisionmaker. Furthermore, these techniques also rely upon the decisionmaker to guide the optimization process by passing or rejecting solutions generated by the optimization algorithm employed. Finally, the addition of new materials to the set under consideration can require a complete reconsideration of the problem, owing to the sensitivity of optimization algorithms to small changes in parameters and variables.

The hedonic regression techniques are limited by both the analytical technique employed and the assumptions underlying the application of the technique. Regression techniques are limited by the fact that they rely upon historical data. Because the technique employs historical data, it can only reliably be applied to treat past situations. Prospective application of this technique to, say, the introduction of a new material would be fraught with uncertainty because of the inherent assumption of regression models that the future will be similar to the past. The hedonic technique is limited also by its assumption that a direct assessment of market behavior can lead to estimates of the value of a characteristic. While such assumptions are suitable for marketing analyses, the marketplace cannot be relied upon to yield meaningful information on the advisability of applying a material in an engineering application. Such a perspective overestimates the amount of information which can be captured in a single number, the price of a commodity.

Beyond these specific limitations, none of these techniques enables the analyst to capture the structure of the materials selection problem. The techniques each attempt to report upon the consequences of this decision structure, but none of them systematically captures the 'why?' and the 'why not?' of a particular selection process.

However, multi-attribute utility analysis does offer the analyst a tool for capturing precisely this sort of information, while also providing a technique for actually selecting a material for an application. By expressing the preference structure of a materials decision maker in an analytical form, utility analysis enables the analyst to explore the differences between alternatives in a quantitative fashion and to assess the pros and cons of several alternatives.

While this technique has been applied to a wide range of decision problems, it has never been employed to treat the problem of materials selection. The application of this technique to that problem is the subject of the remainder of this paper.

Table 7. Summary of Alternative Techniques

Technique	Assumptions	Advantages	Disadvantages
Exclusionary Screening	- All alternatives known - All objectives known	- Conceptually simple	- Limited to known alternatives - Can only refine non-dominated set
Conjunctive Sorting	- All alternatives known - All objectives known - One objective is most important	- Conceptually simple - Selects a 'best' alternative	- Limited to known alternatives - Selection based on a single property
Lexicographic Sorting	- All alternatives known - All objectives known - All objectives can be ranked by importance	- Conceptually simple - Selects a 'best' alternative - Uses all properties to rank alternatives	- Limited to known alternatives - No tradeoffs between properties
Linear Programming	- Objective can be stated as linear function - Constraints on objective can be stated as linear function	- Routine solution algorithm - Yields relative values of constraints	- Reduces problem to single objective - Flip-flop behavior
Non-Linear Programming	- Objective can be stated in a functional form - Constraints on objective can be stated in a functional form	- Can be computerized - Avoids linearity requirement	- Difficult to obtain solution - Functional forms are still limited - May still reduce problem to single objective

Technique	Assumptions	Advantages	Disadvantages
Goal Programming	- Target levels of achievement known - Weighting for objectives known	- Explicitly treats weighting of objectives - Treats multiple objectives	- Will select dominated solution if too-restrictive goals set - Assumes static weighting of objectives
Sequential Optimization	- All alternatives known - All objectives known - Decisionmaker can identify the 'best' solution if presented with it -	- Involves decisionmaker in process - Can rapidly work to solution - No need to explicitly quantify preferences	- Requires access to decision-maker for each analysis - Does not reveal underlying preference structure
Hedonic Analysis	- Market price is function of commodity characteristics - Historical market behavior reveals value of characteristics - Historical data available	- Treats preferences of large sample - Statistically robust tests available -	- Assumes past is like the present - Requires historical data; cannot treat new commodities well

METHODOLOGY

The application of multi-attribute utility analysis to materials selection will be described in this chapter. The process can be broken down into three major steps: performance evaluation, utility estimation, and utility analysis.

PERFORMANCE EVALUATION

The objectives of the performance evaluation step are to identify the set of characteristics to be assessed in the utility assessment and to describe the set of performance criteria which must be met by an alternative application.

The first step of performance evaluation is a definition of the material application under analysis. Because the objective of this analysis is to assess the applicability of alternative materials, this description must focus on the function of the application, rather than physical characteristics of the application. For example, an automobile bumper should not be treated as "a chrome-plated steel box beam, weighing 35 pounds, attached to the car with two energy absorption units". Rather, a bumper is "an element at the front and rear of an automobile serving a variety of structural and styling functions including ...." Such a functional description eliminates material-specific requirements while implicitly specifying design and material guidelines. Thus, a wide range of potential designs and materials may be included in the analysis. Furthermore, performance need not be limited to engineering performance; other measures of performance (such as cost) may also be included in the description of the application.

Once the application has been functionally described, the next step is to identify which of these performance characteristics must be included in the analysis. This screening of characteristics can be done based on several criteria.

- Binary characteristics - Certain of the characteristics will be binary, that is, a particular level of performance must be met, regardless of any other performance exhibited by the alternative. Futher, over-performance is completely irrelevant to the attractiveness of the alternative. For example, regulated performance requirements frequently fall into this category.

- Non-material-based performance - Even if the universe of material/design alternatives is not limited, those performance characteristics which are not a function of the material employed will not enter into the materials selection process, and may be removed from the characteristic set.

- Irrelevant characteristics - Finally, preliminary estimates of the importance of various characteristics can be made based upon the engineering literature of the application and on preliminary discussions with decisionmakers in the field. Such preliminary screening can help to identify which of the characteristics are of particular importance as well. There are a set of decision analysis tools available which enable the analyst to analytically test the relevance or irrelevance of characteristics under consideration [25,26].

This screening process satisfies the objectives of this step in the analysis. On one hand, the identification of particular classes of performance criteria helps to structure a partial sorting of the material/design alternatives. In particular, those alternatives which fail to meet the requirements of the binary characteristics can be eliminated from further consideration. Similarly, as alternatives are eliminated from the set of alternatives, the diversity of the remaining alternatives may be reduced, which may lead to further reductions in the number of characteristics necessary to distinguish the alternatives.

On the other hand, by limiting the number of characteristics, the size of the utility assessment problem is reduced. The administration of a Keeney-Raiffa type questionnaire is extremely time-consuming, and, at best, six characteristics can be treated in the space of an hour. This time period is probably the maximum feasible amount of time for two reasons. First, it is unlikely that the interviewer can expect to be given more than one hour of a decisionmaker's time. Second, it is equally unlikely that the decisionmaker would be able to concentrate fully on the questionnaire for more than one hour.

QUESTIONNAIRE DESIGN

The primary tool of multi-attribute utility analysis is the questionnaire, which is the heart of the process whereby the preferences of decisionmakers are discerned. The interview questionnaire is a combination of engineering analysis and psychometric testing. On one hand, it incorporates questions regarding the attitudes of the interviewee towards the critical performance requirements of the application being analysed. On the other, it employs well-established psychometric techniques (bracketing) to help the interviewee to express his attitudes as consistently and correctly as possible.

Once the list of performance characteristics is reduced to a manageable size, the next step is to develop the framework of the questionnaire. This framework must serve two competing objectives. On one hand, it must confront the decisionmaker with situations that closely resemble actual situations that he has faced in the past. On the other, the situations must be presented with sufficient novelty to force the decisionmaker to perform the decision based upon the question, rather than to parrot past behavior. In keeping with the nature of the problem, questionnaires oriented around materials acceptance problems were found to be particularly applicable to this class of problems.

The object of this framework is to allow the interviewer to estimate the decisionmaker's multi-attribute utility function for the application, as gauged by the values of the performance characteristics selected in the preceding steps. Thus, the questions must be couched in such a fashion as to allow the interviewer to estimate the single-attribute utility functions and the weighting factors for each characteristic, and to perform tests of the independence assumptions and of consistency.

The questionnaire must treat the following areas.

- characteristic verification
- characteristic ranging
- introduction to the process
- single attribute assessment
- utility combination scaling
- consistency checking
- independence checking

Each of these sections are briefly described below.

Characteristic Verification - In this section, the questionnaire should ask the interviewee to verify whether or not the characteristics specified in the text are important considerations in materials selection. Additionally, the interviewee should be encouraged to note any additional characteristics which may be of interest to him in materials selection the application in question. This latter part is of particular importance in the interview. It helps to establish that the interviewer is interested in the attitudes of the interviewee rather than to validate some already established conclusion of the interviewer. The interviewer is, in effect, asking to be led almost from the very first step, helping to establish a good working relationship with the interviewer.

Characteristic Ranging - In this section, the questionnaire should ask the interviewee to establish the maximum, minimium, and mean values of the characteristics being studied, as well as the units of measure. This helps to establish the range of interest in the application being studied, as well as furthering the interviewee's confidence in answering questions.

Introduction to the Process - In this section, the questionnaire should briefly introduce the structure of the remaining questions. It is unlikely that the interviewee would be familiar with the process and he should be introduced to the process carefully. Following this introduction, a simple game (typically involving the toss of a coin and varing stakes) should be presented to acquaint the interviewee with the mechanics of the process. These simple questions not only introduce the process to the interviewee, but they also help to legitimate the objectives of the interviewer by establishing to the interviewee that nonlinearity of preference is common.

Single Attribute Assessment - In this section, a series of questions should examine the attitude of the interviewee to the performance characteristics being studied. For example, these questions can revolve around a materials acceptance question, where a new material is proposed which may offer an improvement in a characteristic, but may also result in a deterioration in performance. By asking the interviewee just how much of a chance he is willing to take to get an improvement in performance, the single attribute utility function of the interviewee can be estmated.

Utility Combination Scaling - The next section of the questionnaire is aimed at determining the k_i interdimensional scaling value for each characteristic. These questions must be predicated on an assumption regarding the form of the utility function. The number and type of questions to be asked in this section depend upon the assumed functional form of the multi-attribute utility function.

Consistency Checking - The next section should consist of a few questions with slight variations from the preceding ones, which allow the analyst to assess the consistency of the interviewee's response. The preceding questions have produced enough information to allow the analyst to compute the answer that should be expected, if the interviewee is consistent.

Independence Checking - The final section consists of a simple set of questions which test whether the independence assumption made in the formulation of the questionnaire and the utility function is valid. The critical element here is not to force the result. Thus, these questions should be somewhat circumspect and, if anything, should tend to imply that independence should not hold.

The next step is the interview itself. While the questionnaire is the central focus of the interview, a great deal of insight can be gained by paying close attention to the interviewee's comments during the interview. The interviewer should be alert to particular features.

- First, the interviewer should watch for any sign from the interviewee that the questionnaire makes no sense to him. In such cases, the interviewer should draw out the subject, focusing on identifying the source of the problem. While in some cases the problem may be with the questionnaire, in other cases the interviewer may find that the subject is having trouble because the problems being presented are problems that he has never faced. It is possible that the subject is not the sort of decisionmaker that was required.

- Many interviewees find that 'thinking out loud' helps them to make their decisions and the interviewer should pay careful attention to what is discussed. "Rules of thumb" and other bases for decisions should be noted and discussed as time permits.

UTILITY ANALYSIS

The product of an interview is a completed questionnaire, containing sufficient information to allow the analyst to construct the interviewee's utility function. With the construction of this function, a number of analyses may be performed.

First, the alternative material/design systems can be ranked according to preference. By so doing, the 'best' material for an application can be selected, which was the original objective of the analysis. Furthermore, this utility function can be used to treat material/design systems which may not have been explicitly considered at the outset, provided the system falls within the scope of the utility function estimated. This implies that new or currently unconsidered materials systems can be easily treated against the materials currently available for an application.

Beyond the ranking of alternatives, the utility function also enables the treatment of the marginal behavior of the decision maker's preferences. In particular, the ratio between partial derivatives of utility with respect to different characteristics can be computed to determine the rate at which the decision maker trades-off one characteristic for another. Alternatively, iso-utility curves can be plotted to show how the rate at which characteristics are traded-off can vary according to the level of performance.

In addition to this analytical information, the analyst frequently comes away from the interview with a greater understanding of the type of decisions made by the subject and the scope of his decision making. Because the interview is explicitly concerned with performance, it is possible to determine which characteristics are important and this list can be compared and contrasted with similiar lists, both within and without the organization. Differences in these lists can lend insight into the decision processes of various organizations or the individuals within the organization.

Another important result of the interview process is that the shape of the entire materials selection process within an industry can frequently be discerned, particularly following a number of interviews. By recognizing how performance guidelines are set and assessed, it is possible to determine where these critical decisions are made and which individuals or groups of individuals make them. Furthermore, the range of discretion exercised by various groups can identify where organizations compete and where successful materials introduction should take place.

SUMMARY

The materials selection technique described above is a proposed alternative to the multiple objective selection techniques described in the preceding chapter. This technique employs a combination of engineering analysis, exclusionary screening, and utility analysis to determine the best material for an application.

The technique relies upon the assumption that materials and material applications are valued in terms of their performance, rather than upon any intrinsic value the material employed might posess. The technique is composed of three steps. In the first step, performance analysis, the application under consideration is characterized in terms of its performance characteristics. Engineering analyses are employed to determine the level of performance for each material alternative as a function of the physical properties of the material as well as the proposed design.

The number of relevant performance criteria are then limited to a manageable number, usually no more than six. The performance criteria are screened on the basis of their ability to resolve the distinctions between the material alternatives and the degree to which different levels of performance are acceptable for the application. In the course of limiting the characteristics, the materials set can be subjected to exclusionary screening based upon the level of performance required.

In the second step, utility assessment, the remaining characteristics are incorporated into a Keeney-Raiffa type interview questionnaire. This questionnaire is then administered to materials decision makers in the relevant field and its results analyzed.

In the final step, the utility function derived from the interviews is used to rank the remaining material alternatives in terms of the decision maker's preferences. This utility function may also be used to determine the rate at which the decision maker trades-off properties and which characteristics are of most importance to him.

This technique offers considerable advantages over the techniques described in the preceding chapter. First, it provides the analyst with an analytical function describing the decision maker's preferences. Unlike techniques which use the decision maker's preferences to guide the search for a solution, this technique results in a description of the decision maker's preference structure which can be applied to different material sets without requiring a new round of interviews and assessments. This flexibility allows the analyst to treat the structure of the decision maker's preferences as well as the consequences of them. Thus, it allows the analyst to conduct a variety of sensitivity analyses, studying the impact of changes in material performance upon the relative attractiveness of alternatives.

Second, the technique gives the analyst a tool for examining the structure of materials decision making within an organization. Through the interview technique, decision makers are encouraged to reveal the ways in which materials decision are made within an organization and how the structure of these decisions effects the preferences of the decision makers.

Finally, the technique explicitly treats the performance of an application, rather than the material employed in the application. This approach enables the analyst to avoid the pitfalls of material biases which can cloud materials selection issues.

APPLICATION OF THE METHODOLOGY

The methodology described in the preceding chapter has been applied to the analysis of materials selection in the automobile industry. In particular, two automotive components were treated; the outer panel of a deck lid and the front bumper. Automobile components were chosen for this analysis because of the wide range of material alternatives available to automobile makers and because of the wide range of performance requirements these components must meet. Additionally, a number of materials manufacturers were interested in improved methods for automaker's attitudes towards materials selection.

The deck lid analysis was the first application of this methodology. Using the results of this analysis, the technique was refined and then applied to bumper system analysis. The following sections describe the application of the methodology to these two cases.

DECK LID OUTER

The automobile deck lid (or trunk lid) is a familiar component to any automobile user. The trunk lid consists of two main components; the inner and the outer deck lid. The inner deck lid is a structural member. It provides stiffness and rigidity to the deck lid and attaches to the rest of the car with a pair of hinged supports. The outer deck lid is a flat panel with a high grade finish which must resist not only the elements, but also repeated impacts from the user of the trunk.

The deck lid outer of a GM-X car was selected as the basis of this analysis. The outer alone was selected because of the difficulty associated with attempting to redesign an entire deck lid for each candidate material. The outer, as a panel member, represented a far less challenging engineering problem. Additionally, a considerable amount of work treating material alternatives for deck lids was available to validate the engineering and economic bases for the multi-attribute utility analysis. [142]

ALTERNATIVE MATERIALS

Three materials were considered for this application. These were steel sheet, aluminum sheet, and sheet molding compound (SMC). These three broad classes represent the three historical competitors for automobile panel applications. Steel sheet has been the preferred material for the last seventy years of automobile manufacture. Aluminum has been used in the past to meet weight performance requirements. SMC has only recently been applied in autmobile panels, most notably the Pontiac Fiero.

Because the treatement of the deck lid was the first application of this methodology, there was a minimum of emphasis on the actual material alternatives to be treated. This limited set of alternatives was chosen to demonstrate the scope of the analysis by treating three distinct, competitive material systems rather than attempting to encompass explicitly the entire scope of the material alternatives available. While the utility function derived from this analysis would be applicable to many other material systems, little benefit would be gained from treating every material system available.

PERFORMANCE EVALUATION

The steel deck lid outer of the 1982 Chevrolet Cavalier was chosen as the base line design. This component weighs 17 pounds and is made of steel sheet with a 0.033 inch gauge.

In order to determine the gauge of the aluminum and the SMC systems, 4 automotive panel design relations were used. According to Chang and Justusson [29], the critical design criteria are

1. Oil canning resistance - a function of modulus and geometry
2. Buckling resistance - a function of modulus, Poisson's ratio, and geometry.
3. Dent resistance - a function of yield strength, modulus, and geometry
4. Vibration resistance - a function of modulus, density, and geometry

In order to compute the geometry and weight of the SMC and aluminum systems, a two assumptions were made. First, the only difference in the geometries of the three alternative systems would be in the gauge of the panel. Second, the SMC and aluminum systems must exhibit the same or better dent resistance, oil canning resistance, and buckling resistance as the steel panel. Based upon these assumptions and the design equations for panels, the following weights and gauges were computed.

Table 8. Computed Gauges for Deck Lid Materials

Material	Weight	Thickness
Mild Steel	17 lbs.	0.033 in.
Al-6009-T4	9.9 lbs.	0.055 in.
SMC-37% Glass	12 lbs.	0.104 in.

This analysis revealed five performance features of the deck lid outer. To recap, these are

1. Weight,
2. Dent Resistance,
3. Oil Canning Resistance,
4. Buckling Resistance, and
5. Vibration Resistance.

A sixth characteristic, the cost of the panel, was added to this list. This cost included the costs of the material, the costs of fabricating and finishing the panel, and the costs of installing the panel. The costs used in this analysis were estimated using engineering cost models for aluminum and steel stamping, SMC molding [24], and automotive finishing and assembly. Please see Appendix B for further descriptions of these models and Appendix C for the output used in this case.

The results of these cost models can be summarized as follows:

Table 9. Cost Model Results - Deck Lids

	Primary	Secondary	Total
Mild Steel	$10.41	$17.20	$27.61
Al-6009-T4	$20.76	$19.32	$40.08
SMC	$17.75	$13.41	$31.16

QUESTIONNAIRE DESIGN

Once the performance criteria were established, the next step was the design of the questionnaire. After conversations with automobile engineers, the question of material acceptance or rejection on the basis of performance was selected as the basis for the questionnaire.

Following a set of questions designed to determine the applicability of the six criteria and the observed range in their values, the utility questions confronted the decision maker with a number of material acceptance problems. In each case, a new material was presented which performed adequately in five of the six areas, with an uncertain performance in a sixth. The decision maker was asked to state how likely improved performance in the sixth area had to be before he would use the new material. These questions were used to determine the single attribute utility functions for each of the sixth characteristics.

The next set of questions again confronted the decision maker with a materials acceptance problem, but this time all six characteristics were involved. Again, he was asked to state how certain he had to be of improved performance before he would select an uncertain outcome to a certain one.

The text of this questionnaire can be found in Appendix A. It is important to note that this questionnaire only treats a range of plus or minus ten percent of the 'average performance; in this case, steel. During preliminary interviews with MIT faculty in the materials field, interviewees gave conflicting opinions on what would be a reasonable range of values to be treated. Because of this uncertainty, it was decided to start with a narrow range and assess the automaker's responses. As a result, this narrow range was selected in spite of the wide range of the weight and cost characteristics noted above.

INTERVIEWS

Interviews were conducted in Detroit during the week of the 1984 SAE Congress. Three materials/design engineers (one from each of the Big Three) and one purchasing engineer were interviewed. Each of the design engineers responded positively to the questionnaire, although each was hesitant at first. The three design engineers pointed out that, while the questionnaire was somewhat more structured than they were used to, the problems presented were similar to problems that they faced on a regular basis. All three pointed out that surface finish was an important characteristic which had been left out of the questionnaire. However, they all agreed that surface finish was a binary-type characteristic, i.e., nothing could make up for inadequate performance in this area. Another characteristic mentioned was corrosion life, which they felt was an important criterion. Finally, they pointed out that vibration resistance was not something that they worried about much.

The interview with the purchasing engineer was also informative, although for a different reason. In all cases, he was unwilling to consider taking any risk in performance. Rather than completing the questionnaire, the nature of his decision making problems were discussed. He pointed out that purchasing engineers were given a set of material specifications which had to be met. While there were incentives to purchase such material at a minimum of cost, under no circumstance, regardless of cost benefit, was he to purchase material not up to specification.

UTILITY ANALYSIS

The responses of the material/design engineers were used to construct their multi-attribute utility functions. The multilinear form was used and the functions were scaled to range between 0 and 1. These functions were used to compute the utilities of the three alternative material systems. The data employed and the results of the calculations are presented below.

Table 10. Deck Lid Responses - Subject 1

Attribute	Utility of Midpoint	k scaling factor
Dent Resistance	0.8	0.2
Cost	0.6	0.3
Weight	0.5	0.3
Oil Canning Resistance	0.6	0.2
Vibration	0.8	0.2
Buckling Resistance	0.9	0.1

Table 11. Deck Lid Responses - Subject 2

Attribute	Utility of Midpoint	k scaling factor
Dent Resistance	0.9	0.8
Cost	0.9	0.8
Weight	0.9	0.8
Oil Canning Resistance	0.99	0.7
Vibration	0.99	0.75
Buckling Resistance	0.7	0.7

Table 12. Deck Lid Responses - Subject 3

Attribute	Utility of Midpoint	k scaling factor
Dent Resistance	0.99	0.4
Cost	0.7	0.95
Weight	0.9	0.95
Oil Canning Resistance	0.9	0.5
Vibration	0.9	0.5
Buckling Resistance	0.9	0.5

Table 13. Material Utilities for SUBJECT1

Mild Steel	0.75
Al-6009-T4	0.67
SMC-37% Glass	0.67

Table 14. Material Utilities for SUBJECT2 & SUBJECT3

Mild Steel	0.99
Al-6009-T4	0.99
SMC-37% Glass	0.99

These results point out the major limitation of this analysis. The narrow range (+/- 10%) of characteristics treated resulted in a utility function unable to capture the full differences between the aluminum and the SMC case. In particular, although there were differences in the performance of aluminum and SMC is several areas, these levels of performance were outside the range of the assessment, requiring that they both be assigned utility values of 1 or 0.

In spite of this limitation, the utility functions correctly capture the fact that steel is the preferred material for this application. For all subjects, the utilities of aluminum and SMC were equal and the utility of steel was greater than that of the alternatives.

SUMMARY AND CONCLUSIONS

The results of this case study were very encouraging. The most important result was that the methodology proved usable in this situation and yielded results consistent with observed behavior. The idea of the questionnaire, while new to the interviewees, was found to be an appropriate mechanism for discussing their preferences for characteristics. The questionnaire was also a useful basis for examining the range of decision making power of individuals and could be used to identify the range of a decision maker's discretion.

The case study also pointed out particular deficiencies in the method used. In particular, the range of plus or minus 10% of the average value was found to be too restrictive for analysis. Interviewees indicated that such a range was almost too small to consider, except when dealing with costs. All other characteristics typically had ranges of plus 100% and minus 50%.

Nevertheless, this first case application of the methodology successfully demonstrated the feasibility of its application to the problem of materials selection.

BUMPER SYSTEMS

Following the completion of the deck lid analysis, a case study of materials selection for bumper systems was undertaken. Bumper systems are an area of active materials change. Less than twenty years ago, all bumpers were chrome plated, stamped steel beams whose primary function was for show. Since that time, a combination of Federal regulations, energy crises, and overseas competition has led to many changes in automobile bumpers, including the introduction of plastic components.

The scope of this case analysis was limited to the treatment of bumper systems for which plastic systems could be feasibly substituted. This scope limited the case to the treatment of the so-called aerodynamic bumper system. These systems are noted for the way in which their lines seem to flow directly from the car, as opposed to older 'hang-on systems. The bumper system of the Ford Tempo was used as the baseline design for the analysis.

ALTERNATIVE MATERIALS

The basis of the case study was to compare the utility of two proposed plastic systems with two currently employed bumper systems. The object of the study was to determine if the proposed systems would be more attractive to automakers than the current systems. The four systems are briefly described below.

- System 1 - A stamped steel beam, mounted to the automobile on hydraulic strokers for energy management, and covered with a reaction injection molded (RIM) polyurethane fascia.
- System 2 - A stamped steel back plate directly mounted to the car. The plate is faced with an EVA honeycomb and covered with a RIM fascia.
- System 3 - A plastic beam, covered with a RIM fascia.
- System 4 - A one-piece, structural plastic fascia, mounted to the car with hydraulic strokers.

PERFORMANCE EVALUATION

The evaluation of bumper performance is based upon a wide range of characteristics. Furthermore, the selection of a bumper material is critically dependent upon styling decisions. For this case study, the selection of the class of systems under consideration had a major influence upon the performance characteristics used.

Cost and weight were included in the analysis, based upon the automobile industry's current concern with economy. Also included was the Federal Motor Vehicle Safety Standard (FMVSS) for automobile bumper impact. At the time of the case, the Federal government had recently reduced this standard from a 5 mile per hour impact test to a 2.5 mile per hour impact test and the value of improved performance in this area was of interest.

The three other characteristics considered for this analysis were the outgrowth of numerous discussions with automobile design engineers and material suppliers to the automobile industry. Two of these characteristics were chosen to reflect Detroit's concern for the longevity of the automobile and its appearance. The appearance of a bumper system suffers either from environmental exposure (such as corrosion or solvent attack) or from impacts. Service life was selected as a characteristic in order to treat environmental degradation and dent resistance was selected to treat impact resistance.

The sixth characteristic was chosen following discussion with bumper design engineers. They pointed out that the most important part of bumper styling and design was related to the distance between the bumper and the rest of the car. This distance is necessary to give the bumper room to deflect and absorb collision energy, instead of transmitting it to the vehicle. Therefore, deflection distance was included in the set of characteristics.

A number of important performance criteria were not included in the analysis, primarily because these characteristics were binary in nature. These included surface finish, paintability, and impact strength at low temperatures. Under no circumstance would other characteristics be able to compensate for inadequate performance in these areas, so they were not included.

QUESTIONNAIRE DESIGN

The questionnaire employed in the bumper case was very similar to the one used in the deck lid case. The situations presented were the same as those presented in the deck lid case, except the range of interest was expanded. For cost, weight, dent resistance, deflection distance, and service life, the range was changed to a 100% improvement over average and a 50% degradation over average. For the FMVSS characteristic, the range was between a 2.5 mph standard and a 7.5 mph standard.

Additionally, the name of the 'new' material was changed from AlloX to Meta-Last, to try to avoid the implication that the test material was a metal.

The text the bumper questionnaire can be found in Appendix E.

INTERVIEWS

A total of five interviews were conducted in Detroit during the months of July and August of 1984. Of these, three were administered to engineers in advanced bumper design or advance engineering, one to an engineer in production engineering, and one to an engineer in materials engineering. (Please refer to Appendices F and G). The interview with the materials engineer was later rejected on the basis of his lack of experience in the area.

These interviews yielded considerable insights into the materials selection process in the automobile industry. The first of these regards the distinction between the product and advance engineering groups. While the advance engineering subjects were willing and interested in taking chances to improve performance, the production engineering subject was not. As long as he could achieve satisfactory performance, he was completely uninterested in improved performance.

This behavior is a consequence of the fact that almost all materials selection takes place in advance engineering. The production engineer's function is to translate the performance targets of the advance engineering staff into actual performance. For him, there is no advantage to doing better than specification, but a great disadvantage if he fails to meet his specification.

The advance engineering subjects also exhibited unexpected behavior during their interviews. While all agreed that dent resistance, service life, deflection distance, and FMVSS performance were important, they all pointed out that there was little benefit associated with better than adequate performance in these areas. Their attitude was that improved performance in any of these four areas would be sacrificed in order to achieve improved cost or weight performance. They all agreed that, as long as adequate performance in these four areas was achieved, cost and weight was all they were really concerned about.

The questionnaire responses of the Advance Engineering subjects are presented below.

Table 15. Bumper Responses - Subject 1

Attribute	Utility of Midpoint	k scaling factor
Dent Resistance	0.60	0.20
Cost	0.70	0.90
Weight	0.80	0.90
Service Life	0.50	0.30
FMVSS	0.50	0.20
Deflection Distance	0.50	0.70

Table 16. Bumper Responses - Advance Engineering Subject 2 & 3

Attribute	Utility of Midpoint	k scaling factor
Dent Resistance	0.90	0.01
Cost	0.80	0.95
Weight	0.85	0.95
Service Life	0.80	0.10
FMVSS	0.95	0.10
Deflection Distance	0.90	0.95

UTILITY ANALYSIS

The utility functions of the three advance engineering subjects were found to yield numerically similar with respect to weight and cost, so the results of only one is presented here. Because of the decision makers expressed indifference to above standard performance in the FMVSS, dent resistance, service life, and deflection distance characteristics, the values of these characteristics were set equal to the standard for all four cases. The computed utilities are as follows:

Table 17. Bumper System Utilities

Case Name	Cost	Weight	Utility
System 1	$ 67.84	31.60	0.96
System 2	$ 55.98	27.00	0.98
System 3	$ 68.80	21.65	0.98
System 4	$ 80.78	27.35	0.95

The utility function gives System 3 (one of the proposed bumper systems) a higher ranking than that of System 1, the most commonly employed system today. Additionally, the ranking of System 2 over System 1 is somewhat surprising, in view of their relative use. However, further engineering analysis reveals that System 2 may not be completely compatible with System

1. System 2 is a special-purpose system which is currently employed on the Pontiac Firebird because of the styling advantages it offers. On the whole, its engineering performance may not be a good as was assumed in this analysis.

In addition to ranking the alternatives, an iso-utility map can be made. This map can be used to identify graphically the relative importance of cost and weight and the degree to which changes in the cost or weight of a system can change the relative preferability of the system. Two plots of the iso-utility map are presented in the following pages. In the first, the four systems are plotted with the iso-utility curve associated with System 1. In the second, a more extensive iso-utility map is presented.

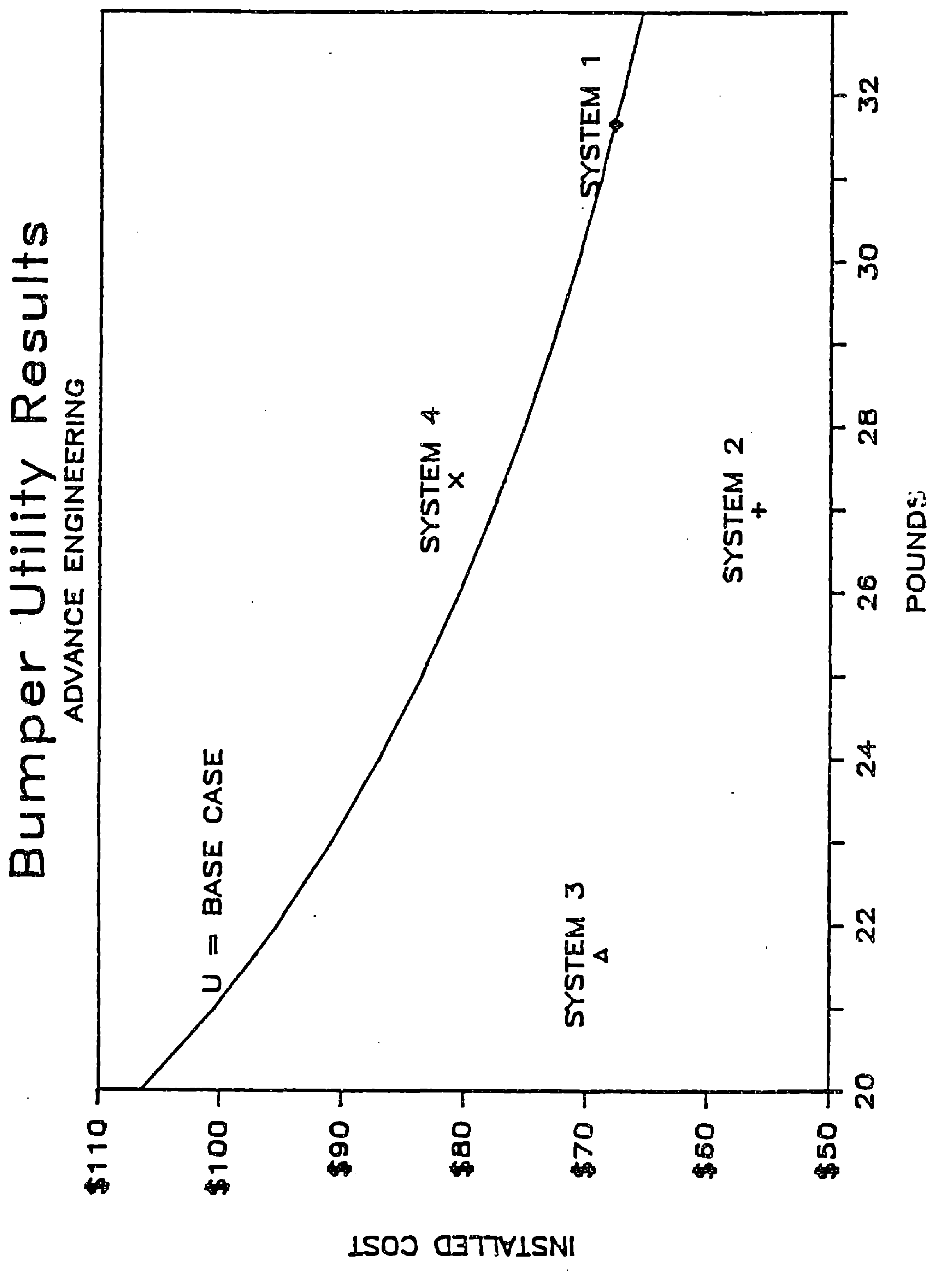


Figure 3. Bumper Ranking Plot

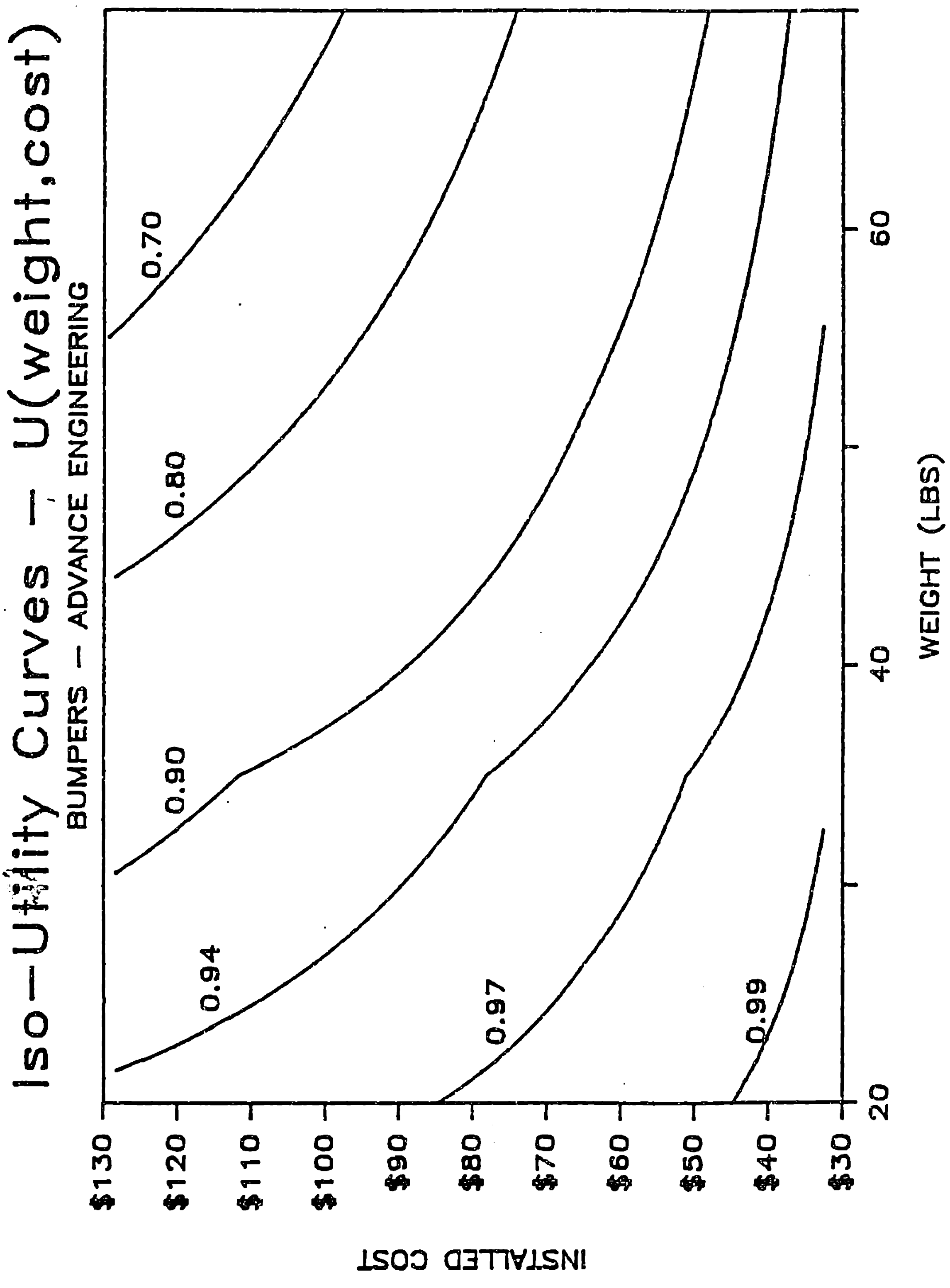


Figure 4. Utility Function Map

SUMMARY AND CONCLUSIONS

The bumper case study was a much more detailed application of the methodology to a particular problem. Through the application of the technique, four different bumper designs using different materials were analyzed. These different systems were defined in terms of six performance characteristics, whose utility was assessed and incorporated in a multi-attribute utility function. This function was then used to rank the alternatives on the basis of their performance. Further, an iso-utility map of this function was developed in order to assess the ability of changes in important performance characteristics to change the ranking of the alternatives.

In addition to the analytical results, the questionnaire proved to be a useful tool for guiding a discussion of the way in which materials decisions are made within the automobile industry. The questionnaire/interview technique also was an effective way to determine the subject's preference structure for the characteristics of interest. The results of this analysis were subsequently presented to several of the engineers interviewed, who substantially confirmed that the utility plots presented above represented their attitudes towards materials selection for automotive bumper systems.

UTILITY ANALYSIS COMPARED WITH OTHER MATERIALS SELECTION TECHNIQUES

In this chapter, the technique presented in this thesis will be compared and contrasted with the most commonly used technique in materials selection, sorting. In particular, the bumper case presented in the preceding chapter will be treated with the conjunctive sorting technique and with the weighted indexing or geometric technique described in the third chapter of this thesis. The results of these techniques will be compared with the proposed technique and the advantages of this technique over the typical techniques will be described.

CASE DESCRIPTION

The materials selection problem to be treated will be the one presented in the preceding section regarding automotive bumper systems. The reader is referred to the preceding chapter for a description of the four systems treated. In this chapter, only the characteristics of interest will be described.

Six characteristics of the bumper systems were proposed as being of particular relevance to the problem of bumper materials selection. These characteristics are:

1. Weight,
2. Cost,
3. FMVSS Performance,

4. Dent Resistance,
5. Deflection Distance, and
6. Service Life.

For the purpose of the analysis, it is assumed that the four bumper systems meet or surpass the exclusionary screening characteristics which pertain to bumper systems. The materials selection problem will then be based upon these six characteristics, or some subset thereof.

For the purposes of illustration, this set of six characteristics will be further limited to just two, cost and weight. As has been discussed, the utility analysis revealed that these were the only two characteristics which automobile materials decision makers were actually willing to balance one against the other. In general, the selection of the characteristics of interest for the sorting techniques would be one of the major tasks facing the analyst using these techniques, while utility analysis enables the analyst to discern the important characteristics readily. However, in the present case, it would be difficult to argue that an automotive materials analyst would not already have focused upon cost and weight as the criteria of particular interest to automobile manufacturers. It should be remembered, however, that other characteristics might otherwise be included.

APPLICATION OF SORTING TECHNIQUES - CONJUNCTIVE SORT

In order to perform a conjunctive sort, the analyst must be able to select a characteristic from the set of characteristics which then becomes the criterion by which the 'best' alternative is selected. Assuming that the analyst selects either cost or weight as the conjunctive sorting criterion, and, furthermore, that the lowest level of these attributes is the most preferable, the following results may be obtained from the data presented in the preceding chapter and in the figure below.

Table 18. Conjunctive Sorting of Bumper Alternatives

Ordered According To Cost

	Cost	Weight
System 2	$55.92	27.00
System 1	$67.84	31.65
System 3	$68.80	21.65
System 4	$80.78	27.35

Ordered According To Weight

	Cost	Weight
System 3	$68.80	21.65
System 2	$55.92	27.00
System 4	$80.78	27.35
System 1	$67.84	31.65

Notice that the data present particular difficulties for this sorting technique. An ordering by cost suggests System 2 is the best, while an ordering by weight suggest System 3. If the analyst believes that only one of these sorts should be used, then either System 2 or System 3 would be chosen.

It is possible that an analyst may feel that the results of both of these sorts should be incorporated in his selection. Noticing that System 2 ranks

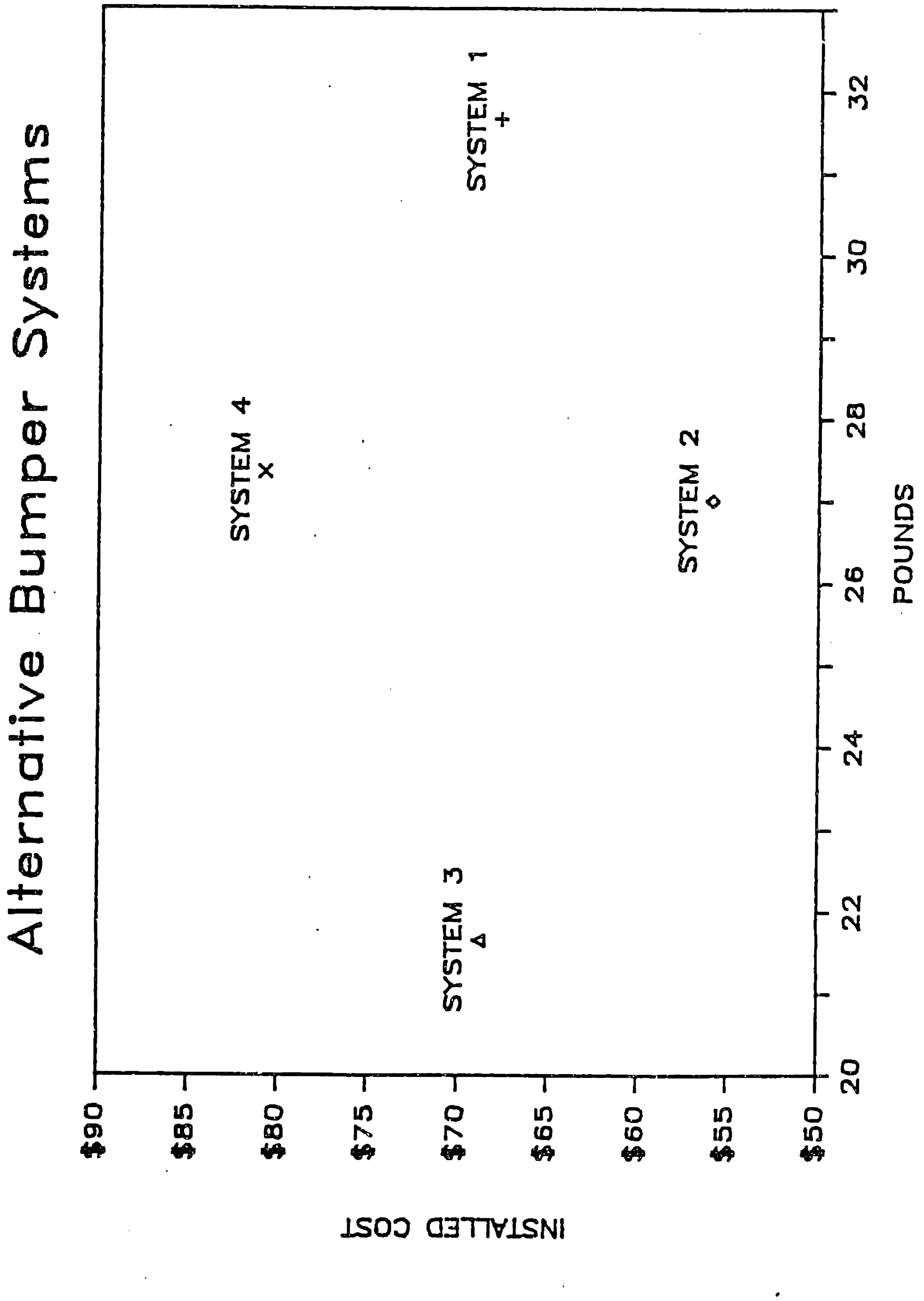


Figure 5. Bumper Alternatives Plot

in the top two in both sorts, an analyst employing the conjunctive sorting technique would likely select System 2.

However, it is important to note that there are two systems with about the same weight (Systems 2 and 4) and there are two systems with about the same cost (Systems 1 and 3). If the analyst ignores the small difference in cost between Systems 1 and 3, he finds that System 2 has the best cost and the second best weight while System 3 has the best weight and the second best cost. Under these conditions, an analyst would have a very difficult time justifying choosing System 2 over System 3 or vice versa solely on the basis of conjunctive sorting.

APPLICATION OF SORTING TECHNIQUES - WEIGHTED INDICES

In order to treat more than one characteristic, a sorting based upon a weighted index of characteristics can be employed. Assuming that the objectives of the selection process are to minimize cost and weight, the most preferable alternative will be the one yielding the lowest index value. If the cost and weight figures are normalized against the largest value under consideration, the following indices can be computed.

Table 19. Bumper Cost and Weight Indices

	Cost	Weight	Normalized Cost	Normalized Weight
System 1	$67.84	31.65	0.84	1.00
System 2	$55.92	27.00	0.69	0.85
System 3	$68.80	21.65	0.85	0.68
System 4	$80.78	27.35	1.00	0.86

[Normalizing basis ($80.78, 31.65 lbs.)]

Based upon a relative weighting factor, these indices can be combined to form a single index for decision between material alternatives. Naturally, the selection will depend upon the weightings selected. In the following figure, the possible index values for varying weightings placed upon each characteristic are presented. The weightings were chosen such that the sum of the weightings placed upon the cost and weight indices summed to one. Therefore, the plot represents, moving left to right, how the ordering of the alternatives changes as cost becomes more important, and weight less important, in the composite index.

Three possible orderings are revealed. At the leftmost edge, the orderings are the same as those derived from the conjunctive sort based on weight (3,2,4,1); at the rightmost edge, the ordering from the cost-based conjunctive sort (2,1,3,4); and, towards the center-right of the plot, the ordering is (2,3,1,4).

Again, this weighted index approach will yield a certain result for a specified set of weightings. However, if the analyst is less certain of the weightings (as would likely be the case), he is again unable to make a clear choice between Systems 2 and 3. Notice that in the vicinity of the 50-50 weighting on the two characteristics, the ordering changes twice. If the weighting put on cost is 0.4, the order is (3,2,4,1); if the weighting on cost is 0.5, the order is (3,2,1,4); and if the weighting on cost is 0.6, the ordering is (2,3,1,4).

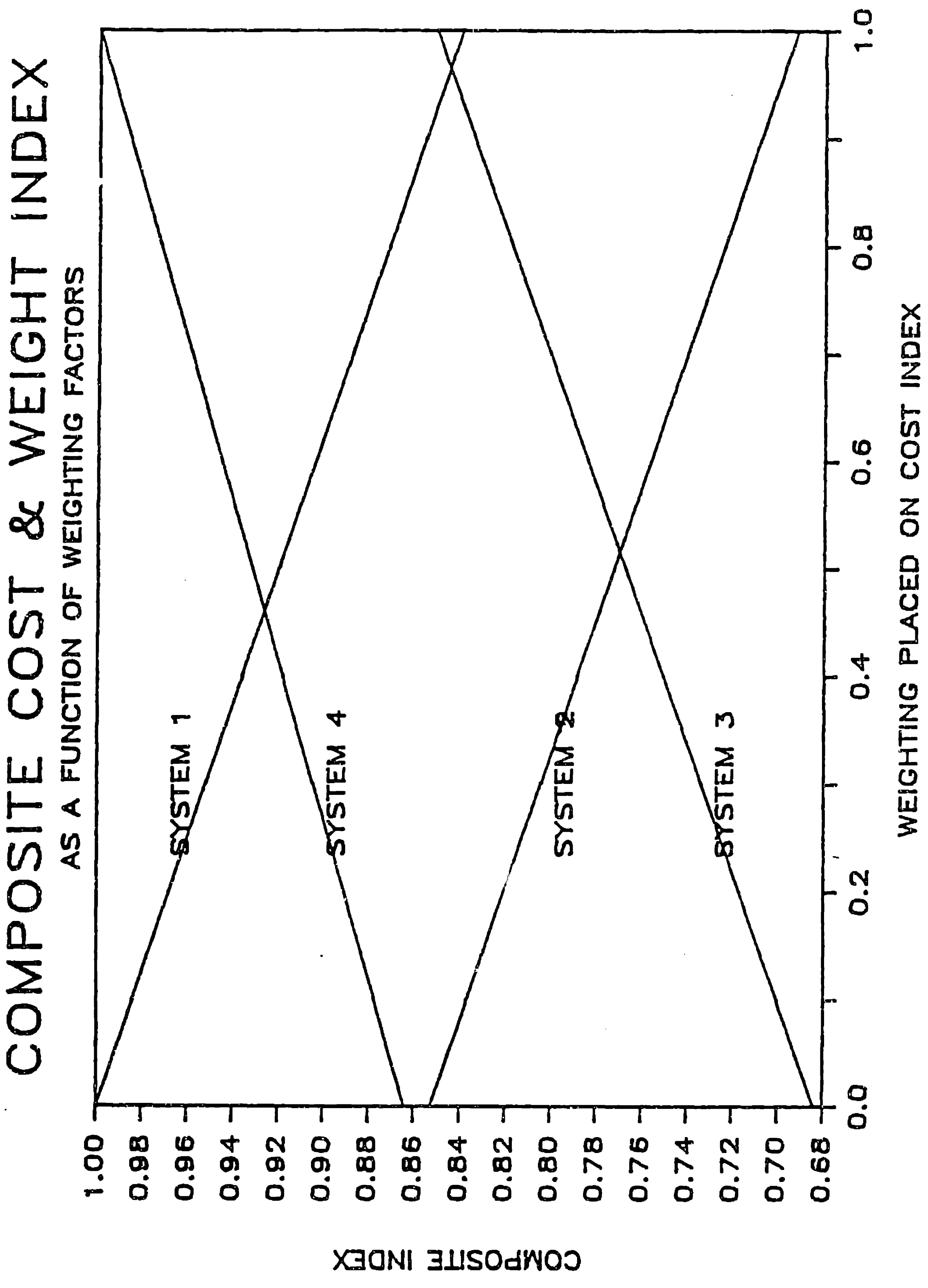


Figure 6. Indices As A Function of Weighting

COMPARISON OF SORTING RESULTS WITH UTILITY RESULTS

The results of the sorting analyses may be summarized as follows:

1. A conjunctive sort on weight leads to the ordering (3,2,4,1), indicating that System 2 should be chosen.

2. A conjunctive sort on cost leads the the ordering (2,1,3,4), indicating that System 3 should be chosen.

3. An application of the weighted indexing or geometric approach weighting cost and weight indexes equally leads to the ordering (3,2,1,4), indicating that System 3 should be chosen.

The utility function developed in the preceding chapter orders the four alternatives somewhat differently. Systems 2 and 3 are ranked first, followed by System 1 and then System 4. The utility function indicates that Systems 2 and 3 are virtually equivalent in terms of their preferability, while Systems 1 and 4 are less preferable.

Thus, the three techniques choose either System 2 or System 3 as the 'best' material/design selection for a bumper system. This result of itself is not particularly surprising or informative. Given the emphasis on cost and weight, one would expect that the preferred system would be the one either with the lowest cost or the lowest weight.

However, the utility function indicates something which the other techniques do not; namely, that the two systems are preferentially equivalent. This implies that, while there are performance differences between the two systems, they are equally attractive to an automotive materials decision maker.

The ranking of the four systems, however, is only a part of the results obtainable from the utility function. At least as important, if not more so, is information which reveals the degree to which one characteristic is traded off against another. This difference between the utility function and the sorting techniques is best illustrated by asking the question 'To what degree must each alternative change in order to make it as good as the best alternative?' The application of these techniques to this question reveals the differences between these techniques.

The conjunctive sorting technique forces the analyst to consider that the ordering of the alternatives may only change according to changes in the characteristic used to sort the alternatives. The following table shows the changes in cost or weight required for each alternative in order to give it the same ranking as the best alternative.

Table 20. System Performance Limitations - Based On Conjunctive Sort

	Cost	Weight	Delta Cost	Delta Weight
System 1	$67.84	31.65	-11.92	-10.00
System 2	$55.92	27.00	0.00	-5.35
System 3	$68.80	21.65	-12.88	0.00
System 4	$80.78	27.35	-24.86	-5.70

An important feature of these results is that no halfway measure will do. If a conjunctive sort is performed with cost as a basis, no amount of change in the weight of the alternative will have any effect upon its ordering in the sort. If the conjunctive sort is based on weight, a reduction in cost will be similarly ineffective.

The weighted index technique does take both characteristics into account when ranking the alternatives. The following table outlines the degree to which cost or weight must change in order to give each alternative the same ranking as the best system. Furthermore, linear combinations of these costs and and weights (i.e., 30% of the cost improvement and 70% of the weight improvement) will also yield the same ranking.

Table 21. System Performance Limitations - Based On Weighted Indices

	Cost	Weight	Delta Cost	Delta Weight
System 3	$68.80	21.65	0.00	0.00
System 2	$55.92	27.00	-0.77	-0.30
System 1	$67.84	31.65	-24.56	-9.62
System 4	$80.78	27.35	-26.53	-10.39

These results may best be summarized by the following figure. The line passing throught the System 3 point constitutes all combinations of cost and weight which yield the same index value as System 3. All points above and to the right of the line have lower index values, and those below and to the left have higher index values. For Systems 1, 2 and 4, any change in cost and weight which puts it on the line will therefore give it the same ranking as System 3.

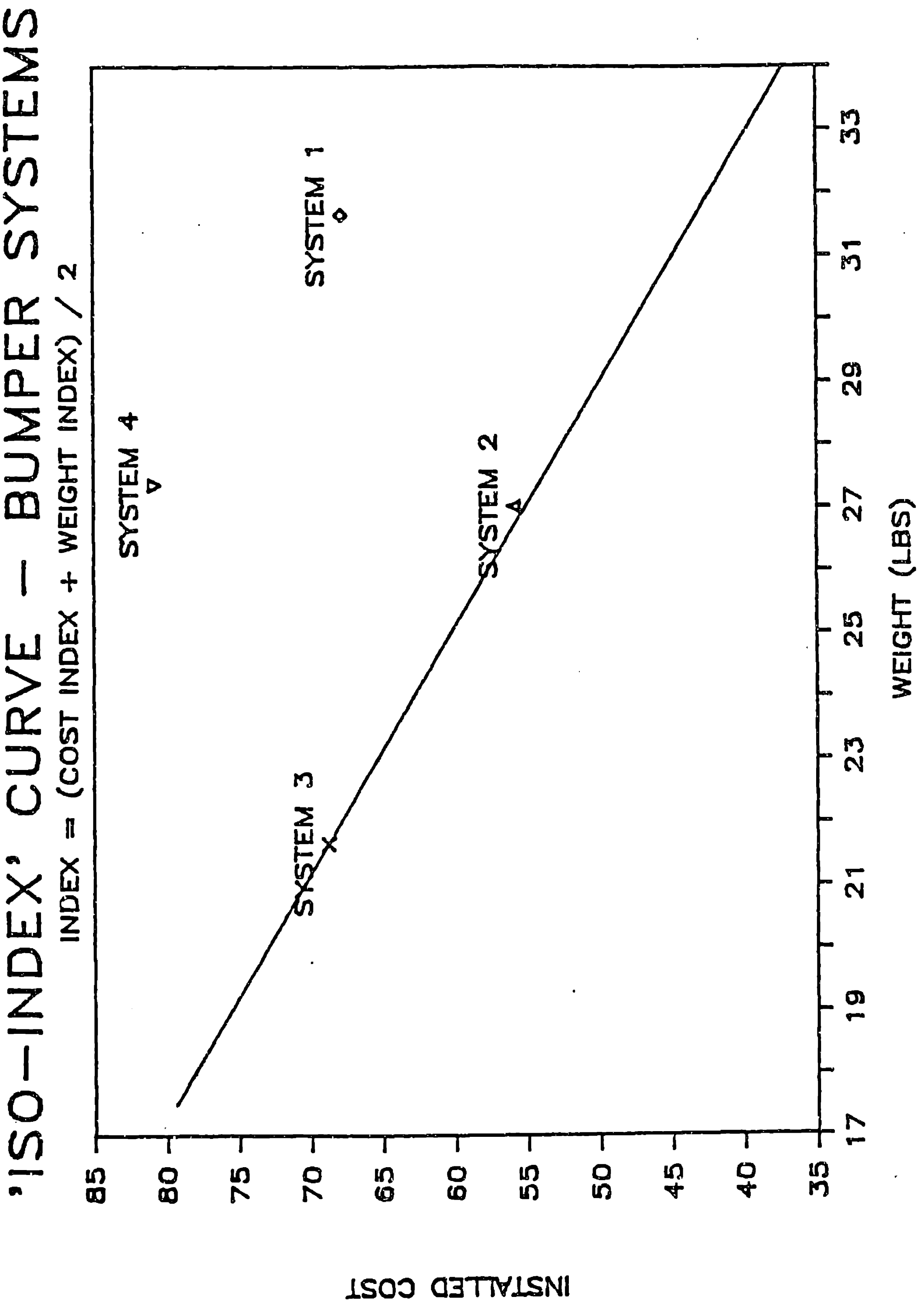


Figure 7. Iso-Index Plot

While such computations can be made, it is not at all clear what they mean. The weighted indexing technique constructs a simplified model of the way in which the characteristics are traded off, but in no way can it demonstrate that this model of preferences correctly reflects the preferences of the decision maker. This is where the utility approach to the problem demonstrates its greatest advantage. First, while the geometric approach invites the decisionmaker to establish the weightings appropriate to the characteristics in question, the utility questionnaire enables the analyst to capture directly the preferences of the decision maker and to incorporate these weightings into the utility function. Second, the utility questionnaire enables the analyst to capture the non-linearities of the decision maker's preferences for different levels of characteristics in a consistent way. This non-linearity of preferences, a frequently observed characteristic of individual decision making, cannot be captured using the sorting or indexing techniques. Finally, the utility function incorporates not only the preferences, but also the structure of the way in which the decision maker balances these preferences. This structure can be tested and the test results can be used to construct a utility function whose functional form will capture this structure.

The following figure superimposes an iso-utility curve onto the iso-index line presented in the preceding graph. This iso-utility curve consists of all combinations of weight and cost which yield the same utility as that of System 3. Naturally, the curve and the line intersect at the point associated with System 3. Also, because of the assumption that cost and weight are equally important, they also intersect near the point associated with System 2. However, notice that the utility curve thereafter is always above the iso-index line, indicating that the degree to which Systems 1 and 4 must reduce their cost or weight in order to be as good as System 3 is not as great as would be required if the iso-index line were used.

The iso-utility and the iso-index curves are quite close in this case, owing to a good guess of the weighting associated with each characteristic. Small differences in the slope of the iso-index curve would not necessarily lead to a different ordering of the alternatives, but it would lead to significant differences in the degree of change necessary for alternatives to become 'as good as' System 3.

SUMMARY OF THE DIFFERENCES BETWEEN SORTING AND UTILITY TECHNIQUES

The major differences between the sorting and the utility approaches to materials selection problems may be summarized as follows;

- Conjunctive sorting techniques are unable to treat tradeoffs between one characteristic and another. The sole measure of the attractiveness of a particular alternative is the characteristic employed in the conjunctive sort. For example, low weight is of no value in a conjunctive sort when low cost is the sorting criterion. This is in direct contrast with either weighted indexing techniques or utility techniques, which employ all relevant characteristics in assigning a ranking to an alternative.

- Weighted indexing techniques are limited in three ways when compared with utility analysis techniques. First, weighted indexing techniques can

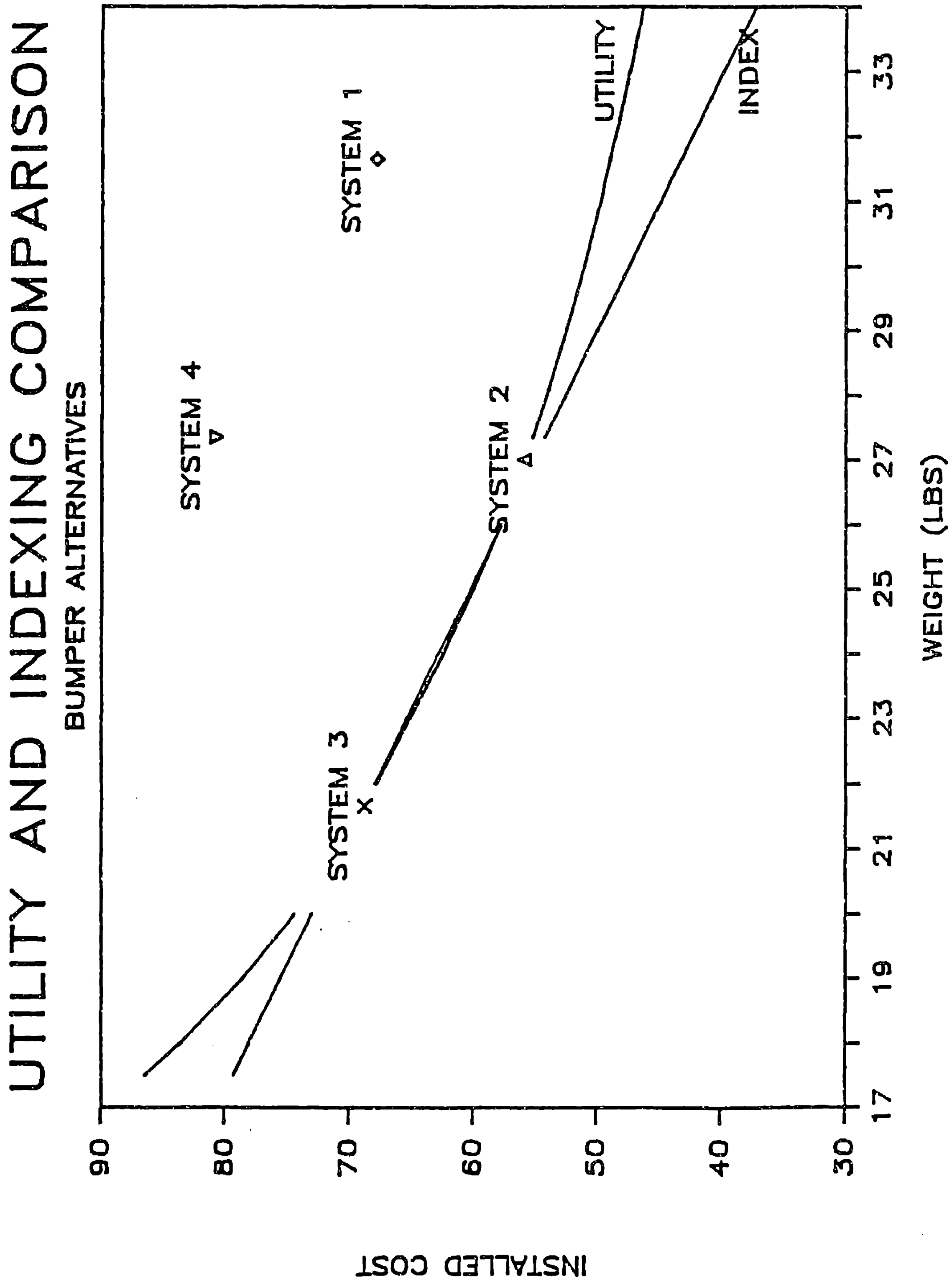


Figure 8. Iso-Index and Iso-Utility Plot

not help the analyst to identify which characteristics are of interest and which are not. The technique does not enable the analyst to identify the relevant characteristics systematically. Second, weighted indexing techniques assume that preferences for characteristics are linear over the range of interest. Third, weighted indexing techniques do not identify the structure of the tradeoffs between characteristics beyond the setting of linear weightings on levels of performance. Because of these last two limitations, it is impossible to satisfactorily employ the differences in index values to identify quantitative differences between alternatives.

- Utility assessment techiques are not limited as the weighted indexing techniques are. Utility assessment techniques enable the analyst to identify which characteristics are relevant and which are simple constraints. Utility assessment techniques are based upon structural assumptions about decision making, which are tested in the course of the analysis. Finally, utility assessment techniques, as a consequence of their structural validity, can be used to make direct, quantitative comparisons between different levels of performance, enabling the analyst to quantitatively measure the degree to which any alternative out- or under-performs another.

Because of these differences, utility analysis represents an important step forward in the analysis of materials selection. Because the technique directly captures the preferences of materials decision makers in a quantitative, verifiable structure, an analyst can address materials issues which have previously been treated only in a qualitative sense. For example, with this tool it is possible to estimate whether or not an improved material property will actually make a material a more attractive alternative for an application, and by how much. With this tool it is possible to identify which characteristic will lead to the greatest change in a material's relative desireability, enabling a company to more carefully delineate a research and development strategy. This tool could be employed to set pricing policy by allowing companies to estimate the value of the properties available in the marketplace.

In each case, these potential applications are a consequence of the way that utility analysis enables the analyst to capture the preferences of materials decision makers in a way that enables him to make quantitative conclusions about the way in which the decision makers trade off material properties. No other materials selection tool affords the materials analyst this capability and this capability makes utility analysis a particularly valuable tool for materials decision analysis.

SUMMARY AND RECOMMENDATIONS

SUMMARY

The preceding pages have described a new technique for the analysis of materials selection in engineering applications. This technique, which employs multi-attribute utility analysis in conjunction with engineering analysis and production cost modeling, has been used to analyze materials selection in the automobile industry. In its application, this technique can be used not only to assess the degree of suitability of a material for an application, but also to analyze the way in which the varying levels of performance supplied by a material alternative are traded off against one another by a decisionmaker.

This technique represents an significant improvement over the analytical tools currently available for the analysis of materials selection. In particular, this technique enables the analyst to treat materials selection as a multi-objective problem, focusing upon the relative desireability of the varying levels of performance each material alternative provides. Furthermore, this technique incorporates the material decisionmaker's preferences in a clear-cut manner, enabling the analyst not only to assess the relative desireability of the material alternatives, but also the way in which the materials decisionmaker balances the varying levels of performance of each alternative.

This technique has been successfully applied to the automobile industry in two cases, which have been presented in this thesis Both the deck lid case and the bumper case led to material rankings that were consistent with observed behavior within the automobile industry. Futhermore, the consequences of the utility function developed in the course of the bumper analysis were subsequently presented and confirmed by some of the decisionmakers upon whom the function was based. These results confirm that the technique described herein can be used to develop insights into materials decisionmaking previously unavailable.

This technique not only offers significant insights into the problem of materials selection, but also insights into the problem of materials demand. While several techniques have been applied to the analysis of materials substitution and demand [103], none have focused upon the Lancastrian concept of demand as a consequence of the degree of performance supplied. By developing the material decisionmaker's utility for performance, the driving force behind the demand for materials is revealed. By using this function, several critical measures of materials demand, such as the price elasticity of demand, can be approximated. Additionally, the elasticity of demand with respect to other performance parameters can similarly be estimated. Finally, the degree to which one property is traded off against another can be estimated.

RECOMMENDATIONS FOR FURTHER WORK

EXTENSION OF TECHNIQUE TO OTHER MATERIALS SELECTION PROBLEMS

The scope of the cases treated by this technique requires significant extension, both within and without the automobile industry. Certainly, two automotive components do not an automobile make. In particular, automotive applications for which cost and weight are not the overriding concern require particular attention. For example, structural elements, such as the vehicle frame/uni-body, must supply a wider range of performance characteristics than those required of skin components or bumpers, and the application of this technique in these areas may reveal materials selection situations in which considerations other than weight and cost can be successfully balanced.

This technique also must be tested in industries other than the automobile industry. While preliminary work analyzing the selection of materials for cutting tools has been encouraging, more detailed and comprehensive analyses are required to test the applicability of this technique to other industries. The Materials Systems Laboratory is pursuing several research programs in conjunction with other materials industries to test the applicability of this technique to materials selection in the aircraft industry and in several ceramics markets. Furthermore, several materials suppliers are exploring the application of this technique to refine the targeting of new materials for particular material markets.

IMPROVEMENTS IN THE TECHNIQUE

In terms of the technique itself, several research areas merit particular attention. In light of the time required to train an analyst in the Keeney-Raiffa assessment technique, alternative utility assessment techniques should be examined for possible improvements. Also, the possible application of computer-aided assessment techniques could profitably simplify the assessment procedure.

The validation of multi-attribute utility functions is presently a function of the degree to which the decision maker feels that the utility function satisfactorily captures his attitudes and preferences. While this technique is probably the most satisfying way to validate the utility function, it is limited by the accessibility of the materials decision maker to the analyst. Better questionnaire design could lead to more immediate testing of the utility function developed in the course of the interview. Additionally, computer-aided utility assessment tools could be applied in conjunction with the utility questionnaire to enable the analyst to derive the interviewee's utility function at the close of the interview and validate the major features of the resulting function.

In the present work, a considerable homogeneity of preference was observed among materials decision makers in the automobile industry. While the preliminary deck lid case did lead to two broad classes of preference, subsequent analyses, which were better targeted at appropriate materials decision makers, lead to remarkably similar utility functions. This homogeneity has also been observed in the preliminary ceramic cutting tools analyses. While this homogeneity may not be unique to these materials selection problems, the technique should be extended to be able to treat situations with more inhomogeneous results.

EXTENSION OF THE TECHNIQUE TO TREAT MATERIALS DEMAND ESTIMATION

The potential applicability of this technique or extensions upon it to the analysis of materials demand should be explored. This technique directly addresses some of the limitations of the basic econometric techniques employed to analyze materials demand in the past, and it potentially can be used to extend these analyses to the treatment of materials demand on a performance-basis, rather than a materials basis.

While economic utility functions are at the heart of economic demand theory, the relationships between multi-attribute utility functions and demand functions have not been fully developed. Some work [63] has been done to estimate potential market shares as a function of several analytical results, including utility functions, but further refinements are needed before this technique can be applied to materials demand. However, the results of the present research suggest that the use of utility functions may lead to a model of materials demand which is more representative of the actual situation than the products of other tools.

APPENDIX A - DECK LID QUESTIONNAIRE

Introduction

This questionnaire is designed to explore, briefly but quantitively, your preferences for different characteristics of materials. 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 (steel, aluminum, etc.) 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.

Audience

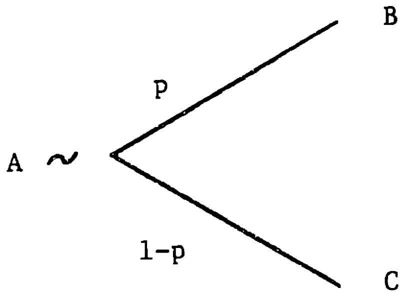
This questionnaire is directed toward an automotive design engineer responsible for choosing a production specification for an automotive part; in this case, a body panel. By a production specification we mean the list of engineering performance criteria used to accept or reject a fabricated part for use.

This questionnaire is experimental in nature. We are aware that this questionnaire is limited in several ways and we hope you will feel free to comment on the content.

This questionnaire is designed to help us understand your expert professional judgment. As such, there are no right or wrong answers to questions. Rather, through your answer to these questions, we hope to outline how you tradeoff different characteristics about materials.

Technical Note

The quantification of the intensity of your preferences is based upon specific questions regarding your preference between certain events (A) and uncertain situations. The uncertain situations are defined as lotteries with two possible outcomes: one outcome (B) with probability p, where p is less than 1; and a second outcome (C) with the complementary probability of occurrence (1-p). Graphically, the uncertain situation is shown as:



We recognize that by expressing decision situations in this way we are asking you to react to an artificial problem. However, please bear with us and try to answer the questions as completely and as thoroughly as you can.

Before we talk about automobile body panels, let's try a simpler problem, to familiarize you with the technique we will be using. Suppose you have an opportunity to bid for the chance to win \$10 on the toss of a fair coin. If you make a successful bid and win, you keep the \$10 and make a profit of (\$10 - bid) If you make a successful bid and lose the coin toss, you lose your bid. (The expected value of the lottery is \$5, so your average expected winnings if you play are (\$5 - bid).)

Would you pay \$0.50 to play?	YES	NO
Would you pay \$5.00 to play?	YES	NO
Would you pay \$1.00 to play?	YES	NO
Would you pay \$3.00 to play?	YES	NO
Would you pay \$2.00 to play?	YES	NO

What is the maximum you would be prepared to bid for the chance to play this game? \$__________________________

Suppose that you are offered the chance to play the same kind of game again, but this time the stakes are $1000. You still have a 50:50 chance of winning so that the expected value of participating is $500 - bid.

Would you pay $10 to play?	YES	NO
Would you pay $500 to play?	YES	NO
Would you pay $50 to play?	YES	NO
Would you pay $200 to play?	YES	NO
Would you pay $100 to play?	YES	NO

What is the maximum you would be prepared to bid for the chance to play this game? $__________________________

(Note: For most people, their answer on this last question will not be 100 times as large as their final answer to the previous set of questions. People's attitudes toward uncertain situations depend significantly upon what is at stake.)

Automobile Body Panels

We have selected several characteristics of automotive body panels which we believe are taken into consideration when designing these parts. These characteristics are:

	RELEVANT?	
	YES	NO
1. Cost		
2. Dent Resistance		
3. Weight		
4. Oil Canning Resistance		
5. Vibration Resistance		
6. Buckling Resistance		

7. Other(s): ____________________________________
____

Like so much of this questionnaire, this list is a preliminary one. We are very interested in your opinions on its components. 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.

Before we talk about how uncertainty effects your choice of characteristics, let's set up some basic parameters.

- First, in what terms or units do you think about these characteristics? Are these the units used when making a decision between several alternative materials?

- Next, in your experience, what have you found to be the average value of these characteristics?

- What is the largest possible value of these characteristics that you have observed? The smallest?

Characteristic	How Measured	Average	Maximum	Minimum
Cost				
Weight				
Dent Resistance				
Oil Can Resist.				
Vibration				
Buckling Resist.				
Other				
Other				

Suppose that you must prepare a material specification for an automotive body panel. You have complete freedom to specify the material to be used and the performance required of the panel as produced. Your materials testing staff has been studying a a new series of metal alloys, which one of your suppliers has been promoting quite heavily. These alloys, members of a series named AlloX-N, are being considered as possible substitutes for the traditional automotive body panel material. Body panels produced with the traditional panel material, SAE-TRAD, exhibit average characteristics, as described by you above. Your job is to consider under what situations the use of an AlloX series alloy will be preferred over the use of the traditional material.

Question 1

You know that the panel, when made of the traditional material, exhibits average dent resistance. The metallurgy department feels that a body panel made with AlloX-1 will perform exactly the same as a traditional panel, EXCEPT for dent resistance. Based upon test results, they conclude that there is a probability p that the AlloX-1 panel will exhibit a 10% improvement in dent resistance and a probability (1-p) that the AlloX-1 panel will exhibit a 10% reduction in dent resistance performance, as measured against the traditional panel.

Would you prefer the AlloX-1 panel to the traditional panel if the probability p were:

Probability of 10% Improvement in Dent Resistance

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use AlloX-1 in the panel specification? __________

Question 2

The metallurgy department has found that AlloX-4 behaves just the same as the traditional alloy in panel applications. However, the production staff has indicated that fabrication of flat panels with AlloX-4 will require new processing techniques. The cost of employing these techniques is uncertain. Specifically, these techniques may lead to a 10% reduction in the cost of fabricating flat panels. However, there is a complementary possibility that AlloX-4 panels will cost 10% more to to fabricate.

Setting the probability of the 10% reduction in cost equal to p, would you prefer the AlloX-4 panel to the traditional panel if the probability p were:

Probability of 10% Reduction in Cost

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use AlloX-4 in the panel specification? __________

Question 3

AlloX-5w has presented a particular problem to your metallurgists. Tests have indicated that alloy exhibits structural properties identical to those of SAE-TRAD, your traditional panel material. However, the samples received by your staff had a wide range in material density, making your production staff very uncertain about the weight of finished panels made of AlloX-5w. Based upon their tests, the metallurgy staff estimates that there is a probability p that panels made of AlloX-5w will weigh 10% less than traditional panels, while retaining all other features of traditional panels. However, there is a probability (1-p) that the panel will weight 10% more than traditional panels.

Would you prefer the AlloX-5w panel to the traditional panel if the probability p were:

Probability of 10% Reduction in Panel Weight

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use AlloX-5w in the panel specification? ___________

Question 4

Your metallurgy department reports that a new AlloX alloy, when used to fabricate body panels, may offer improvements in oil canning resistance, while retaining the same characteristics in all other respects. They report that there is a probability p that panels made of this alloy will yield a 10% improvement in oil canning resistance; however, there is also a probability 1-p that the panels will actually display a 10% reduction in oil canning resistance. Which values of p will lead you to employ this alloy in body panel fabrication?

Probability of 10% Improvement in Oil Canning Resistance

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use this alloy in the panel specification? ___________

Question 5

Another alloy in this series, AlloX-4b, represents a novel problem to your design and testing staffs. Body panels made using this alloy perform exactly the same as those made with SAE-TRAD, except for their vibration resistance. Your designers report that there is a probability p that the vibration resistance of a panel using this material will be improved by 10%. Once again, however, there is also a probability 1-p that the vibration resistance of these panels will be reduced by 10%. Which values of p will lead you to use this alloy in body panels?

Probability of 10% Improvement in Vibration Resistance

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use AlloX-4b in the panel specification? ___________

Question 6

Another AlloX alloy, AlloX-8a, changes the buckling resistance of a body panel, while retaining all the features of the average body panel, like cost and weight. However, there again is some unceratinty about the change in buckling resistance. There is a chance p that the panel will display a 10% increase buckling resistance. However, there is a chance 1-p that the panel will have a 10% reduction in buckling resistance. What values of p will lead you to employ this alloy in body panels?

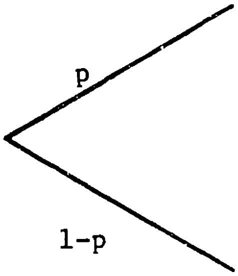
Probability of 10% Reduction in Panel Weight

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use AlloX-8a in the panel specification? ___________

Question 7

Faced with this proliferation of AlloX alloys, you have asked the metallurgy department to develop a new way of describing the results of their testing procedures. In light of the uncertainties that they have experienced, they have devised the following approach. They will assign a probability to each AlloX alloy that they test. This probability, p, will be the probability that the alloy will behave like a hypothetical alloy, AlloX-PLUS. This alloy exhibits a 10% improvement in all six characteristics (dent resistence, cost, weight, oil canning resistance, vibration resistance, and buckling resistance) over the traditional panel material. Alternatively, the probability (1-p) will be the likelihood that the alloy will behave like AlloX-MINUS. This alloy exhibits a 10% decrease in performance in all six characteristics. In effect, their test result, p, will be related to the following lottery:



AlloX-PLUS Specification	
Weight	10% better
Cost	10% better
Dent Resistence	10% better
Oil Canning	10% better
Vibration	10% better
Buckling	10% better

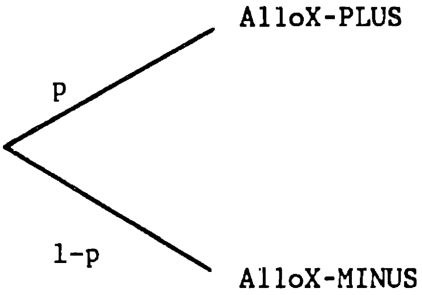
AlloX-MINUS Specification	
Weight	10% worse
Cost	10% worse
Dent Resistence	10% worse
Oil Canning	10% worse
Vibration	10% worse
Buckling	10% worse

The results of a new test series on a shipment of AlloX-9 have just been delivered to you. AlloX-9 is advertized as a material which exhibits a 10% improvement in cost, but a 10% decrease in dent resistence, weight, oil canning, vibration, and buckling performance.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-9 Advertized Specs	
Weight	10% worse
Cost	10% better
Dent Resistence	10% worse
Oil Canning	10% worse
Vibration	10% worse
Buckling	10% worse

$\sim$



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

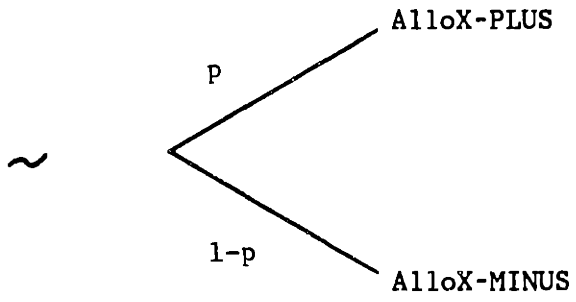
What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

Question 8

The results of a new test series on a shipment of AlloX-11 have just been delivered to you. AlloX-11 is advertized as a material which exhibits a 10% improvement in dent resistence, but the cost, weight, oil canning, vibration, and buckling performance of the alloy are 10% worse than the traditional panel material.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-11 Advertized Specs	
Weight	10% worse
Cost	10% worse
Dent Resistence	10% better
Oil Canning	10% worse
Vibration	10% worse
Buckling	10% worse



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ___________

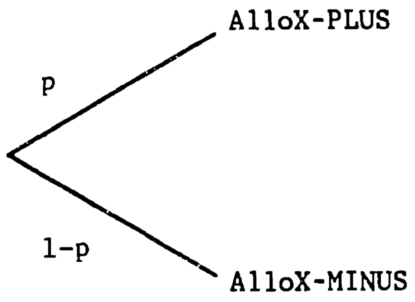
Question 9

The results of a new test series on a shipment of AlloX-12 have just been delivered to you. AlloX-12 is advertized as a material which exhibits a 10% improvement in weight performance, but the cost, dent resistance, oil canning, vibration, and buckling performance of the alloy are 10% worse than the traditional panel material.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-12 Advertized Specs	
Weight	10% better
Cost	10% worse
Dent Resistence	10% worse
Oil Canning	10% worse
Vibration	10% worse
Buckling	10% worse

~



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

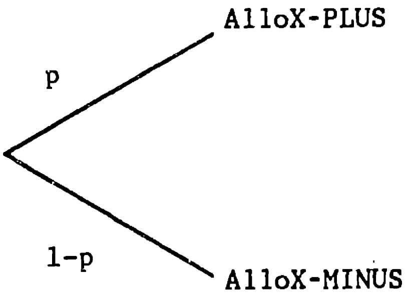
Question 10

The results of a new test series on a shipment of AlloX-13 have just been delivered to you. AlloX-13 is advertized as a material which exhibits a 10% improvement in oil canning, but the weight, cost, dent resistance, vibration, and buckling performance of the alloy are 10% worse than the traditional panel material.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-13 Advertized Specs	
Weight	10% worse
Cost	10% worse
Dent Resistence	10% worse
Oil Canning	10% better
Vibration	10% worse
Buckling	10% worse

~



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

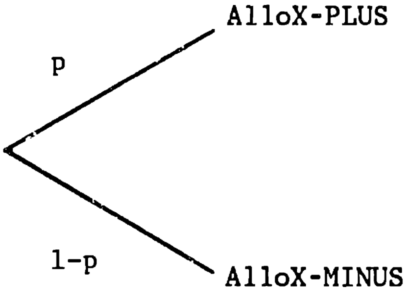
Question 11

The results of a new test series on a shipment of AlloX-14 have just been delivered to you. AlloX-14 is advertized as a material which exhibits a 10% improvement in vibration, but the weight, cost, dent resistance, oil canning, and buckling performance of the alloy are 10% worse than the traditional panel material.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-14 Advertized Specs	
Weight	10% worse
Cost	10% worse
Dent Resistence	10% worse
Oil Canning	10% worse
Vibration	10% better
Buckling	10% worse

$\sim$



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

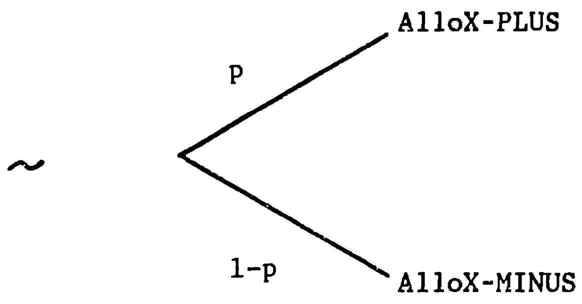
What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

Question 12

The results of a new test series on a shipment of AlloX-19 have just been delivered to you. AlloX-19 is advertized as a material which exhibits a 10% improvement in buckling, but the weight, cost, dent resistance, oil canning, and vibration performance of the alloy are 10% worse than the traditional panel material.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-19 Advertized Specs	
Weight	10% worse
Cost	10% worse
Dent Resistence	10% worse
Oil Canning	10% worse
Vibration	10% worse
Buckling	10% better



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ___________

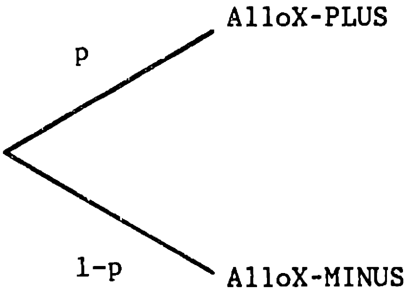
Question 13

The results of a new test series on a shipment of AlloX-24 have just been delivered to you. AlloX-24 is advertized as a material which exhibits a 10% improvement in dent resistence and in cost, but weight performance of the alloy is 10% worse than the traditional panel material.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-24 Advertized Specs	
Weight	10% worse
Cost	10% better
Dent Resistence	10% better
Oil Canning	10% worse
Vibration	10% worse
Buckling	10% worse

$\sim$



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

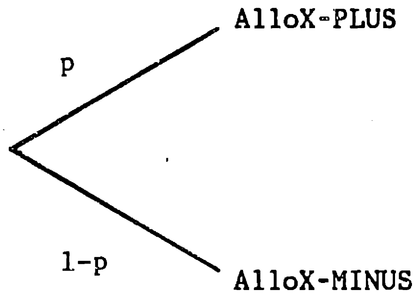
Question 14

The results of a new test series on a shipment of AlloX-20a have just been delivered to you. AlloX-20a is advertized as a material which exhibits a 10% improvement in dent resistence and in cost, but weight performance of the alloy is 10% worse than the traditional panel material.

For what value of p would you prefer to use the current shipment of metal instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

AlloX-24 Advertized Specs	
Weight	10% better
Cost	10% better
Dent Resistence	10% worse
Oil Canning	10% worse
Vibration	10% worse
Buckling	10% worse

~



Probability That Test Alloy Will Behave Like AlloX-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ___________

Question 15

Now, we have a final series of questions to ask. These questions are designed to explore the degree to which the values of one characteristics influence your attitudes towards other characteristics. Depending upon the situation, the values of other characteristics may influence the way that you rank possible outcomes.

For example, your preference for the color of an automobile is likely to be independent of what the automobile weighs. If you prefer a RED car that weighs 2000 pounds over a BLUE car that weighs 2000 pounds, it is likely that you would also prefer a RED car that weighs 2500 pounds over a BLUE car that weighs 2500 pounds.

On the other hand, you may prefer a 1500 cc engine in a 2000 pound car to a 3000 cc engine in a 2000 pound car. But, if the car weighed 3000 pounds, you may prefer a 3000 cc engine to a 1500 cc engine.

Basically, we would like to know whether the values of one set of characteristics would be likely to change your attitudes on the preferability of other characteristics.

Suppose that you were faced with a 50:50 chance of producing a body panel with one of these two sets of characteristics:

Case One	
Cost All others	10% worse Average

Case 2	
Cost All Others	10% better Average

Now, if you could select a certain alternative to this uncertain situation, and if all you could select were the cost, (all other characteristics left as they are above) which values of cost would you select?

Would you select:

10 % better	YES	NO
10 % worse	YES	NO
8 % better	YES	NO
5 % worse	YES	NO
5 % better	YES	NO
average	YES	NO

What would be the worst cost situation that you would accept instead of the uncertain situation?

Now, suppose that the 50:50 lottery were between these two alternatives:

Case One	
Cost	10% worse
All others	10% better

Case 2	
Cost	10% better
All others	10% better

Now, if you could select a certain alternative to this uncertain situation, and if all you could select were the cost, (all other characteristics left as they are above) would your answer in this case differ from the above situation?

APPENDIX B - ENGINEERING COST MODELS

POLYMER COST MODEL

An interactive cost estimation model was used to estimate the cost of fabricating plastic components. The cost of a specific component was estimated based on:

- the fabrication process,
- a physical description of the component (weight, geometry, etc.),
- the number of components produced per year,
- cost data imbedded within the model.

[For a more detailed description of the Polymer Cost Model, the reader is referred to: Primary Fabrication Methods and Costs in Polymer Processing for Automotive Applications M.S. Thesis, John V. Busch, M.I.T., 1983]

The polymer cost model is structured in three major sections.

1. input
2. computation
3. output

Inputs

The inputs which must be provided by the user of the model are:

1. material of construction (menu)
2. generic geometry of the component (menu)
3. fabrication process (menu) <optional>
4. weight of the component (lbs.)
5. number of components to be produced per year
6. maximum wall thickness (in.)
7. number of cavities in mold <optional>

The first three inputs are selected from menus. The remaining inputs are entered as numeric values.

Specification of the fabrication process is an optional input. If not specified, the feasible alternatives will be selected by an algorithm within the model. In automatic selection, the fabrication process is selected based on the material being processed and the generic geometry of the component.

The number of cavities is selected by an optimization routine which iteratively searches for the number of cavities which yield the lowest per piece fabrication cost.

Computation

The equations used to estimate the cost of fabrication are presented below.

Variable Cost ($/piece)

Variable cost = Raw material + Utilities + Direct labor

1) Raw materials = (Weight × Price/lb.)/(1 - Scrap)
   Scrap = Process scrap rate × Mtl adjust × Geo adjust

2) Utilities = Weight × Process energy consumption/lb. × Mtl adjust × Price of energy/kwh

3) Direct labor = (Cycle time × Wage × Laborers/machine) ÷ Productivity
   Cycle time = (A × log(part wgt) + B) × Mtl adjust × Geo adjust

Fixed Cost ($/yr)

Fixed cost = Machine + Mold + Installation + Maintanence + Building + Auxiliary equipment + Overhead labor + Interest

1) Machine = (A × log(part wgt) + B) × Mtl adjust ÷ Machine life
   Machine life = Process machine life × Mtl adjust

2) Mold = (A × log(part wgt) + B) × Mtl adjust × Geo adjust ÷ Mold life
   Mold life = Process mold life × Mtl adjust × Geo adjust

3) Installation = Process percent of machine cost ÷ Machine life

4) Maintenance = Process percent of machine cost

5) Building = Area/machine × (1+0.3(Number of machines-1) × Price per sqft ÷ Building life

6) Auxiliary equipment = Process percent of machine cost × Mtl adjust

7) Overhead labor = Process percent of fixed costs

8) Interest = Capital recovery - Investment premium

The variables which appear in these equations can be grouped into the following categories:

1. exogenous variables
2. regression variables
3. coefficient multipliers
4. adjustment factors

Exogenous variables include factors such as the wages of laborers, the price of raw materials, and the cost of energy. While these factors vary regionally and through time, they can be considered to be constant when applied to a specific production environment.

Regression variables are used to correlate a known factor of the component to an element of the fabrication cost. For example, regression variables are used to relate the weight of a component to the cost of the required injection molding machine. All of the regression equations are of the form:

$$\log(\text{cost factor}) = A \times \log(\text{component factor}) + B$$

where A and B are the regression variables.

The values of A and B vary depending on the fabrication process and are not reproduced here. The interested reader is again referred to Reference 24

Coefficient multipliers are used to relate one element of the cost to another, already estimated element. For example, overhead labor costs are estimated to be a percentage of other fixed costs.

Adjustment factors are used to adjust the cost estimates for known variations which arise from two sources: the material being processed and the geometry of the component being produced. For example, a material adjustment factor is used to increase the estimated cost of tooling when the material being processed is abrasive or corrosive such as glass reinforced polyethylene terephthalate.

Key Assumptions

Several major assumptions were made in constructing this model. The ones with the greatest significance are discussed below.

1. Dedicated Equipment

It is assumed that the fabrication of a component is accomplished using dedicated equipment. The cost of the equipment is distributed totally and uniformly onto the components being produced.

This assumption has only minor significance in large production volumes, where the equipment is fully utilized in the production of a single component. For very large volumes (or for components which require long cycle times) several machines may be required. Under these circumstances, the assumption that the equipment is dedicated to the production of a single component is valid.

For smaller production volumes and rapid cycle times, the assumption of dedicated equipment can introduce serious errors.

2. Variable Labor

It is assumed that the availability of direct labor is infinitely flexible. Under this assumption, laborers can be switched from the production of one component to the production of another without penalty. Therefore, direct labor costs are incurred only for the time in which components are being fabricated (i.e., the cycle time). The validity of this assumption depends on the production volume and on the nature of the production facility.

Data Requirements and Sources

The data utilized in the Polymer Cost Model were collected from a large number of sources. Primary among these were the open literature (including periodicals, textbooks, and handbooks), personal conversations with plastics fabricators, manufacturers of polymer processing equipment, and automotive custom molders. Other data (e.g., cycle time and utilities cost material adjustment factors) were derived from developed theory.

A detailed description of the specification and exact usage of each of the cost estimating variables is presented in Reference 24 and will not be repeated here.

STAMPING COST MODEL

A cost model was employed to calculate the manufacturing cost of the stamping process as a function of process factors, including the shape and size of the stamped part, the material used, and the number of parts produced per year.

Structure of the Model

The stamping cost model was developed to determine the cost of processing components at each stage in the stamping process. The following steps were included:

- blanking,
- drawing (with optional multiple passes),
- trimming and piercing, and
- inspection.

The model was based on a simple engineering flow model, treating material, labor, and energy flows as variable costs, with the cost of the equipment employed in the fabrication spread over the entire volume of production. The model was implemented on an IBM PC with the Lotus® 123 program.

Key Assumptions

1. It was assumed that all stamping equipment (except tooling) was not dedicated to the production of the parts of interest. Rather, the

cost of this equipment was distributed evenly over the total number of parts which the equipment could be expected to produce in a year.

2. Tooling costs were distributed evenly over the production run (limited to either 1.2 million parts or 3.3 years, a typical production lifetime)

3. Prompt industrial scrap was given a positive value, set equal to 4 cents per pound.

Input Requirements

The operation of the model requires the following inputs:

1. the part type,
2. the part weight,
3. the number of stamping passes,
4. a part complexity rating,
5. the annual production volume, and
6. the fabrication material.

Using these inputs, the model computes a first-order estimate of the cost of production at each stage. These estimates can then be revised according to discussions with individuals within the stamping industry.

Data Requirements and Sources

Data requirements include factor prices, labor rates, and equipment costs. These data were collected in the course of several trips to Detroit and from sources including;

- <u>Automotive Manufacturing Process: Volume IV - Metal Stamping and Plastic Forming Processes</u>, Booz-Allen & Hamilton; Bethesda, MD; 1981
- American Metal Stamping Association

ASSEMBLY AND FINISHING COST MODEL

In order to complete the analysis of the costs of fabricating automobile components, an analysis of the costs of finishing and assembling automobile components was performed.

The assembly cost model is not limited to describing a single process. Rather, it seeks to encompass a wide variety of processes whose costs may not properly be construed as assembly costs. In general, this distinction results from the nature of these processes; they tend to be either appearance operations (painting, polishing, plating, etc.) or pure assembly operations (welding, bonding, etc.). Those operations included in the model are listed below.

1. Surfacing
    - Cleaning
    - Priming
    - Painting (On-line)
    - Painting (Off-line)
    - Plating
2. Assembling
    - Captive Fastening
    - Spot Welding
    - Adhesive Bonding
    - Major Bolting
    - Minor Bolting
3. Machining
    - Grinding
    - Fine Polishing
    - Rough Polishing
    - Drilling
    - Milling
    - Threading

Structure of Model

The assembly of an automobile is a major task of logistics and planning. This is a result of the tremendous number of parts that comprise an automobile and of the sheer number of automobiles produced annually. That this process results in economical automobiles is due to the organization of this assembly process around the assembly line.

The assembly cost model mimics the features of an assembly line by avoiding the rigid format of the preceding models. This model is composed of a set of independent 'unit assembly operations' which the model user must apply to the component being studied. As a result, the model user must be familiar with the likely assembly practice that will be employed for each of the material/component combinations being examined.

This model was implemented on an IBM PC using the Lotus® 123 program. Like the preceding program, it treats material, energy, and labor flows as variable costs of operation, while the costs of the equipment employed are treated as fixed costs and spread evenly over the volume of production.

Key Assumptions

1. Perhaps the most critical assumption embedded in the model is the assumption that these operations can be so easily segmented as has been done here. Although this assumption seems justified within the context of the desired output of these studies, changes are taking place in the automobile industry which may lead to a more integrated

assembly process. Whether this more integrated fabrication process will lead to less segmentation of the workplace remains to be seen.

2. The model assumes that the assembly line will change its pace to take advantage of the changes in operating rates that alternative materials would require. This assumption may not be valid if a mixed line (using identical components made of two or more type of materials) is being run. In these cases, the line will not be optimized for the materials being used but will instead reflect the requirements of the limiting component material.

3. To a lesser degree, the model assumes that the equipment used to handle the components is optimized based on the weight of the part. Conveyors and other handling equipment is assumed to be sized for the part being manipulated.

4. Finally, the model assumes that certain operations cannot be performed in the assembly line. These assumptions are embodied in limits being placed on the size of parts which can be treated by certain operations.

APPENDIX C - DECK LID COST OUTPUTS

STEEL STAMPING COST MODEL INPUTS AND RESULTS - DECK LID OUTER

```
                    FACTOR PRICES
 ===============================================================
                                                units   $/unit
                                               -----------------
 =========> ENERGY
                                  Electricity    Kwh    $0.0525

 =========> MATERIALS

             INPUT METAL SHEET COST HERE =======>          $0.21
                                 Carbon steel    lbs       $0.21


                    INPUT FACTORS
 ===============================================================
                            Part Weight (lbs)                 17
                            Die Last (parts)              500000
        Die Complexity (1=simp,2=med,3=cmplx)                  2


 ---------------------------------------------------------------
                              Total Cost
 ---------------------------------------------------------------


                         Total Cost ($/part)  $10.41

                      Material Cost ($/part)   $6.09     58.52%
                  Direct Labor Cost ($/part)   $0.22      2.16%
                       Utility Cost ($/part)   $0.02      0.17%
                         Other Cost ($/part)   $0.24      2.31%
         Miscellaneous Material Cost ($/part)   $0.05      0.48%
                       Tooling Cost ($/part)   $3.79     36.37%
```

ALUMINUM STAMPING COST MODEL INPUTS AND RESULTS - DECK LID OUTER

FACTOR PRICES

		units	$/unit
==========> ENERGY			
	Electricity	Kwh	$0.0525
==========> MATERIALS			
	INPUT METAL SHEET COST HERE ========>		$1.10
	Aluminum Sheet 7020	lbs	$1.10

INPUT FACTORS

Part Weight (lbs)	9.9
Die Last (parts)	500000
Die Complexity (1=simp,2=med,3=cmplx)	2

Total Cost

Total Cost ($/part)	$20.76	
Material Cost ($/part)	$17.91	86.26%
Direct Labor Cost ($/part)	$0.22	1.08%
Utility Cost ($/part)	$0.01	0.07%
Other Cost ($/part)	$0.19	0.93%
Miscellaneous Material Cost ($/part)	$0.05	0.24%
Tooling Cost ($/part)	$2.37	11.42%

POLYMER COST MODEL INPUTS AND RESULTS - DECK LID OUTER

```
     -- MASSACHUSETTS INSTITUTE OF TECHNOLOGY --
         -- MATERIALS SYSTEMS LABORATORY --
 -- PRODUCTION COSTS OF POLYMERIC AND COMPOSITE PARTS  --


 ENTER THE COMPONENT NAME (UP TO 36 LETTERS)
DECK LID OUTER


 SELECT A MATERIAL BY NUMBER (RANGE 1 TO 23)

18.  POLYESTER SMC 37% GLASS



 SELECT A GEOMETRY BY NUMBER (RANGE 1 TO 16)

2.  COMPLEX CURVED PANELS


 ENTER THE COMPONENT WEIGHT (RANGE 0.1 TO 50 LBS)
12.061
 ENTER THE MAXIMUM CROSS-SECTIONAL THICKNESS (RANGE 0.05 TO 1 IN)
 .104
 ENTER THE PRODUCTION VOLUME (RANGE 1,000 TO 1,000,000 /YR)
250000
 SELECT THE PROCESS BY NUMBER (RANGE 1 TO 10)
10.  SMC COMPRESSION MOLDING

        ********************************************
        FABRICATION COSTS OF PRODUCING PLASTIC PARTS
        ********************************************
```

COMPONENT NAME: DECK LID OUTER

METHOD OF FABRICATION:

SMC COMPRESSION MOLDING

Material:
POLYESTER SMC 37% GLASS
Component Geometry:
COMPLEX CURVED PANELS
Component Weight (lbs): 12.06
Annual Production Number: 250000

VARIABLE COST ELEMENTS:

	$/component	$/year	fraction
Material Cost:	14.294	3573376.	.805
Utilities Cost:	0.207	51862.	.012
Direct Labor Cost:	1.089	272355.	.061
--------------------	------	--------	----
Total Variable Cost:	15.590	3897594.	.878

FIXED COST ELEMENTS:

	$/component	$/year	fraction
Main Machine Cost:	0.496	123943.	.028
Mold or Die Cost:	0.462	115402.	.026
Overhead Labor Cost:	0.413	103184.	.023
Building Cost:	0.009	2171.	.000
Installation Cost:	0.050	12394.	.003
Auxiliary Equip Cost:	0.149	37183.	.008
Maintanence Cost:	0.015	3718.	.001
Cost of Capital:	0.565	141220.	.032
-----------------	-----	-------	----
Total Fixed Cost:	2.157	539216.	.122

TOTAL FABRICATION COST

$/component	$/year	fraction
17.747	4436809.	1.000

ADDITIONAL INFORMATION:

Raw Material Price ($/lb):	1.05
Scrap Rate on Material Usage (%):	0.11
Utilities Price ($/kw hr):	0.043
Direct Labor Wage Rate ($/hr):	15.32
Man-hours of Direct Labor (per yr):	17777
Number of Direct Laborers/Shift:	4.0
Cycle Time (s):	96.0

Number of Parallel Production Streams: 2
Run-time for One Machine (%): 161.0
Mold Life (yrs): 3.18
Required Building Space (sq ft): 1913
Interest Rate (%): 16.0

```
ASSEMBLY COST RESULTS - STEEL DECK LID OUTER

  COMPONENT/OPERATION SPECIFICATION
---------------------------------------------------------------

      COMPONENT WEIGHT (lbs) =====>       17
        SURFACE AREA (sq in) =====>     1728


             MATERIAL NUMBER =====>        1
                              Steel        1
                     Aluminum Sheet        2
                                SMC        3


        ------- OPERATIONS -------   $/opn  opn/PART   SubTot

             Surfacing
                           Cleaning    $1.08        1    $1.08
                            Priming    $2.88        1    $2.88
                Painting (in-line)    $3.54        2    $7.09
               Painting (off-line)    $3.65        0    $0.00
                            Plating    $4.93        0    $0.00


             Assembling
                  Captive Fastening    $1.19        0    $0.00
                       Spot Welding    $1.92        1    $1.92
                   Adhesive Bonding    $1.34        0    $0.00
                      Minor Bolting    $1.35        0    $0.00
                      Major Bolting    $1.66        1    $1.66


             Machining
                           Grinding       NA        0    $0.00
                     Fine Polishing    $0.94        1    $0.94
                    Rough Polishing    $0.78        1    $0.78
                           Drilling    $0.28        0    $0.00
                            Milling       NA        0    $0.00
                          Threading       NA        0    $0.00


         Material Handling
                        Warehousing    $0.83        1    $0.83
                        Overhead       $0.02        1    $0.02

                                             TOTAL ==>  $17.20
```

ASSEMBLY COST RESULTS - ALUMINUM DECK LID OUTER

COMPONENT/OPERATION SPECIFICATION

COMPONENT WEIGHT (lbs) ====> 9.9
SURFACE AREA (sq in) ====> 1728

MATERIAL NUMBER ====> 2

Steel	1
Aluminum Sheet	2
SMC	3

------- OPERATIONS -------	$/opn	opn/PART	SubTot
Surfacing			
Cleaning	$1.08	1	$1.08
Priming	$2.88	1	$2.88
Painting (in-line)	$3.71	2	$7.43
Painting (off-line)	$3.82	0	$0.00
Plating	$4.93	0	$0.00
Assembling			
Captive Fastening	$0.77	0	$0.00
Spot Welding	$2.87	1	$2.87
Adhesive Bonding	$1.52	0	$0.00
Minor Bolting	$0.83	0	$0.00
Major Bolting	$1.73	1	$1.73
Machining			
Grinding	NA	0	$0.00
Fine Polishing	$0.94	2	$1.87
Rough Polishing	$0.78	1	$0.78
Drilling	$0.20	0	$0.00
Milling	NA	0	$0.00
Threading	NA	0	$0.00
Material Handling			
Warehousing	$0.65	1	$0.65
Overhead	$0.02	1	$0.02
		TOTAL ==>	$19.32

```
ASSEMBLY COST RESULTS - SMC DECK LID OUTER

  COMPONENT/OPERATION SPECIFICATION
---------------------------------------------------------------

      COMPONENT WEIGHT (lbs) ====>     12.1
        SURFACE AREA (sq in) ====>     1728

             MATERIAL NUMBER ====>        3
                             Steel        1
                   Aluminum Sheet         2
                               SMC        3

        -------  OPERATIONS -------   $/opn  opn/PART   SubTot

             Surfacing
                          Cleaning    $1.08         1    $1.08
                           Priming    $2.88         1    $2.88
                Painting (in-line)    $3.71         0    $0.00
               Painting (off-line)    $3.98         1    $3.98
                           Plating    $4.93         0    $0.00


             Assembling
                 Captive Fastening    $1.19         0    $0.00
                      Spot Welding    $1.92         0    $0.00
                  Adhesive Bonding    $1.34         1    $1.34
                     Minor Bolting    $1.25         0    $0.00
                     Major Bolting    $1.66         1    $1.66


             Machining
                          Grinding       NA         0    $0.00
                     Fine Polishing   $0.94         1    $0.94
                    Rough Polishing   $0.78         1    $0.78
                          Drilling    $0.18         0    $0.00
                           Milling       NA         0    $0.00
                         Threading       NA         0    $0.00


         Material Handling
                       Warehousing    $0.71         1    $0.71
                       Overhead       $0.02         1    $0.02

                                         TOTAL ==>  $13.41
```

SUMMARY OF COSTS FOR DECK LID OUTER

	Primary	Secondary	Total
Steel	$10.41	$17.20	$27.61
Aluminum	$20.76	$19.32	$40.08
SMC	$17.75	$13.41	$31.16

APPENDIX D - BUMPER COST BREAKDOWNS

BUMPER SYSTEM 1

Concept: RIM fascia, high strength steel back-up beam, hydraulic strokers.

Design Specifics:

RIM Fascia
- Material - unreinforced flexible polyurethane
- Average Wall Thickness - 0.200 in.
- Weight - 8 lbs

Steel Back-up Beam
- Material - 120 ksi galvanized steel
- Gauge - 2.16 mm
- Weight - 13 lbs.

Hydraulic Strokers (Energy Absorption Units)
- Design - hydraulic, purchased from out-source
- Weight - 4.8 lbs/ea.
- Unit Cost - $7.50/ea.

Manufacturing Process:

1. RIM Fascia (total cost $34.92)
    - a. mold ($15.08)
    - b. trim/inspect (included in molding)
    - c. post cure ($1.05)
    - d. clean ($1.73)
    - e. prime ($4.28)
    - f. paint top coat & clear coat ($11.46)
    - g. ship ($1.32)

2. Steel Back-Up (total cost $8.54)
    - a. raw material ($4.92)
    - b. blank from coil ($0.10)
    - c. draw blank to shape ($1.46)
    - d. trim and pierce ($0.16)
    - e. inspect ($0.17)
    - f. clean ($1.73)

3. Assembly, 1 lb. hardware (total cost $24.38)
    - a. procure strokers ($7.50/ea. = $15.00)
    - b. bolt strokers to frame ($2.71)
    - c. bolt back-up beam to strokers ($2.71)
    - d. bolt fascia to frame ($3.96)

TOTAL SYSTEMS COST ===> $67.84

TOTAL SYSTEM WEIGHT ===> 31.6 Lbs.

BUMPER SYSTEM 2

Concept: RIM fascia, high strength steel back-up beam, EVA honeycomb.

Design Specifics:

RIM Fascia
- Material - unreinforced flexible polyurethane
- Average Wall Thickness - 0.200 in.
- Weight - 8 lbs

Steel Back-up Beam
- Material - 120 ksi galvanized steel
- Gauge - 2.16 mm
- Weight - 13 lbs.

EVA Honeycomb
- Fabrication - Injection molding
- Material - DuPont Elvax 760
- Weight - 5.0 lbs.

Manufacturing Process:

1. RIM Fascia (total cost $34.92)
2. Steel Back-Up (total cost $8.54)
3. EVA Honeycomb (total cost $5.39)
   a. mold ($5.39)
4. Assembly, 1 lb. hardware (total cost $7.13)
   a. bolt back-up to frame ($2.71)
   b. rivet EVA to back-up ($0.46)
   c. bolt fascia to frame ($3.96)

TOTAL SYSTEM COST ===> $55.98

TOTAL SYSTEM WEIGHT ===> 27 Lbs.

BUMPER SYSTEM 3

Concept: RIM fascia, plastic back-up beam

Design Specifics:

RIM Fascia
    Material - unreinforced flexible polyurethane
    Average Wall Thickness - 0.200 in.
    Weight - 8 lbs

Plastic Back-Up Beam
    Weight - 12.65 lbs

Manufacturing Process:

1. RIM Fascia - (total cost $34.92)

2. Plastic Back-Up (total cost $27.21)

3. Assembly, 1 lb. hardware (total cost $6.67)
    a. bolt back-up beam to frame ($2.71)
    b. bolt fascia to frame ($3.96)

TOTAL SYSTEM COST ====> $68.80

TOTAL SYSTEM WEIGHT ====> 21.65 Lbs.

BUMPER SYSTEM 4

Concept: 1-piece fascia/bumper, Surlyn rub-strip, hydraulic strokers.

Design Specifics:

1-piece fascia/bumper
    Weight - 15 lbs
    Maximum Wall Thickness - .200 in.

Surlyn Rub Strip
    Material - DuPont Surlyn (1.35 $/lb)
    Weight - 2.75 lbs
    Average Wall Thickness - .200 in.

Hydraulic Strokers (Energy Absorption Units)
    Design - hydraulic, purchased from out-source
    Weight - 4.8 lbs/ea.
    Unit Cost - $7.50/ea.

Manufacturing Process:

1. 1-piece Fascia/Bumper (total cost $54.93)
    a. mold ($36.14)
    b. trim/inspect (included in molding)
    c. clean ($1.73)
    d. prime ($4.28)
    e. paint ($11.46)
    f. ship ($1.32)

2. Surlyn Rub Strip (total cost $4.83)
    a. mold ($4.83)
    b. trim/inspect (included in molding)

3. Hydraulic Strokers - ($15.00)

4. Assembly & Finishing (total cost $6.02)
    a. bolt hydraulic strokers to frame ($2.71)
    b. bolt fascia/bumper to strokers ($2.71)
    c. fit rubstrip to fascia/bumper ($0.60)

TOTAL SYSTEM COST ===> $80.78

TOTAL SYSTEM WEIGHT ===> 27.35 Lbs.

SUMMARY TABLE - BUMPERS

SYSTEM COSTS & WEIGHTS

Bumper System	Total Cost	Total Weight
System 1	$67.84	31.6 lbs
System 2	$55.98	27.0 lbs
System 3	$68.80	21.65 lbs
System 4	$80.78	27.35 lbs

APPENDIX E - BUMPER QUESTIONNAIRE

Introduction

This questionnaire is designed to explore, briefly but quantitively, your preferences for different characteristics of materials. 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 (steel, aluminum, etc.) 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.

Audience

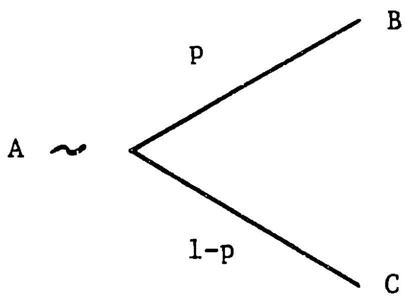
This questionnaire is directed toward an automotive design engineer responsible for choosing a production specification for an automotive part; in this case, a bumper. By a production specification we mean the list of engineering performance criteria used to accept or reject a fabricated part for use.

This questionnaire is experimental in nature. We are aware that this questionnaire is limited in several ways and we hope you will feel free to comment on the content.

This questionnaire is designed help us understand your expert professional judgment. As such, there are no right or wrong answers to questions. Rather, through your answer to these questions, we hope to outline how you tradeoff different characteristics about materials.

Technical Note

The quantification of the intensity of your preferences is based upon specific questions regarding your preference between certain events (A) and uncertain situations. The uncertain situations are defined as lotteries with two possible outcomes: one outcome (B) with probability p, where p is less than 1; and a second outcome (C) with the complementary probability of occurrence (1-p). Graphically, the uncertain situation is shown as:



We recognize that by expressing decision situations in this way we are asking you to react to an artificial problem. However, please bear with us and try to answer the questions as completely and as thoroughly as you can.

Before we talk about automobile bumpers, let's try a simpler problem, to familiarize you with the technique we will be using. Suppose you have an opportunity to bid for the chance to win $10 on the toss of a fair coin. If you make a successful bid and win, you keep the $10 and make a profit of ($10 - bid) If you make a successful bid and lose the coin toss, you lose your bid. (The expected value of the lottery is $5, so your average expected winnings if you play are ($5 - bid).)

Would you pay $0.50 to play?	YES	NO
Would you pay $5.00 to play?	YES	NO
Would you pay $1.00 to play?	YES	NO
Would you pay $3.00 to play?	YES	NO
Would you pay $2.00 to play?	YES	NO

What is the maximum you would be prepared to bid for the chance to play this game? $__________________________

Suppose that you are offered the chance to play the same kind of game again, but this time the stakes are $1000. You still have a 50:50 chance of winning so that the expected value of participating is $500 - bid.

Would you pay $10 to play?	YES	NO
Would you pay $500 to play?	YES	NO
Would you pay $50 to play?	YES	NO
Would you pay $200 to play?	YES	NO
Would you pay $100 to play?	YES	NO

What is the maximum you would be prepared to bid for the chance to play this game? $__________________________

(Note: For most people, their answer on this last question will not be 100 times as large as their final answer to the previous set of questions. People's attitudes toward uncertain situations depend significantly upon what is at stake.)

Automobile Bumpers

We have selected several characteristics of automotive bumpers which we believe are taken into consideration when designing these parts. These characteristics are:

	RELEVANT?	
	YES	NO
1. Cost		
2. Dent resistance		
3. Weight		
4. Service Life		
5. FMVSS Impact Resistance		
6. Deflection under Load		

7. Other(s): ______________________________

____

Like so much of this questionnaire, this list is a preliminary one. We are very interested in your opinions on its components. 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.

Before we talk about how uncertainty effects your choice of characteristics, let's set up some basic parameters.

- First, in what terms or units do you think about these characteristics? Are these the units used when making a decision between several alternative materials?
- Next, in your experience, what have you found to be the average value of these characteristics?
- What is the largest possible value of these characteristics that you have observed? The smallest?

Characteristic	How measured	Average	Maximum	Minimum
Cost				
Weight				
Dent resistance				
Service Life				
FMVSS Impact				
Deflection				
Other				
Other				

Suppose that you must prepare a material specification for an automotive bumper. You have complete freedom to specify the material to be used and the performance required of the bumper as produced. Your materials testing staff has been studying a a new series of materials, which one of your suppliers has been promoting quite heavily. These materials, members of a series named <u>Meta-Last-N,</u> are being considered as possible substitutes for the traditional automotive bumper material. Bumpers produced with the traditional bumper material, SAE-TRAD, exhibit average characteristics, as described by you above. Your job is to consider under what situations the use of an <u>Meta-Last</u> series material will be preferred over the use of the traditional material.

Question 1

You know that the bumper, when made of the traditional material, exhibits average dent resistance. The engineering department feels that a bumper made with Meta-Last-1 will perform exactly the same as a traditional bumper, EXCEPT for dent resistance. Based upon test results, they conclude that there is a probability p that the Meta-Last-1 bumper will exhibit a 100% improvement in dent resistance (twice as good) and a probability (1-p) that the Meta-Last-1 bumper will exhibit a 50% reduction (half as good) in dent resistance performance, as measured against the traditional bumper.

Would you prefer the Meta-Last-1 bumper to the traditional bumper if the probability p were:

Probability of 100% Improvement in Dent Resistance

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use Meta-Last-1 in the bumper specification? __________

Question 2

The materials department has found that Meta-Last-4 behaves just the same as the traditional alloy in bumper applications. However, the production staff has indicated that fabrication of bumpers with Meta-Last-4 will require new processing techniques. The cost of employing these techniques is uncertain. Specifically, these techniques may lead to a 50% reduction in the cost of fabricating flat bumpers. However, there is a complementary possibility that Meta-Last-4 bumpers will cost twice as much (100% increase) to fabricate.

Setting the probability of the 50% reduction in cost equal to p, would you prefer the Meta-Last-4 bumper to the traditional bumper if the probability p were:

Probability of 50% Reduction in Cost

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use Meta-Last-4 in the bumper specification? __________

Question 3

Meta-Last-5w has presented a particular problem to your materiallurgists. Tests have indicated that alloy exhibits structural properties identical to those of SAE-TRAD, your traditional bumper material. However, the samples received by your staff had a wide range in material density, making your production staff very uncertain about the weight of finished bumpers made of Meta-Last-5w. Based upon their tests, the materials staff estimates that there is a probability p that bumpers made of Meta-Last-5w will weigh 50% less than traditional bumpers (half the weight), while retaining all other features of traditional bumpers. However, there is a probability (1-p) that the bumper will weigh 100% more than traditional bumpers.

Would you prefer the Meta-Last-5w bumper to the traditional bumper if the probability p were:

Probability of 50% Reduction in Bumper Weight

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use Meta-Last-5w in the bumper specification? __________

Question 4

Your materials department reports that a new Meta-Last alloy, when used to fabricate bumpers, may offer improvements in service life, while retaining the same characteristics in all other respects. They report that there is a probability p that bumpers made of this alloy will yield a 100% improvement in service life (bumpers last twice as long as traditional bumpers); however, there is also a probability 1-p that the bumpers will actually display a 50% decrease in service life. Which values of p will lead you to employ this material in bumper fabrication?

Probability of 100% Improvement in Service Life

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use this material in the bumper specification? __________

Question 5

Another material in this series, Meta-Last-4a, represents a novel problem to your design and testing staffs. Bumpers made using this material perform exactly the same as those made with SAE-TRAD, except for their performance in the FMVSS impact tests. Your designers report that there is a probability p that bumpers composed of this material will survive a simulated 7.5 mile per hour impact; however, there is a probability (1-p) that these bumpers will only survive a 2.5 mile per hour impact. Bumpers composed of your traditional material survive a 5 mile per hour impact. Which values of p will lead you to use this material in bumpers?

Probability of Surviving a 7.5 MPH FMVSS Test

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use Meta-Last-4a in the bumper specification? ___________

Question 6

Another member of the Meta-Last series, Meta-Last-8a, changes the mean deflection of the bumper under load, while retaining all the features of the average bumper, like cost and weight. However, there again is some uncera-tinty about the change in mean deflection. There is a chance p that the bumper will display a 50% decrease in mean deflection. However, there is a chance 1-p that bumpers composed of this material will exhibit a 100% increase in mean deflection. What values of p will lead you to employ this material in bumpers?

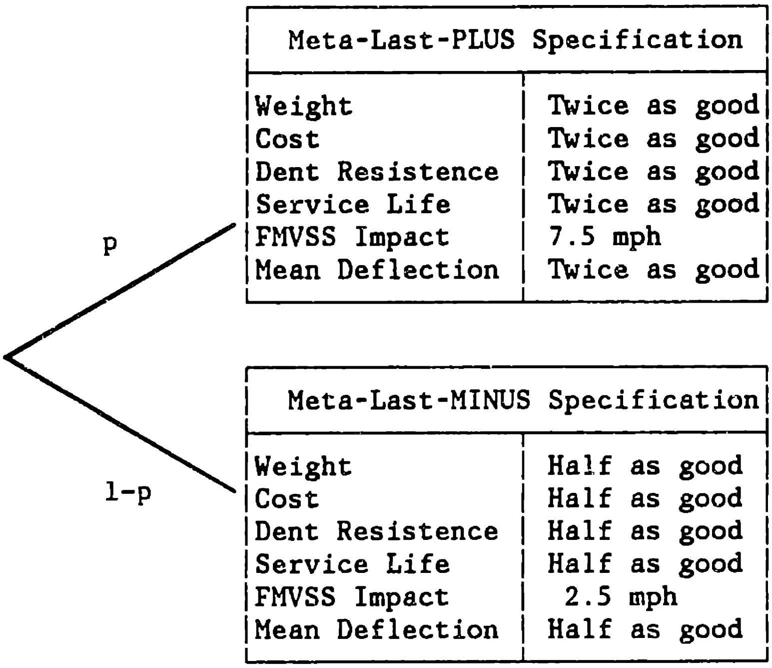
Probability of 50% Reduction in Mean Bumper Deflection

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use Meta-Last-8a in the bumper specification? ___________

Question 7

Faced with this proliferation of Meta-Last materials, you have asked the materials department to develop a new way of describing the results of their testing procedures. In light of the uncertainties that they have experienced, they have devised the following approach. They will assign a probability to each Meta-Last series material that they test. This probability, p, will be the probability that the material will behave like a hypothetical material, Meta-Last-PLUS. Bumpers composed of this material exhibit improvements in all six characteristics (dent resistance(2x), cost (0.5x), weight (0.5x), FMVSS impact resistance (7.5 mph), service life (2x), and mean deflection (0.5x)) over the traditional bumper material. Alternatively, the probability (1-p) will be the likelihood that the material will behave like Meta-Last-MINUS. Bumpers composed of this material exhibit decreased performance in all six characteristics. In effect, their test result, p, will be related to the following lottery:



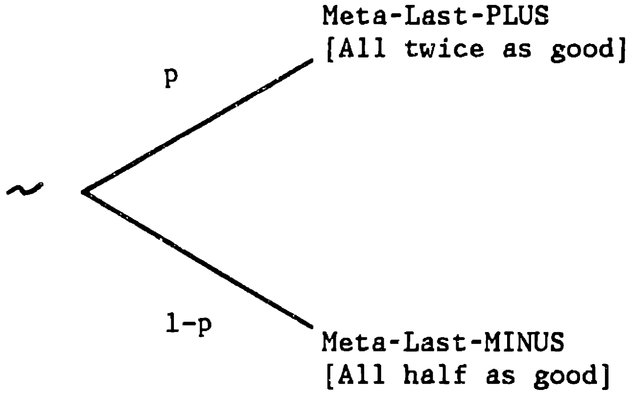
Meta-Last-PLUS Specification	
Weight	Twice as good
Cost	Twice as good
Dent Resistence	Twice as good
Service Life	Twice as good
FMVSS Impact	7.5 mph
Mean Deflection	Twice as good

Meta-Last-MINUS Specification	
Weight	Half as good
Cost	Half as good
Dent Resistence	Half as good
Service Life	Half as good
FMVSS Impact	2.5 mph
Mean Deflection	Half as good

The results of a new test series on a shipment of Meta-Last-9 have just been delivered to you. Meta-Last-9 is advertized as a material which has twice the cost performance of the traditional bumper material, but a decrease in dent resistence, weight, service life, FMVSS impact, and deflection performance.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-9 Advertized Specs	
Weight	Half as good
Cost	Twice as good
Dent Resistance	Half as good
Service Life	Half as good
FMVSS Impact	2.5 mph
Mean Deflection	Half as good



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

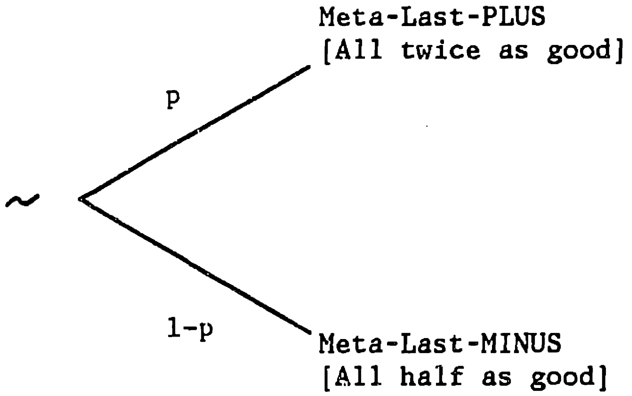
What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ___________

Question 8

The results of a new test series on a shipment of Meta-Last-11 have just been delivered to you. Meta-Last-11 is advertized as a material which exhibits a 100% improvement in dent resistance, but the cost, weight, service life, FMVSS impact, and mean deflection performance of the alloy are worse than the traditional bumper material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-11 Advertized Specs	
Weight	Half as good
Cost	Half as good
Dent Resistance	Twice as good
Service Life	Half as good
FMVSS Impact	2.5 mph
Mean Deflection	Half as good



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

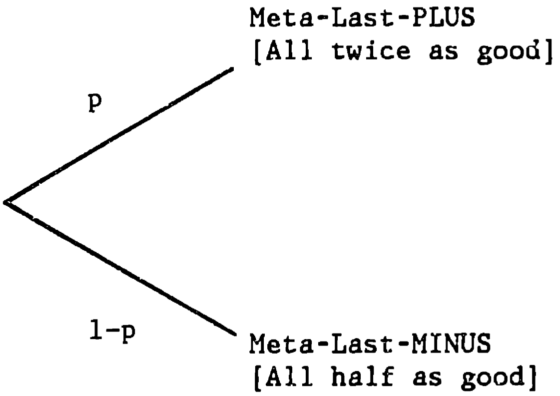
Question 9

The results of a new test series on a shipment of Meta-Last-12 have just been delivered to you. Meta-Last-12 is advertized as a material which exhibits a 50% improvement in weight performance, but the cost, dent resistance, service life, FMVSS impact, and mean deflection performance of the alloy are worse than the traditional bumper material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-12 Advertized Specs	
Weight	Twice as good
Cost	Half as good
Dent Resistance	Half as good
Service Life	Half as good
FMVSS Impact	2.5 mph
Mean Deflection	Half as good

$\sim$



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

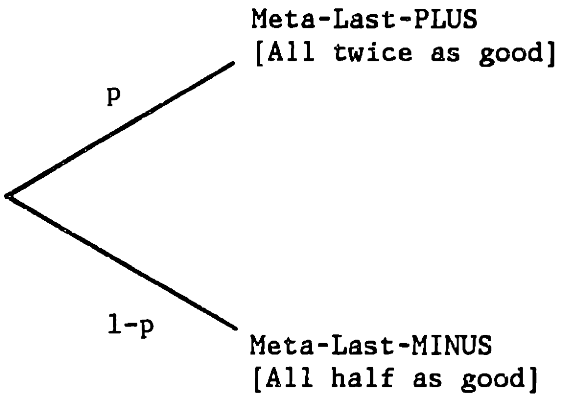
Question 10

The results of a new test series on a shipment of Meta-Last-13 have just been delivered to you. Meta-Last-13 is advertized as a material which exhibits a 100% improvement in service life, but the weight, cost, dent resistance, FMVSS impact, and mean deflection performance of the alloy are worse than the traditional bumper material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-13 Advertized Specs	
Weight	Half as good
Cost	Half as good
Dent Resistance	Half as good
Service Life	Twice as good
FMVSS Impact	2.5 mph
Mean Deflection	Half as good

$\sim$



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

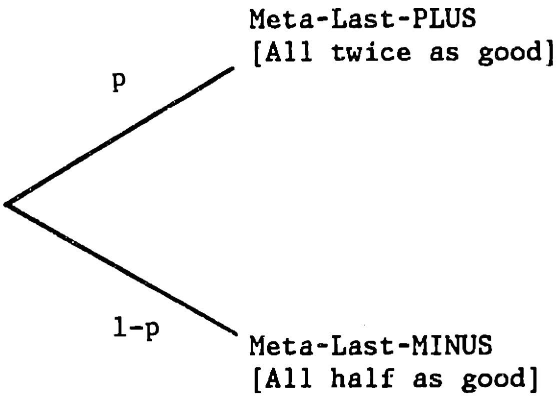
Question 11

The results of a new test series on a shipment of Meta-Last-14 have just been delivered to you. Meta-Last-14 is advertized as a material which exhibits a 50% improvement mean deflection, but the weight, cost, dent resistance, service life, and FMVSS impact performance of the alloy are worse than the traditional bumper material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-14 Advertized Specs	
Weight	Half as good
Cost	Half as good
Dent Resistance	Half as good
Service Life	Half as good
FMVSS Impact	2.5 mph
Mean Deflection	Twice as good

~



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

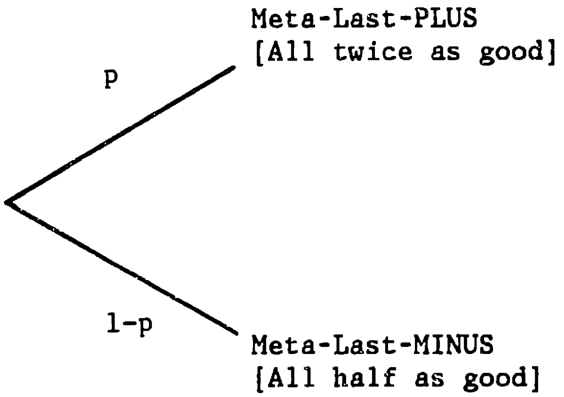
Question 12

The results of a new test series on a shipment of Meta-Last-19 have just been delivered to you. Meta-Last-19 bumpers can withstand a simulated 7.5 mph impact in the FMVSS tests, but the weight, cost, dent resistance, service life, and mean deflection performance of the material are worse than the traditional bumper material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-19 Advertized Specs	
Weight	Half as good
Cost	Half as good
Dent Resistance	Half as good
Service Life	Half as good
FMVSS Impact	7.5 mph
Mean Deflection	Half as good

~



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

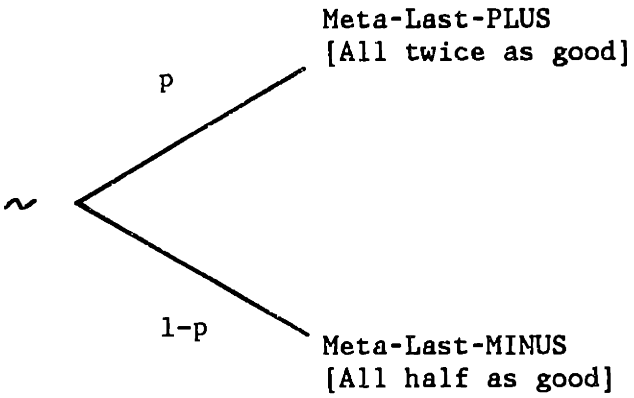
What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ___________

Question 13

The results of a new test series on a shipment of Meta-Last-24 have just been delivered to you. Meta-Last-24 is advertized as a material which exhibits a 50% improvement in weight and in cost, but performance of the material in service life, mean deflection, dent resistence, and FMVSS impact is worse than the traditional bumper material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-24 Advertized Specs	
Weight	Twice as good
Cost	Twice as good
Dent Resistance	Half as good
Service Life	Half as good
FMVSS Impact	2.5 mph
Mean Deflection	Half as good



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ____________

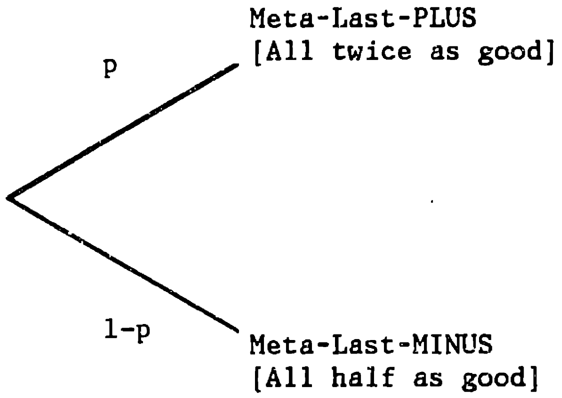
Question 14

The results of a new test series on a shipment of Meta-Last-20a have just been delivered to you. Meta-Last-20a is advertized as a material which exhibits improvements in FMVSS impact performance and in cost, but the weight, dent resistance, service life, and mean deflection performance of the material is worse than the traditional bumper material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding the manufacturer satisfy his advertized claims?

Meta-Last-24 Advertized Specs	
Weight	Half as good
Cost	Twice as good
Dent Resistance	Half as good
Service Life	Half as good
FMVSS Impact	7.5 mph
Mean Deflection	Half as good

~



Probability That Test Material Will Behave Like Meta-Last-PLUS

p	>	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
YES	>											
NO	>											

What is the lowest probability p that would lead you to use the current shipment instead of an as-advertized shipment? ___________

Question 15

Now, we have a final series of questions to ask. These questions are designed to explore the degree to which the values of one characteristics influence your attitudes towards other characteristics. Depending upon the situation, the values of other characteristics may influence the way that you rank possible outcomes.

For example, your preference for the color of an automobile is likely to be independent of what the automobile weighs. If you prefer a RED car that weighs 2000 pounds over a BLUE car that weighs 2000 pounds, it is likely that you would also prefer a RED car that weighs 2500 pounds over a BLUE car that weighs 2500 pounds.

On the other hand, you may prefer a 1500 cc engine in a 2000 pound car to a 3000 cc engine in a 2000 pound car. But, if the car weighed 3000 pounds, you may prefer a 3000 cc engine to a 1500 cc engine.

Basically, we would like to know whether the values of one set of characteristics would be likely to change your attitudes on the preferability of other characteristics.

Suppose that you were faced with a 50:50 chance of producing a bumper with one of these two sets of characteristics:

Case One	
Cost	Twice
All others	Average

Case 2	
Cost	Half
All Others	Average

Now, if you could select a certain alternative to this uncertain situation, and if all you could select were the cost, (all other characteristics left as they are above) which values of cost would you select?

Would you select:

50% average cost	YES	NO
200% average cost	YES	NO
75% average cost	YES	NO
150% average cost	YES	NO
90% average cost	YES	NO
average cost	YES	NO

What is the highest cost situation that you would accept instead of the uncertain situation?

Now, suppose that the 50:50 lottery were between these two alternatives:

Case One	
Cost	Twice
All others	Better

Case 2	
Cost	Half
All others	Better

Now, if you could select a certain alternative to this uncertain situation, and if all you could select were the cost, (all other characteristics left as they are above) would your answer in this case differ from the above situation?

APPENDIX F - AUTOMOBILE INDUSTRY VEHICLE DEVELOPMENT PROCESS

An understanding of the stages of development of an automobile, from vehicle concept to final vehicle assembly, is necessary in order to analyze the critical features of the materials selection process in these applications. Typical stages of development are described below.

VEHICLE CONCEPT

The first step in the manufacture of any automobile is the Concept stage. 'Concept' is an all-embracing term when used in this respect. With the word 'concept', automobile management describes the styling, cost, price, performance, production volume, weight class, and image of a to-be-developed automobile.

It is possible to summarize 'concept' as, on one hand, a description of the target market for the vehicle, and on the other hand, a basic description of the engineering problem to be considered. Responsibility for the 'concept' definition is interdisciplinary, residing primarily with upper management and marketing groups. However, coordination with engineering and production is required for successful concept development.

STYLING

Once the concept decision has been made, the vehicle passes on to Styling. Here, a group of artists, engineers, and market experts translate the concept into a set of preliminary drawings and clay models. By and large, the primary concerns of the styling groups rest with preliminary design and vehicle marketing. Engineering work here is done in conjunction with the vehicle engineering and advance engineering staffs.

Styling efforts are governed by four bodies of knowledge. The first and most potent of the three is historical practice. Just like the weather, the easiest and most reliable guide to the style of tomorrow's cars is to look at the style of today's cars.

The second body of knowledge is the current practice of the competing automakers. Every engineering division has its tear down labs, where the competition's products are subjected to intense scrutiny by both the engineering and the styling staffs. The use of this information is based on the assumption that the automobile firm can make anything that the competition can make. Additionally, examining the style of a successful model line provides insight into consumer preferences. Certainly, little else can explain why every automaker has had at one time a car line that looks like a Mercedes sedan.

The third source of information is the engineering staff of material suppliers, usually in conjunction with the in-house engineering staff. Through cooperative effort, materials suppliers and automobile engineers work to develop innovative materials usage in their vehicle lines. One example of this sort of cooperation is the Ford Escort all-plastic bumper, which was a product of active cooperation between the styling and engineering staffs of Ford with the engineering staff of General Electric, the supplier of the XENOY® resin.

The fourth source of information is developed internal to the companies themselves. Internal innovation does occur within these organizations, although rarely on a material basis. Recent innovations include the mini-van and the rebirth of the convertible.

The net result of all this effort is a clay model, which is arrayed before upper management. Management reviews the models, assuring themselves that the proposed vehicle reflects the concept that they have chosen.

ADVANCE ENGINEERING

Following approval by management, the styling drawings are passed to Advance Engineering. In Advance Engineering, these preliminary drawings are converted into engineering design drawings.

The engineering work, like the styling work, is firmly grounded in the past. Historical data is employed to make basic analyses of the necessary design specifications of vehicle parts. Furthermore, this data is used to make preliminary estimates of the cost and weight of the proposed vehicle.

In addition to historical data, most Advance Engineering divisions include several design groups which work on problems of general interest and applicability. Some of these groups look into the design and fabrication of novel vehicle structures while others look into the application of novel materials. Rather than being wedded to particular vehicle design programs, these groups develop general design information and procedures that may be employed during the design of any vehicle line. These general development groups are usually created with a particular problem or class of problems in mind (e.g., plastic body panels).

Finally, other data sources, if available, are also used to treat the engineering design problem. For example, GM makes use of insurance information collected from GMAC to assess the performance of its designs under operating conditions. Warranty information is similarly employed.

In conjunction with the development of the preliminary engineering drawings, the advance engineering staff breaks the proposed vehicle into major subassemblies, such as body, powertrain, etc. For each of these groups, performance specifications (or 'bogeys') are set for both the engineering and the economic performance of the parts. Many of these 'bogeys' are actually long-standing management policies, and are common to all car lines of the producer (e.g., bumper impact standards).

Once these 'bogeys' are set, the vehicle is almost completely defined. From this point onward, authorization for a relaxation of the performance specifications of the major subassemblies is almost impossible to receive. These engineering and economic performance bogeys become <u>the</u> required minimum for engineering achievement.

Another responsibility of Advance Engineering is to uncover engineering 'impossiblities' which may be found in the styling drawings. Usually, these impossibilities have to do with unreconcilable goals between styling, fabricability, and cost. If the difficulty is severe enough, the Advance Engineering and styling staffs must meet with senior management for approval of modifications to the approved clay model.

ENGINEERING DIVISIONS

The Advance Engineering design drawings and performance bogeys are passed to the respective engineering groups responsible for each vehicle subassembly. For these groups, the performance bogeys are cast in stone. Their efforts are directed toward achieving in material what is desired on paper. These efforts are wide ranging and encompass a broad spectrum of activity.

First, the preliminary engineering drawings are used to make assembly drawings, outlining the process to be employed during manufacture. From the assembly drawings, physical plant requirements and tooling needs are assessed. The necessary tools are ordered, as are the necessary physical plant changes.

Concurrently, the materials specifications for the assembly components are finalized. Based upon these materials specifications, requests are passed to Purchasing to acquire the necessary materials. Similarly, if subassemblies are to be purchased from outside suppliers, detailed engineering descriptions are prepared to be included in the requests for bids.

Finally, in conjunction with process engineering, test assemblies are prepared and tested against the performance 'bogeys' set by Advance Engineering and management. In the event that 'bogeys' cannot be met, consultations are held with members of the other engineering groups and management. By establishing the performance of the other groups, whatever leeway available is awarded to the weakest group. Depending upon the degree of difficulty, any number of quick, but expensive, fixes may be applied. For instance, aluminum has been substituted for steel in hoods and trunks when the weight of a car model exceeds the targeted EPA weight class.

ASSEMBLY

The efforts of the engineering divisions continue up to and through the 'launch' of the new car line. As the tools arrive and the physical plant is prepared, test runs of the new vehicle are begun. These test vehicles are extensively examined and tested against the performance bogeys established years ago by advance engineering and management. Also, the performance of the subassemblies supplied by outside firms are tested. Again, performance problems are treated as well as possible within the framework of the vehicle concept. At this stage, however, it is usually the engineering divisions which hold the upper hand in negotiation, since extensive retrofitting and redesign is usually too expensive to be considered.

Vehicle 'launch' is not an instantaneous event. Depending upon the firm, launch can take as little as two weeks, or up to more than three months. During this process, the engineering departments have a smaller and smaller hand in managing the problems that arise. However, members of the engineering divisions are available to the assembly divisions for the day-to-day problems that turn up on the line.

APPENDIX G - AUTOMOBILE INDUSTRY MATERIALS SELECTION

This appendix gives a brief outline of the materials selection decisions which are made within the framework of the vehicle development process (See the preceding Appendix for an outline of the vehicle development process). In particular, this appendix will focus upon the materials selection process for bumpers.

Bumper material selection is intertwined with the entire vehicle design process. The bumper is a major factor in determining the 'profile' of an automobile and, unlike most components, several basic styling decisions have a major influence upon the material from which the bumper is made.

Bumper Materials and Styling

One of the key styling decisions is "Will this car have a 'bright' (i.e. chrome-plated) bumper?" If the answer is "Yes," then all possible plastic bumper materials are rejected. Detroit carmakers have little faith in the performance and durability of metallized plastics and aluminum. If a 'bright' bumper is part of the design concept, almost all automakers will select steel.

Another design decision having a major influence upon the material specification of a bumper is "Will this car have a European (i.e., aerodynamic) profile?" If the answer to this question is "Yes," then a plastic fascia system is indicated. While some of the aerodyanamic shapes that are proposed could be stamped from metal, they are far too expensive. Furthermore, designing such systems to satisfy FMVSS requirements would lead to even greater expense.

Bumper Materials and Advance Engineering

Most of the remaining bumper materials decisions are made in the Advance Engineering groups. Based upon their historical experience, basic material selections are made. For bumpers, the major parameters of interest include:

- Weight
- Paintability
- Service lifetime
- Barrier impact regulations
- Impact strength at all service temperatures
- Total deflection of the bumper
- Solvent resistance
- Dent resistance
- Cost

Of these parameters, weight and cost are the most critical, whose values are minimized subject to the engineering requirements of the application.

Based upon these considerations and upon the design passed to them by styling, the advance engineering groups make a preliminary materials selection. In general, this materials selection is not particularly specific. However, in special cases, where a particular project is being pursued, the material specification can be quite definite (such as the use of XENOY® resins by Ford).

Bumper Materials and Component Engineering

By the time the bumper design reaches the component engineering staffs, the basic material selection and the target component performance has been defined. For the component engineer, the problem of material selection is reduced to a satisficing process - any material that meets the performance bogeys established by the Advance Engineering group is acceptable. However, overperformance on any of these bogeys, except weight and cost, is irrelevant. Most component engineers rarely have incentives to exceed specification; usually they are struggling to meet specification.

As the specifics of the bumper design are thrashed out, the component engineer may find that he cannot meet his performance specfication. If the failure is dramatic enough, a respecification of the bumper design or the bumper material must be made. By dramatic, we mean:

- any weight problem that puts the vehicle into a higher EPA weight class,
- any cost problem that puts the vehicle into a higher priced class, or
- any structural problem that will lead to a failure to meet impact regulations.

Bumper Materials and Assembly

By the assembly stage, very little is done to select the material to be used in bumpers. The objective of the preceding engineering steps is to assure that the assembly groups merely deal with assembling the vehicle. However, under certain situations, some changes can be made.

First, if the ordered material does not meet the manufacturer's specification, alternative material suppliers may be contacted for a new material. Alternatively, a different grade of material may be ordered from the same supplier.

Second, if the actual weight of the vehicle is high enough to put it into a higher EPA weight class, different materials may be used to bring the curb weight down. The assembly groups have learned over the past years where they can strategically change the material specification to save weight. However, bumpers are not generally targeted for this type of last-minute weight reduction.

Finally, failure of the vehicle to pass the FMVSS impact tests will lead to major changes in both material and design. Under no circumstance will any of the Big Three risk putting a non-regulation bumper system on the road.

APPENDIX H - COMPUTER PROGRAM LISTING

```
/*
        This routine computes the utility of a set of alternatives
        according to the results of a utility questionnaire.  Employed
        in the bumper case, this routine only accepts cost and weight
        data about each alternative.  The routine displays the utility
        of each alternative, as well as computing the cost at which
        each alternative would have the same utility as the base case.

        The program reads several inputs from a disk file, whose name
        is supplied by the user.  The file contains the results of a
        bumper questionnaire, which consist of

                - the number of characteristics in the utility function,
                - the average value of each of the characteristics,
                - the single dimension utility of each average value, and
                - the ki scaling factor for each characteristic.

        In addition, the weight and cost of a base case system is input,
        followed by up to twenty other combinations of cost and weight.
        The routine computes the utility of each case, and then computes
        the cost at which each alternative system would have the same
        utility as the base case system.
```

```
*/

#include "stdio.h"

/*
        Given a set of single attribute utility values, the single
        dimension scaling factors, and the function scaling
        factor (K), this routine computes the multiattribute utility.

        order  = the number of dimensions in the utility function
        litl_k = an array of size order containing the interdimensional
                 scaling factors for each dimension
        utils  = an array of size order containing the single attribute
                 utility values for the case being treated
        kappa  = the multi-attribute utility function scaling factor
*/
float utilcalc (utils,litl_k,order,kappa)

float utils[],litl_k[],kappa;
int order;


int i;
float work;

work = 1;
for (i=0;i<order;i++)

        work = work * (kappa * utils[i] * litl_k[i] + 1);

work = (work - 1)/kappa;
return(work);
```

```
/*
        Given a characteristic level, the utility of the average level,
        and the value of the average level, this routine computes the
        utility of the characteristic level given.  The routine assumes
        that the lowest level of the characteristic is the most
        preferred
*/
float costutil (cost,avgcost,uavg)

float avgcost,uavg,cost;


float max,min,work;

max = avgcost + avgcost;
min = avgcost / 2;

if (cost > max) return(0);
if (cost < min) return(1);
if (cost <= avgcost)

        work = uavg + (1 - uavg)*(cost - avgcost)/(min - avgcost);

else

        work = uavg * (cost - max) / (avgcost - max);

return (work);
```

```
/*
        This routine computes the cost at which an alternative
        would have the same utility as the base case

        The algorithm first solves for the single attribute utility
        value that must be associated with cost in order to result in
        a multi-attribute utility value equal to that of the base case.
        The routine then calculates the cost which gives the required
        single attribute utility level for cost.

        Given n-1 attributes for a known multilinear multi-attribute
        utility function, what must be the single attribute utility
        of the nth attribute to yield a multi-attribute utility level
        of U?

        1)  Using the n-1 attributes, compute the multi-attribute
            utility value, assuming that the single attribute utility
            of the nth characteristic is 0.

        2)  Divide (K * U + 1) by (K times the value computed in step 1
            plus 1.

        3)  Subtract 1 and divide the result by the scaling factor K
            and the interdimensional scaling factor k associated with
            the nth characteristic.

        4)  The result is the single attribute utility required of the
            nth characteristic in order to achieve the target multi-
            attribute utility level.

*/
float valinuse(cost,avg,uavg,k,utils,kappa,order,bu)

float cost,avg[],uavg[],k[],utils[],kappa,bu;
int order;


float work,targetc;

/* step one - compute the target cost utility
        1. set the utility of cost = 0;
        2. divide (K*baseu + 1) by (K*caseu w/ costu =0 + 1)
        3. result = (K*kcost*target costu + 1)
*/
utils[0] = 0;
work = utilcalc(utils,k,order,kappa);  /* here we are computing the
                                          mau assuming u(cost) = 0 */
targetc = ((kappa * bu) + 1);
targetc = targetc / ((kappa * work) + 1);
targetc = (targetc - 1) / (kappa * k[0]);  /* targetc now equals the
```

```
                                                  required utility of cost */
/* now, deal with the easy cases */

if (targetc > 1)

        printf("\nOVERFLOW ERROR - Please check data. %f\n",targetc);
        return(0);

if (targetc < 0)

        printf("\nUNDERFLOW ERROR - Please check data. %f\n",targetc);
        return(0);

if (targetc == 1) return ( avg[0] / 2);  /* best - least cost */
if (targetc == 0) return ( 2 * avg[0] ); /* worst - highest cost */
if (targetc == uavg[0]) return (avg[0]); /* average - average cost */

/* so much for the easy cases -- now to solve for the cost that
   gives targetc - linear interpolation between know points */

if (targetc > uavg[0])

        work = (targetc - uavg[0]) * (-avg[0]/2)/(1 - uavg[0]);
        work = work + avg[0];

else

        work = targetc * (- avg[0]) / uavg[0];
        work = work + avg[0] * 2;

return(work);

/*
```

```
        Supplemental function - computes  (π(Kki+1) - 1)/K

        Required to solve for K in the function big_k

*/
double funkshun (guess,litl_k,order) /* computes value of the function */

float guess;
float litl_k[20];
int order;


        double tot, sub;
        int i;

        tot = - 1 - guess;
        sub = 1;
        for (i = 0; i < order; i++)

                sub = sub * (guess * litl_k[i] + 1);

        tot = tot + sub;
        return (tot);

/*
```

```
        Computes the numerical derivative of funkshun

*/

double deriv (guess,litl_k,order)

float guess;
float litl_k[20];
int order;


        double first,second;

        first = funkshun(guess - 0.0001,litl_k,order);
        second = funkshun(guess + 0.0001,litl_k,order);
        return ((second - first) / 0.0002);
```

```
double abs (val) /* takes the absolute value */
double val;


        if (val >= 0)
                return (val);
        else
                return (-val);

/*
```

```
        Given the interdimensional scaling factors for each dimension,
        this function uses Newton's Method to solve for the K scaling
        factor for the multi-attribute utility function

        1)  Sum the interdimensional scaling factors for all dimensions

        2)  If the sum is greater than 1, K will be < 0
            If the sum is less than 1, K will be > 0
            If the sum is 1, K will be 0 and the MAU function is a
                linear combination if the single attribute functions

        3)  Depending on the sum of the ki's, start searching for a
            change of sign in the value of funkshum (to assure that
            Newton's Method will start in the vicinity of the zero
            of the function that is appropriate)

        4)  Apply Newton's method to find the zero of the function

        5)  The K which gives the zero is the K scaling factor for
            the utility function being treated

*/
float big_k(dim,k)
int dim;
float k[];

float kap, k_sum;
double val,v1,v2;
int i;
        k_sum = 0;
        for (i = 0; i < dim; i++) k_sum = k_sum + k[i];
        if (k_sum > 1.0001)

                kap = -.001;

        else if (k_sum < 0.9999)

                kap = 0.001;

        else kap = 0;
        v1 = funkshun(kap,k,dim);
        printf("Searching for change of sign.");
        do

                kap = kap * 2;
                v2 = funkshun(kap,k,dim);
                if (v2 == 0) v2 = -v1;
                printf (".");

        while ((v1 / v2) > 0);
```

```
printf("\nSearching for solution.");
for (i = 0; i < 1000 ; i++)

        val = funkshun(kap,k,dim);
        if (abs(val) > 0.000001)

                kap = kap - ( funkshun(kap,k,dim) / deriv(kap,k,dim));
                printf (".");

        else break;

if (i != 1000)

        printf ("\nK = %7.4f \n",kap);
        printf ("Val = %7.4f \n",val);
        return (kap);

else

        printf("\nNo convergence after 1000 tries.\n");
        return (0);
```

```
/*
        data collection routine
*/
readata(pdim,pk,puavg,pavg,pcases,pcost,pbcost,pwgt,pbwgt,names,bn,s)

int *pdim,*pcases;
float pk[],puavg[],pavg[],pcost[],pwgt[],*pbcost,*pbwgt;
char names[20][20],bn[],s[];


int i,j;
char work;

printf("Subject's name: ");
scanf("%s",s);
printf("How many dimensions:  ");
scanf("%d",pdim);
for (i = 0;i < *pdim; i++)

        printf("What is the k for dimension(%d)?   ",i+1);
        scanf ("%f",&pk[i]);
        printf("What is the average value for dimension(%d)?   ",i+1);
        scanf("%f",&pavg[i]);
        printf("What is the average utility for dimension(%d)?   ",i+1);
        scanf("%f",&puavg[i]);

printf("\nFor the cases being considered, please supply the following");
printf(" data.\n");
printf("What is the name of the base case: ");
scanf("%s",&bn[0]);
printf("What is the cost of the base case: ");
scanf("%f",pbcost);
printf("What is the weight of the base case: ");
scanf("%f",pbwgt);
printf("How many cases are to be treated: ");
scanf("%d",pcases);
for (i = 0 ; i < *pcases ; i++)

        printf("What is the name of case #%d: ",i+1);
        scanf("%s",&names[i][0]);
        printf("What is the cost of case #%d: ",i+1);
        scanf("%f",&pcost[i]);
        printf("What is the weight of case #%d: ",i+1);
        scanf("%f",&pwgt[i]);

return;
```

```
main()

int i,j,l,dim,cases;
char names[20][20],bn[20],s[80];
float k[20],uavg[20],avg[20],utils[20],cost[20];
float weight[20],bcost,bwgt,work;
float bu,cu[20],valcost[20];
double kap;

/* get the relevant data */
readata(&dim,k,uavg,avg,&cases,cost,&bcost,weight,&bwgt,names,bn,s);

/* compute the kappa scaling factor */
kap = big_k(dim,k);

/* assign average utility values for non-cost and non-weight
        dimensions */
for (i=2;i<dim;i++) utils[i] = uavg[i];


/* first compute base cost and weight utilities */
utils[0] = costutil(bcost,avg[0],uavg[0]);
utils[1] = costutil(bwgt,avg[1],uavg[1]);
work = utils[1];

/* compute base utility */
bu = utilcalc(utils,k,dim,kap);

/* now solve for utility and valinuse of each case */
for (i=0;i<cases;i++)

        /* compute case cost and weight utilities */
        utils[0] = costutil(cost[i],avg[0],uavg[0]);
        utils[1] = costutil(weight[i],avg[1],uavg[1]);

        /* compute case utility */
        cu[i] = utilcalc(utils,k,dim,kap);

        /* reset utils for valinuse calculation */
/*      utils[1] = work;  */

        /* compute equivalent value */
        valcost[i] = valinuse(cost[i],avg,uavg,k,utils,kap,dim,bu);


/* dump the results */
printf ("\n\nComputation Summary\n\n");
printf("Subject: ");
i = 0;
while ((s[i] != '\0') && (i < 79))
```

```
        if (s[i] != '_') putchar(s[i++]);
        else

                putchar(' ');
                i++;

printf("\n\n");
for (i=0;i<dim;i++)

        printf("k(%d) = %f  avg(%d) = %10.6f",i+1,k[i],i+1,avg[i]);
        printf("  uavg(%d) = %10.6f\n",i+1,uavg[i]);

printf("\nK = %f\n\n",kap);
printf("\nVALUE IN USE OUTPUT\n\n");

printf("Case Name              Cost      Weight    Utility");
printf("        Value-In-Use\n");
printf("---------------       ------     ------    -------");
printf("        ------------\n");
i = 0;
while ((bn[i] != '\0') && (i < 19))
        if (bn[i] != '_') putchar(bn[i++]);
        else

                putchar(' ');
                i++;

if (i != 19) for (j = i; j < 19 ; j++) putchar(' ');
printf("  $%6.2f    %6.2f    ",bcost+.005,bwgt);
printf("%5.4f         $%6.2f\n",bu,bcost+.005);
for (l = 0 ; l < cases ; l++)

        i = 0;
        while ((names[l][i] != '\0') && (i < 19))
        if (names[l][i] != '_') putchar(names[l][i++]);
        else

                putchar(' ');
                i++;

        if (i != 19) for (j = i;j < 19;j++) putchar(' ');
        printf("  $%6.2f    %6.2f    ",cost[l]+.005,weight[l]);
        printf("%5.4f         $%6.2f\n",cu[l],valcost[l]+.005);
```

APPENDIX I - REFERENCES

1. Adams, D. G., et al., "High Strength Materials and Vehicle Weight Reduction Analysis", Society of Automotive Engineers Technical Paper No. 750221, Warrendale, PA, 1975.

2. Adams, D. G., et al., "Charger XL: A Lightweight Materials Development Vehicle", Society of Automotive Engineers Technical Paper No. 760203, Warrendale, PA, 1976.

3. Adams, David G., "Automobile Panel Sweep Stiffness Analysis", Society of Automotive Engineers Technical Paper No. 740080, Warrendale, PA, 1974.

4. Agarwal, Manoj K. and Brian T. Ratchford, "Estimating Demand Functions for Product Characteristics: The Case of Automobiles", Journal of Consumer Research, Vol. 7, December 1980, p. 249.

5. Alexander, W. O. and P. M. Appoo, "Materials Selection - The Total Concept", Design Engineering, November, 1977, p. 59.

6. Andon, Jerar and Ronald Falk, "Oldsmobile Omega X-Body Baseline Weight Data", DOT-HS-805-212, National Technical Information Service, Springfield, VA, 1979.

7. Appoo, P. M., and W. O. Alexander, "Computer Analysis Speeds Assessment of Engineering Materials", Metals and Materials, July/August, 1976, p. 42.

8. Artinian, L. and S. L. Terry, "The Total Cost of Weight", Society of Automotive Engineers Preprint No. 1961-325D, Warrendale, PA, 1961.

9. Baboian, Robert and Gardner S. Haynes, "Performance of Stainless Steel Clad Aluminum in Bumper Applications", Society of Automotive Engineers Technical Paper No. 840287, 1984.

10. Bartell, B. E., "Automotive Sheet Metal Component Conversion From Steel to Aluminum", Society of Automotive Engineers Technical Paper No. 760057, Warrendale, Pennsylvania, 1976.

11. Belleau, C. and D. K. Kelley, "Characterizations of One-and-a-Half Side Galvanized Steels for Automotive Applications", Society of Automotive Engineers Technical Paper No. 840284, 1984.

12. Bittence, John C., "When Computers Select Materials", Materials Engineering, January, 1983, p. 38.

13. Blanchfield, Dennis E., Donald E. Lewis, and Michael G. Woodbury, "A Simplified Approach for Estimating Manufacturing Costs at the Part Level", Society of Automotive Engineers Technical Paper No. 730908, Warrendale, PA, 1973.

14. Blelloch, Andrew, ed., Measurements of the Impacts of Materials Substitution - A Case Study in the Automobile Industry, American Society of Mechanical Engineers, New York, 1979.

15. Booz-Allen and Hamilton, Inc., Automotive Manufacturing Processes, Volumes III, IV, and V, DOT-TSC-NHTSA-80-21 (DOT-HS-805 574 through 576), National Technical Information Service, Springfield, VA, 1981.

16. Bureau of Labor Statistics, Wage Chronology: Martin Marietta Aerospace and the Auto Workers, March 1944 - November 1975, Bulletin 1884, US Department of Labor, US Government Printing Office, Washington, DC, 1977.

17. Bureau of Labor Statistics, Wage Chronology: International Harvester Company and the Auto Workers, February 1946 - Septermber 1976 Bulletin 1887, US Department of Labor, US Government Printing Office, Washington, DC, 1976.

18. Bureau of Labor Statistics, Industry Wage Survey: Motor Vehicles and Parts 1973-74, Bulletin 1912, US Department of Labor, US Government Printing Office, Washington, DC, 1976.

19. Bureau of Labor Statistics, Wage Chronology: Ford Motor Company and the Auto Workers, Volume II, 1973-79, Bulletin 1994, US Department of Labor, US Government Printing Office, Washington, DC, 1978.

20. Bureau of Labor Statistics, Productivity Measures for Selected Industries, 1954-79, Bulletin 2093, US Department of Labor, US Government Printing Office, Washington, DC, April, 1981.

21. Bureau of Labor Statistics, Productivity and the Economy: A Chartbook, Bulletin 2172, US Department of Labor, US Government Printing Office, Washington, DC, June, 1983.

22. Burley, C. E. and B. A. Neimeier, "Denting Properties of Aluminum Autobody Components", Society of Automotive Engineers Technical Paper No. 770199, Warrendale, PA, 1977.

23. Burst, Hermann E., Hans-Peter Bauerle, and Wolfrm F. Thull, "The All Aluminum Auto Body - A Study Based on the Porsche 928", Society of Automotive Engineers Technical Paper No. 830094, 1983.

24. Busch, John V., Primary Fabrication Methods and Costs in Polymer Processing for Automotive Applications, SM Thesis, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, 1983.

25. Byer, Phillip H., A Screening Model for the Selection of Evaluation Techniques for Engineering System Designs, Ph. D. dissertation, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, 1975.

26. Byer, Philip H., and R. de Neufville, "Choosing the Dimensions and Uncertainties of an Evaluation", from Formal Methods in Policy Formulation, D. W. Bunn and H. Thomas, eds., Birkhauser Verlag, Basel, 1978.

27. Chandler, Harry E., "A Look Ahead at Auto Materials and Processes in the 80's", Metal Progress, May, 1980, p. 24.

28. Chandler, Harry E., "Materials Competition in Autos", Metal Progress, February, 1983, p. 19.

29. Chang, David C. and J. William Justusson, "Structural Requirements in Material Substitution for Car-Weight Reduction", Society of Automotive Engineers Technical Paper No. 760023, Warrendale, PA, 1976.

30. Chang, David C. and Martin R. Barone, "Structural Optimization in Panel Design", Society of Automotive Engineers Technical Paper No. 770610, Warrendale, PA, 1977.

31. Checkland, P. B., "Towards a Systems-Based Methodology for Real-World Problem Solving", Journal of Systems Engineering, Vol. 3, No. 2, Winter, 1972.

32. Clauser, Henry R., ed., The Encyclopedia of Engineering Materials and Processes, Reinhold Publishing, London, 1963.

33. Clauser, Henry R., Robert J. Fabian, and John A. Mock, "How Materials Are Selected", *Materials In Design Engineering*, Vol. 62, No. 1, July, 1965, p. 109.

34. Compton, W. D., "Materials Substitution in the Automotive Industry" in *Measurements of the Impact of Materials Substitution - A Case Study in the Automobile Industry*, Andrew Blelloch, ed., American Society of Mechanical Engineers, NY, 1978.

35. Crane, F. A. A. and J. A. Charles, *Selection and Use of Engineering Materials*, Butterworth & Co., London, 1984.

36. Dargie, P. P., K. Parmeshwar, and W. R. D. Wilson, "MAPS-1: Computer-Aided Design System for Preliminary Material and Manufacturing Process Selection", *Journal of Mechanical Design*, Vol. 104, January, 1982, p. 126.

37. DeGarmo, E. Paul, et al., *Materials and Processes in Manufacturing*, MacMillan Publishing Company, New York, 1984.

38. Dhrymes, Phoebus J., "Price and Quality Change in Consumer Capital Goods: An Empirical Study" from *Price Indexes and Quality Change - Studies in New Methods of Measurement*, Zvi Griliches, Ed., Harvard University Press, Cambridge, Mass., 1971.

39. DiCello, J. A., and R. A. George, "Design Criteria for Dent Resistance of Auto Body Panels", Society of Automotive Engineers Technical Paper No. 740081, Warrendale, PA, 1974.

40. Dorgham, M. A., ed., Technological Advances in Vehicle Design, Interscience Enterprises, Ltd., United Kingdom, 1982.

41. Ericsson, T., ed., Computers In Materials Technology, Pergamon Press, New York, 1981.

42. Farag, Mahmoud M., Materials and Process Selection in Engineering, Applied Science Publishers, London, 1979

43. Fenton, John, Vehicle Body Layout and Analysis, Mechanical Engineering Publications, London, 1981.

44. Form, William H., Blue Collar Stratification, Princeton University Press, Princeton, NJ, 1976.

45. Gentle, Derek F., "Manufacturing of Large Thermoplastic Components for European Cars", Society of Automotive Engineers Technical Paper No. 830994, 1983.

46. Gillam, E., "Materials Selection: Principles and Practice", Metallurgist and Materials Technologist, Vol. 11, No. 9, September, 1979, p. 521.

47. Gladstone, R., et al., Estimation of Weight and Consumer Price Relating to the Implementation of FMVSS 201 in Passenger Cars and FMVSS 103 and 104 int Light Trucks, Autosafety Engineering Corp., Troy, MI, 1982

48. Gladstone, R., et al., Weight and Consumer Prices of Components of the 1980 General Motors Chevrolet Citation and the 1981 Chrysler Plymouth Reliant, Autosafety Engineering Corp., Troy, MI, 1983.

49. Glagow, Klaus C., "Ford Australia Gathers Experience in the Development, Design, and Manufacture of Large PU-RIM Components", Society of Automotive Engineers Technical Paper No. 830989, 1983.

50. Glance, R. M., "Determining Structural Equivalency for Dissimilar Materials", Materials Engineering, June, 1976, p. 18.

51. Goicoechea, Ambrose, Don R. Hansen, and Lucien Duckstein, Multiobjective Decision Analysis with Engineering and Business Applications, John Wiley & Sons, New York, 1982.

52. Gottwald, Carl, "Decision-Making in Preliminary Design", Society of Automotive Engineers Technical Paper No. 730889, Warrendale, PA, 1973.

53. Graham, James A., ed., Use of Computers in Managing Material Property Data, American Society of Mechanical Engineers, MPC-14, New York, 1980.

54. Gray, Edward K. and Roy W. McLeefe, "The New Trade-offs in Engineering Materials Selection", Society of Automotive Engineers Technical Paper 760263, Warrendale, Pennsylvania, 1976.

55. Griliches, Zvi, "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change" from Price Indexes and Quality Change - Studies in New Methods of Measurement, Zvi Griliches, Ed., Harvard University Press, Cambridge, Mass., 1971.

56. Gupta, Indra, Richard S. Cline, and Ram S. Patil, "Effect of Iron-Zinc Alloy Layer on the Mechanical Properties and the Formability of Hot Dip Galvanized Sheet", Society of Automotive Engineers Technical Paper No. 840216, 1984.

57. Gutteridge, P. A. and J. Turner, "Computer Aided Materials Selection and Design", Materials and Design, Vol. 3, August, 1982, p. 506.

58. Haberfield, A. B. and R. C. Hudd, "High Strength Steels for Bodyweight Reduction", The Metallurgust and Materials Technologist, Vol. 14, No. 9, September, 1982, p. 405.

59. Hanley, D. P. and E. Hobson, "Computerized Materials Selection", American Society of Mechanical Engineers, Paper No. 73-Mat-CC, 1973.

60. Hanley, D. P., Introduction to the Selection of Engineering Materials, Van Nostrand Reinhold Co. Ltd., Berkshire, England, 1980.

61. Hardy, David, ed., Plastics Edition 6 - A Desk-Top Data Bank, The International Plastics Selector, San Diego, California, 1983.

62. Harvey, Malcolm R. and Daniel J. Chapinsky, "Development of a Motor Vehicle Materials Historical High Volume Industrial Processing Cost Data Bank (Compact-Type Car)", DOT HS-802 066, National Technical Information Service, Springfield, VA, 1976.

63. Hauser, John R. and Glen L. Urban, "A Normative Methodology for Modeling Consumer Response to Innovation", Operations Research, Vol. 25, No. 4, June/July, 1977, P. 579.

64. Himmel, L., ed. et al, Perspectives in Materials Research, Office of Naval Research, Department of the Navy, Washington, D.C., 1963.

65. Holtz, Mark, Jim Davis, and Dan Crawford, "Selecting Forged Aluminum for Automotive Applications", Society of Automotive Engineers Technical Paper No. 840124, 1984.

66. von Horde, Klaus R., "The Development and Future of Plastic Applications in the European Car Industry", Society of Automotive Engineers Technical Paper No. 830993, 1983.

67. Hsia, Hsi-Sheng, and James A. Kidd, "Weight Reduction Potential of Passenger Cars and Light Trucks by Materials Substitution", Society

of Automotive Engineers Technical Paper No. 800803, Warrendale, PA, 1980.

68. Hundy, B. B., "Selection of Materials for Production", Production Engineer, Vol. 56, No. 1/2, January/February, 1977, p. 26.

69. Hwang, Ching-Lai and Abu Syed Md. Masoud, Multiple Objective Decision-Making - Methods and Applications, Springer Verlag, New York, 1979.

70. Hwang, Ching-Lai and Kwangsum Yoon, Multiple Attribute Decision Making - Methods and Applications, Springer-Verlag, New York, 1981.

71. Johnson, T. E., Jr., and W. O Schaffnit, "Dent Resistance of Cold-Rolled Low-Carbon Steel Sheet", Society of Automotive Engineers Technical Paper No. 730528, Warrendale, PA, 1973.

72. Johnson, W. R. and J. B. Vrable, "Corrosion Resistance and Paintability of Zinc and Zinc-Alloy Coatings for Automotive Sheet", Society of Automotive Engineers Technical Paper No. 840213, 1984.

73. Kamal, Mounir M. and Joseph A. Wolf, ed., Modern Automotive Structural Analysis, Van Nostrand Reinhold, New York, 1982.

74. Karn, Bengt and John Westberg, "New Process Technology Required When Introducing Aluminum Parts into the New Volvo 760 Body", Society of Automotive Engineers Technical Paper No. 840290, 1984.

75. Kary, John J., "Weight Reduction of Automobile Bumper Systems", Society of Automotive Engineers Technical Paper No. 760012, Warrendale, PA, 1976

76. Keeney, Ralph L., "Decision Analysis: An Overview", Operations Research, Vol. 30, No. 5, September - October, 1982, p. 803.

77. Keeney, R. L., and H. Raiffa, Decisions With Multiple Objectives: Preferences and Value Tradeoffs, Wiley, New York, 1976.

78. Keeney, Ralph L. and Alan Sicherman, "Illustrative Comparison of One Utility's Coal and Nuclear Choices", Operations Research, Vol. 31, No. 1, January/February, 1983, p. 50.

79. Kirby, Gary N., "How To Select Materials", Chemical Engineering, Vol. 87, No. 22, November 3, 1980, p. 86.

80. Kojima, M. and Y. Hayashi, "A Study on the Selection of High Strength Steel Sheet for Auto Body Panels", Society of Automotive Engineers Technical Paper No. 800369, Warrendale, PA, 1980.

81. Kopchick, Joseph C., "Automotive Application of Ultra-High Strength Sheet Steel", American Society for Metals Technical Paper No. 8306-018, Metals Park, OH, 1983.

82. Koske, Charles E., "New Materials for Lightweight Trucks", Society of Automotive Engineers Technical Paper No. 820988, 1982.

83. Kusy, Paul F., "Plastic Material Selection Guide", Society of Automotive Engineers Technical Paper No. 760663, Warrendale, Pennsylvania, 1976.

84. Ladd, George W. and Martin Zober, "Model of Consumer Reaction to Product Characteristics", Journal of Consumer Research, Vol. 4, September 1977, p. 89.

85. Lancaster, Kelvin J., "A New Approach to Consumer Theory", Journal of Political Economy, Vol. 74, April 1966, p. 132.

86. Levy, B. S., and A. G. Preban, "The Use of Increased Curvature to Reduce the Weight of Body Panels", Society of Automotive Engineers Technical Paper No. 800370, Warrendale, PA, 1980.

87. Levy, Bernard S., "Prediction of Thickness Reductions from Fatigue Properties of High Strength Steel", Society of Automotive Engineers Technical Paper No. 840009, 1984.

88. Lewis, L. L and M. V. Murray, "Effect of Die Hardness and Lubrication on Stamping Performance of One-Side Electrogalvanized and Cold-Rolled Sheet Steels", Society of Automotive Engineers Technical Paper No. 840368, 1984.

89. Limpert, Rudolf, Vehicle System Component Design and Safety, John Wiley & Sons, New York, 1982.

90. Magee, C. L., "The Role of Weight Reducing Materials in Automotive Fuel Savings", Ford Technical Research Report No. SR-81-70, 1981. (Also Society of Automotive Engineers Technical Paper No. 820147, 1982.)

91. Mahmood, Hikmat F., "Dent Resistance of Surface Panel and Slam Area", Society of Automotive Engineers Technical Paper No. 810099, Warrendale, PA, 1981.

92. Maynard, Dale A., "Selecting the Optimum Connecting Rod Manufacturing Process", Society of Automotive Engineers Technical Paper No. 790023, Warrendale, PA, 1979.

93. McCord, Mark Robert, Empirical Demonstration of Utility Dependence on the Fundamental Assessment Parameters - Revised Assessment Methodology, Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1983.

94. McCord, M. and R. de Neufville, "Fundamental Deficiency of Expected Utility Decision Analysis", in Multi-Objective Decision Making, S. French, et al., eds., Academic Press, New York, 1983.

95. McQuiston, Henry, "Plastics and the Mid-80s Automobile", Plastics Engineering, October, 1979, p. 22.

96. McVetty, T. N., et al., Weight and Detailed Process Cost Study of the 1981 Chrysler K-Car (Reliant/Aries) Components, Illinois Institute of Technology Research Institute, Chicago, IL, 1981.

97. Menzes, G. and H. Derek, "SMC Parts - Report on Processing and Automation for Cost Reduction", Society of Automotive Engineers Technical Paper No. 830991, 1983.

98. Meuleman, D. J., S. G. Denner, and F. L. Cheng, "The Effect of Zinc Coatings on the Formability of Automotive Sheet Steels", Society of Automotive Engineers Technical Paper No. 840370, 1984.

99. Miaw, D. C. and W. R. D. Wilson, "Use of Figures of Merit in Computer-Aided Material and Manufacturing Process Design", Journal of Mechanical Design, Vol. 104, October, 1982, p. 806.

100. Miller, William K. and Edward F. Ryntz, "Magnesium for Automotive Applications - A State-of-the-Art Assessment", Society of Automotive Engineers Technical Paper No. 830521, 1983.

101. Mital, K. V., Optimization Methods in Operations Research and Systems Analysis, John Wiley & Sons, New York, 1976.

102. National Academy of Science, Materials and Man's Needs, Committee on the Survey of Materials Science and Engineering, National Academy of Science, Washington, D.C., 1975.

103. National Materials Advisory Board, Methodological Approaches for Studying Substitution Among Materials, NMAB-385, 1982.

104. de Neufville, Richard, How Do We Evaluate and Choose Between Alternative Codes for Design and Performance?, Department of Civil Engineering Report No. 17, MIT-CE R75-3, Massachusetts Institute of Technology, Cambridge, MA, February, 1975.

105. de Neufville, R. and R. L. Keeney, "Use of Decision Analysis in Airport Development in Mexico City", in Analysis of Public Systems, A. W. Drake, R. L. Keeney, and P. M. Morse, eds., MIT Press, Cambridge, MA, 1972.

106. Ohsawa, Makoto and Mitsuru Noguchi, "Trends of Auto Materials in Japan", Society of Automotive Engineers Technical Paper No. 811408, 1981.

107. Ostrom, Peter, "Work Hardening and Brake Hardening in Five Body Components - Volvo's New Standard for High-Strength Sheet Steel", Society of Automotive Engineers Technical Paper No. 840006, 1984

108. Patil, Ram S., Gary W. Henger, and Raymond J. Glatthorn, "Minispangling of Hot Dip Galvanized Steel", Society of Automotive Engineers Technical Paper No. 840211, 1984.

109. Plevy, T. A. H., "A Systems Approach to Materials and Process Selection", Metallurgist and Materials Technologist, Vol. 13, No. 9, September, 1981, p. 469.

110. Prekopa, A., ed., Survey of Mathematical Programming, Proceedings of the 9th International Mathematical Programming Symposium, North-Holland Publishing Co., New York, 1979.

111. Rao, S. S., Optimization Theory and Applications, John Wiley & Sons, New York, 1984.

112. Ratchford, Brian T., "The New Economic Theory of Consumer Behavior: An Interpretive Essay", Journal of Consumer Research, Vol. 2, September 1975, p. 65.

113. Reinhardt, R. W., R. E. McMaken, and B. C. Singer, "Development of a Motor Vehicle Materials Historical High Volume Industrial Processing

Cost Data Bank (3500-4500 pounds) Full Size", DOT HS-803 894, National Technical Information Service, Springfield, VA, 1978.

114. Riffe, William J., "No-Damage Steel Bumpers - A New Approach", Society of Automotive Engineers Technical Paper No. 770212, Warrendale, PA, 1977.

115. Rivett, R. M. and W. Lucas, "Joining Aluminum for Mass Production Industries", Society of Automotive Engineers Technical Paper No. 830599, 1983.

116. Rolf, R. L., M. L. Sharp, and H. H. Stroebel, "Structural Characteristics of Aluminum Body Sheet", Society of Automotive Engineers Technical Paper No. 770200, Warrendale, PA, 1977.

117. Rolf, R. L., M. L. Sharp, and W. C. Herbein, "Minimizing the Weight of Aluminum Body Panels", Society of Automotive Engineers Technical Paper No. 790164, Warrendale, Pennsylvania, 1979.

118. Rosen, Harold J, and Philip M. Bennett, Construction Materials Evaluation and Selection - A Systematic Approach, John Wiley & Sons, New York, 1979.

119. Rosen, Sherwin, "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition", Journal of Political Economy, Vol. 82, 1974, p. 34.

120. Sharp, H. J., ed., Engineering Materials - Selection and Value Analysis, American Elsevier Publishing Co., New York, 1966.

121. Sharp, M. L., J. R. Jombock and B. S. Shabel, "Structural Performance of Aluminum Bumpers", Society of Automotive Engineers Technical Paper No. 780140, Warrendale, PA, 1978.

122. Sharp, M. L., R. M. Peters, and R. B. Weiss, "Structural Design Considerations for Aluminum Bumpers", Society of Automotive Engineers Technical Paper No. 770269, Warrendale, PA, 1977.

123. Smith, Charles O., The Science of Engineering Materials, Prentice Hall, Englewood Cliffs, NJ, 1977.

124. Spurgeon, William M., "The Contribution of Materials Technology to Profitable Manufacturing", Society of Manufacturing Engineers Engineering Technical Paper MM75-910,

125. Starkey, J. A., "Government Requirements and Voluntary Standards - International Considerations", Society of Automotive Engineers Technical Paper No. 830386, 1983.

126. Toda, Munetaka, et al., "Development of Two-Layered Zn-Fe Alloy Electroplated Steel Sheet - New Coated Steel Sheet for Automotive Body", Society of Automotive Engineers Technical Paper No. 840212, 1984.

127. Triplett, Jack E., "Automobiles and Hedonic Quality Measurement", Journal of Political Economy, Vol. 77, 1969, p. 408.

128. Unterweiser, Paul M., "Computer-Aided Engineering at Deere: A Materials Selection-Data System", Metal Progress, Vol. 111, No. 4, April, 1977, p. 38.

129. Vadhavkar, A. V., et al., "Panel Optimization Program (POP)", Society of Automotive Engineers Technical Paper No. 810230, 1981.

130. Verink, E. D., Jr., ed., Methods of Materials Selection, Gordon and Breach, New York, 1968.

131. Waterman, N. A., The Selection of Materials, Oxford University Press, 1979.

132. Waterman, N. A., "Computer Aided Materials Selection", Materials & Design, Vol. 3, August, 1982, p. 502.

133. Waterman, N. A., "Materials Substitution in the Mass Produced Automobile", Materials In Engineering, Vol. 3, 1982.

134. Waughtal, Richard F., "Advanced Concepts in Automobile Weight Reduction Using High-Performance Plastics", Society of Automotive Engineers Technical Paper No. 780358, Warrendale, PA, 1978.

135. Weymueller, Carl R., "Selection and Using Economical Alternative Materials", Metal Progress, Vol. 100, No. 3, September, 1971, p. 71.

136. Wimber, R. T., "A Preliminary Materials Selection Guide", Society of Automotive Engineers Technical Paper No. 760139, Warrendale, Pennsylvania, 1976.

137. Wong, Winston A., "Monotonic and Cyclic Fatigue Properties of Automotive Aluminum Alloys", Society of Automotive Engineers Technical Paper No. 840120, 1984.

138. Wyatt, Leslie M., ed., The Fulmer Materials Optimizer, Fulmer Research Institute, Ltd., Stoke Poges, Slough, Berkshire, England, 1981.

139. "Cost-Effective Weight Reduction With Sheet Steel", American Iron and Steel Institute, Washington, DC.

140. "Guide for Preliminary Design of Sheet Steel Automotive Structural Components", American Iron and Steel Institute, Washington, DC, 1981.

141. "High Strength Steel for Automotive Use", Society of Automotive Engineers, Document No. P-124, Warrendale, PA, 1983.

142. "Minimizing the Weight and Cost of a Production Deck Lid", Society of Automotive Engineers, Document No. SP-489, Warrendale, PA, 1981.

143. *Plastics in Passenger Cars*, Society of Automotive Engineers, Document No. SP-566, Warrendale, PA, 1984.

144. "Dawson v. Chrysler", *Federal Reporter*, Second Series, Vol. 630, West Publishing Co., St. Paul, Minnesota, 1980, p. 950.

145. "Seese v. Volkswagenwerk", *Federal Reporter*, Second Series, Vol. 648, West Publishing Co., St. Paul, Minnesota, 1981, p. 833.

146. "Dreisonstok v. Volkswagenwerk", *Federal Reporter*, Second Series, Vol. 489, West Publishing Co., St. Paul, Minnesota, 1974, p. 1066.

147. "Part 571 - Federal Motor Vehicle Safety Standards", *United States Code*, Title 49, Section 571.

148. "Part 581 - Bumper Standard", *United States Code*, Title 49, Section 581.

BIOGRAPHICAL NOTE

BIOGRAPHICAL NOTE

I was born in Augusta, Georgia on February 17, 1956. Raised in North Augusta, South Carolina, I attended Augusta Preparatory School, where I graduated with salutatorian honors in 1974. I entered the Massachusetts Institute of Technology in the fall of 1974, graduating with an S.B. in Nuclear Engineering in 1974. Continuing my eduation at MIT, I received an S.M. in Technology and Policy and an S.M. in Nuclear Engineering in 1981. I then began an interdepartmental doctoral program in Materials Systems Analysis in the Deparment of Materials Science and Engineering.

Upon the completion of my doctorate, I will pursue post-doctoral work with the Materials Systems Laboratory at MIT.