MULTIATTRIBUTE UTILITY ANALYSIS
OF MATERIALS SELECTION DECISIONS

by

DEBORAH LEE THURSTON

SB, Civil Engineering, University of Minnesota
(1978)

SM, Civil Engineering, Massachusetts Institute of Technology
(1984)

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Signature of Author ... ..
Department of Civil Engineering
April 17, 1987

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

Accepted by ....
Professor David H. Marks
Chairman, Doctoral Thesis Committee

Accepted by ....
sor Ole S. Madsen
Chairman, Departmental Graduate Committee

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DEBORAH LEE THURSTON

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ABSTRACT

Multiattribute utility analysis is applied to the decision problem of materials selection for automotive systems. Steel, aluminum and polymer composite materials are considered by automotive design engineers for structural frame and body skin systems. The design engineer is faced with a confusing array of alternatives, each of which may be represented as a bundle of incommensurate attributes.

A new methodology is developed which facilitates the application of utility analysis to a large, complex, engineered system. The system is first broken down into subsystems delineated on the basis of functional requirements. Multiattribute utility functions for each subsystem are assessed, then aggregated to derive an expression for the overall utility of the entire system as a function of attribute levels in each subsystem. This approach facilitates redesign of the system in order to optimize the characteristics of any given material.

The methodology was applied in seven different automotive companies in the United States and in Europe. Four types of alternatives were analyzed. Six performance characteristics were determined to be both relevant and non-binary. These negotiable attributes are capital cost, variable cost, weight, design flexibility and corrosion resistance. The preference structures varied between sets of decision makers, resulting in strategic differences as to the identification and selection of the material system which optimizes overall utility or value to the design engineer. The quantification of tradeoffs between performance characteristics each decision maker was willing to make also differed. Although the existing decision making environments do not at this time allow for radical design change, the methodology proved useful as a decision making tool to be used by design engineers to select the best system and as a marketing tool to be used by materials manufacturing interests.

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

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CHAPTER 1 - INTRODUCTION

CURRENT SITUATION

Materials selection decisions for automotive systems have recently become extremely difficult. Traditionally, this has been a relatively simple task. The automotive design engineer was forced to work within the constraints of a handful of available materials, namely wood and steel. Steel gained wide acceptance due to its strength and mass produceability characteristics. Its limitations such as those in the areas of corrosion resistance and weight were tolerated. Materials selection decisions consisted of determining the type of steel and forming process which satisfied the engineering characteristics at the lowest production cost. Cars were made of steel. Since steel became accepted as the standard automotive engineering material, changes have taken place which make the materials selection task much more complex. The three major changes which have taken place which complicate the materials selection environment are consideration of a broader range of design criteria, the availability of a larger set of alternative materials to meet these criteria and a greater range and degree of uncertainty as to the ultimate levels of performance each alternative will attain.

A BROADER RANGE OF DESIGN CONSIDERATIONS

First, the oil embargos of the 1970's and concern for the environmental impact of gas-guzzling cars resulted in a need to add fuel efficiency as a new performance characteristic to be considered when designing automobiles. Lighter and better designed cars consume less fuel, resulting in conservation of natural energy resources and decreased emissions from the combustion system.

Design engineers now consider several attributes at once, which generally cannot be converted to a common metric such as dollars. Many groups of advanced design engineers now consider performance characteristics or attributes which go beyond conventional structural analysis factors such as torsional stiffness and bending strength. Fuel efficiency, corrosion resistance, manufacturability, styling, marketing and accounting concerns are all addressed in the early stages of design. Consideration of these aspects in the preliminary design and decision making stage has proven to be more efficient than addressing these issues after a design has been formulated and materials selection decisions made. The problem arises in that the decision maker is faced not with choices based on a single indicator of value (such as dollars) but with choices between bundles of incommensurable attributes.

A LARGER SET OF AVAILABLE MATERIALS

A wider variety of plastic, plastic composite, aluminum and steel materials are increasingly being considered and utilized in automotive applications. Cost estimation and engineering design problems are made more complex by the fact that there are many materials and processing technologies available today which simply did not exist even a few years ago. New polymer materials are being introduced at a rapid rate. New reinforcing fibers and manufacturing processes are also being developed, resulting in new fiber reinforced polymer composite materials for both structural and nonstructural applications. Also, some previously "exotic" materials such as aluminum have become widely available at a price which is potentially competitive with that of steel. Steel itself is now available in a much larger variety of types, whose strength, corrosion resistance and other performance characteristics can all be made to order.

The reason that this proliferation of alternatives causes problems is twofold. First, significantly different manufacturing, forming and assembly operations make comparative cost estimation difficult. Deriving comparable cost estimates for stamping a high strength, low alloy (HSLA) steel component vs. filament winding the same component from a polymer composite material is much more difficult than deriving comparable cost estimates for stamping the component from carbon steel vs. stamping the component from HSLA steel. Second, engineering design is made more difficult. In addition to offering a broader range of values for traditionally considered engineering characteristics such as bending strength, these new materials in some cases behave structurally in fundamentally different ways from traditionally used steel materials. Polymer composites require the consideration of characteristics never before taken into account. For example, the degree of and extent to which anisotropy can be controlled is significantly more pronounced in polymer composite materials than in steel. While this aspect greatly improves design flexibility, it literally adds a whole new dimension to the design problem.

UNCERTAINTY

Design engineers today are faced with a greater range and degree of uncertainty for alternatives, and have no systematic method by which to incorporate this uncertainty or their attitude towards it into their decision making process. The levels of performance characteristics (such as cost, weight and corrosion resistance) actually achieved after design, production and assembly processes are carried out is often not known with certainty, even for traditional materials. Also, the character and degree of this uncertainty may vary significantly between systems which incorporate new materials and those which utilize more traditional materials. The automotive design engineer's attitude toward this risk or uncertainty must somehow be included in the decision making process.

CURRENT APPROACH

From automotive design engineers perspective, the problem is that of materials selection decisions. What can these new materials and processes do for us? How can they best be used? How much should I pay for their special performance characteristics? The need is for a decision making tool for this complex decision making environment.

From materials marketing perspective, the problem is that of market demand estimation. What do automotive design engineers want, what do they need, and how much will they pay for it? Do the answers to these questions differ between automakers, and if so, how? The need is for a quantitative description of the various decision making environments.

How are design engineers dealing with materials selection problems now? Generally, with direct substitution of isolated components.

DIRECT SUBSTITUTION OF INDIVIDUAL COMPONENTS

Reinforced polymer composites are often first considered for "problem" components, where the steel solution is less than satisfactory. Examples are large cast components where the potential for weight reduction is great, components that are particularly prone to corrosion, that are difficult or expensive to form from steel and components that have requirements for both great strength and low weight. Thus, reinforced polymer composites are often compared to steel on a component by component basis. Examples are floor pans [34] and bumpers [23].

It may seem that this type of comparison offers the greatest potential for polymer composites to be chosen over steel, since the application calls for special characteristics that polymer composites possess. However, this direct substitution of individual, isolated components often results in an unrealistic or unfavorable comparison with the traditional material. The comparison is usually made on the basis of cost and weight [47], [43], or even cost alone [31]. The material design and selection problem becomes a question of whether the polymer system performs as steel would perform in the same shape, size and configuration, and do it lighter and cheaper [22]. The potential benefits of corrosion resistance and manufacturing flexibility are considered mainly as "extras" after the system is approved, which occurs only if structural specs have been met at a cost lower than steel.

This type of comparison does not allow the option of redesign of the component or of the subsystem of which it is a part. Redesign allows the engineer to meet structural requirements in a way which most efficiently utilizes the materials' characteristics.

When comparing alternative materials for direct substitution of an isolated component into a larger system (which was presumably designed with the original material in mind) the design engineer frequently faces so many constraints that use of a new material is infeasible. For example, if the design dictates that the reinforced polymer composites component be of the same shape as the steel component, that structural loads placed on the component be managed within narrowly defined deflection limits, and that a specific joining method such as welding be employed, use of any material other than steel may be impossible.

Compensating measures must also be captured. It is not meaningful to simply calculate the cost difference between a steel door of a particular design and a plastic door of the same design, since direct substitution of SMC for steel in a door outer panel is infeasible without redesign of the entire door system. Steel fulfills important structural requirements in many door panel designs, including specific crash shock absorption criteria. Substituting plastic for steel in the outer panel requires that an additional reinforcing component be added in order to meet these criteria. This, in addition to gauge increases necessary for the plastic outer panel to achieve the same stiffness as the steel outer panel, results in the "plastic" system being heavier than the all steel system it was intended to replace. Thus, when plastic materials are used extensively in the body skin, it becomes necessary to redesign the frame in order to provide greater structural integrity of the frame itself [49]. Analysis of an isolated component or even the entire body skin would not be complete without including the necessary frame redesign and other indirect impacts.

Direct substitution also prevents the advantage of of parts consolidation from being realized. The potential is great; a front end composed of 20 separate metal parts may be replaced by a single injection molded plastic component, as illustrated in Figure 1[5]. The cost savings of this consolidation may be significant, since assembly accounts for a large percentage (30%-40%) of the total production cost.

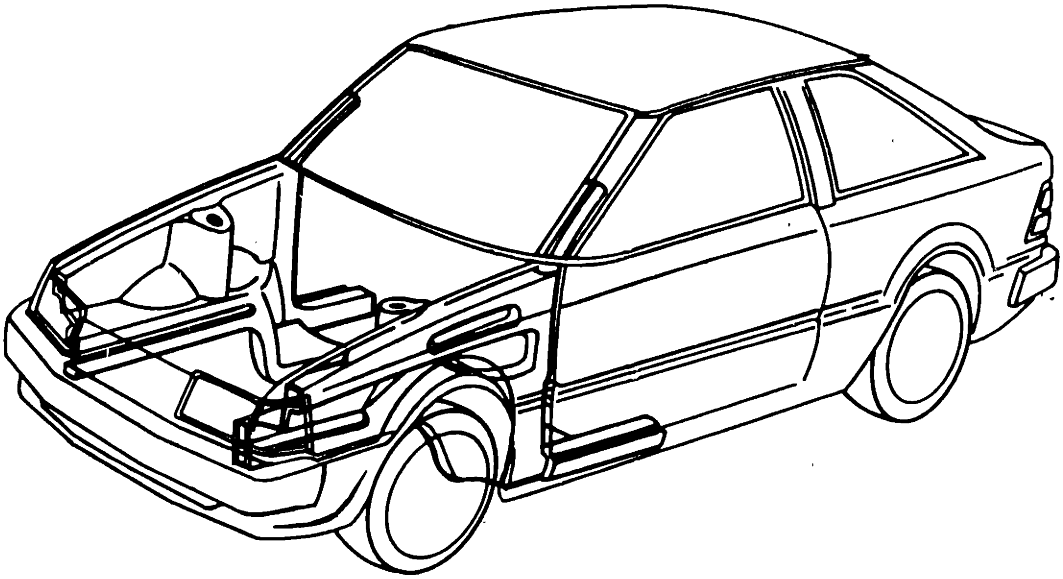


Figure 1. Parts Consolidation

The entire front end structure of a Ford Escort made as an experimental one-piece polymer composite molding, replacing 42 steel components. The structure passes the standard automotive crash test.

Source; J.C. Bittence, ed."Automakers Take Advanced Composites Seriously", Advanced Materials and Processes, February, 1986.

OBJECTIVE

The traditional approach of selecting the lowest cost material that meets engineering specifications for that component is no longer adequate. It is also no longer meaningful to reduce one or two materials performance characteristics to a common metric such as dollars and select the lowest cost alternative. capability to design structures based on the special characteristics of polymers[50]. There is a need for the development of a method by which decision makers can compare a wide range of fundamentally different materials for a complex system in a rational manner. The objective of this thesis is to develop and apply a quantitative analytic tool (multiattribute utility analysis) for problems of materials selection decisions for automotive systems which facilitates redesign.

CHAPTER 2 - PROBLEM DEFINITION

In this chapter, a systems analytic approach is taken to define the decision making problem in greater detail.

SYSTEM DEFINITION

The system to be analyzed is the entire "frame and skin" system, illustrated in Figure 2 [1]. This includes all internal load bearing structural and external body panel components. External components may be load bearing or non-load bearing. When designed in steel, this system is referred to as the "body in white" or "uni-body", and is composed of roughly 50 major and 250 minor components. Not included are the engine, drivetrain, exhaust system, suspension system and interior.

This system is much larger and more complex than the individual, isolated components such as fenders, bumpers and deck lids which have been analyzed to this point. This expansion is necessary in order to capture all potential advantages and disadvantages of each material system, and allow for redesign to optimize materials characteristics.

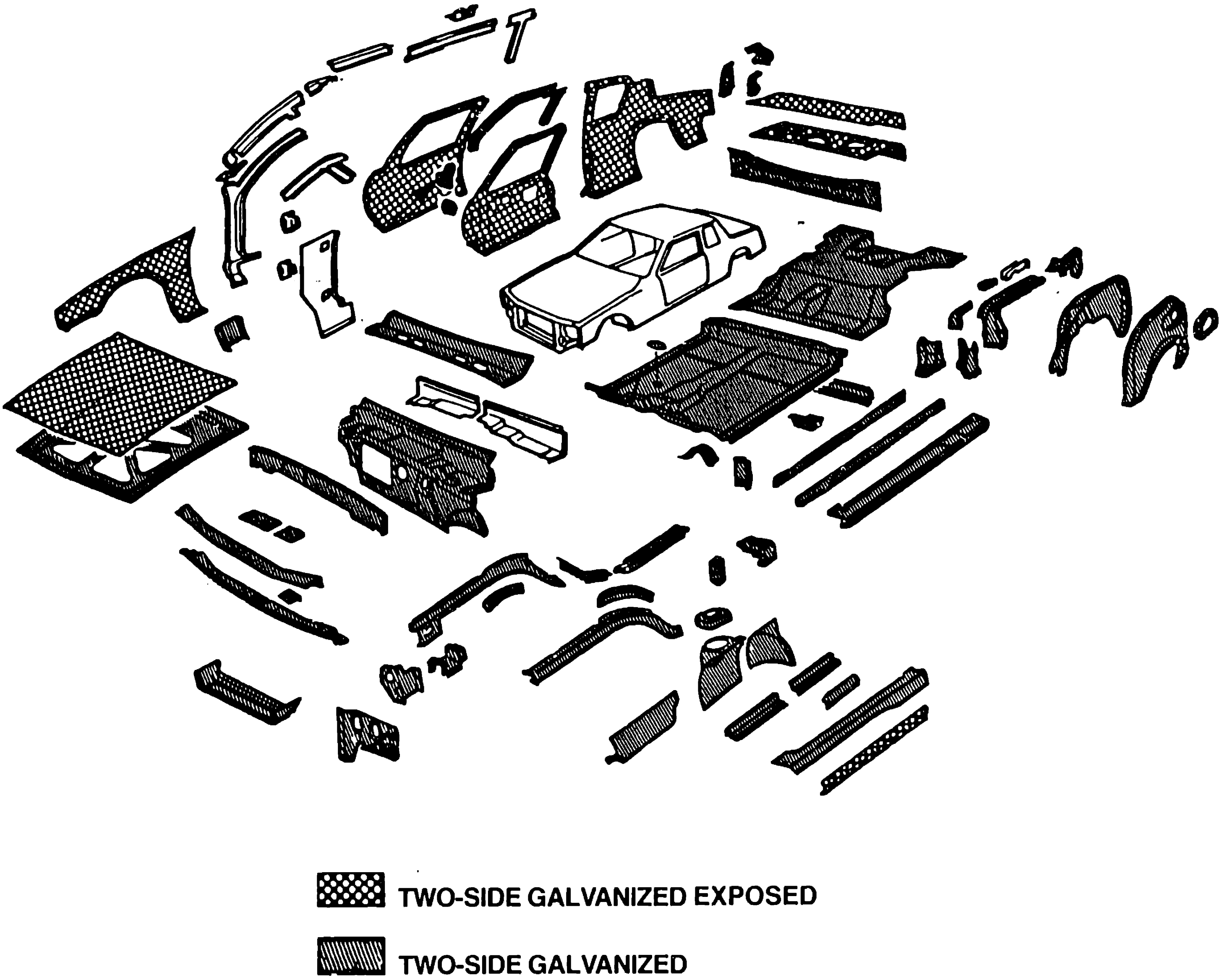


Figure 2. Uni-Body Structure

Source: American Iron and Steel Institute, Publication SG-437

Design concepts are often material specific in order to optimize the characteristics of the chosen material. A key point in the definition of "the system" is to do so in such a way as not to preclude a particular design concept, thus limiting materials choices. Thus, design alternatives which perform the same function as the steel uni-body but using a different load bearing system may be objectively considered. The most notable of these alternative designs are the "space frame" and "platform" concepts discussed in the next section.

IDENTIFICATION OF DECISION MAKERS

Automotive engineers engaged in the process of designing and selecting alternative materials systems are the target group. There are several distinct types of automotive design engineers. Those involved in short term design (ie. next year's model) are forced to work within severe constraints imposed by the manufacturing and styling groups. The styling group dictates the outward appearance of the car, and instructs the design engineers to fit a frame within that shape, while the manufacturing group dictates which material (which grade of steel) and manufacturing processes are to be used. For the purposes of our analysis, it is necessary to work with engineers involved in longer term projects, or "advanced design". The engineers who benefit most from our approach are those with the freedom to seriously consider a broad range of alternative material system designs, typically engineers involved in longe term projects, or "advanced design" groups. This group enjoys more flexibility than groups involved in shorter term projects, who are constrained to a preselected material, forming process and styling.

The engineers in the target group are cognizant of the preferences and requirements of manufacturing, styling, marketing and accounting groups, in addition to their own engineering requirements. They also consider the preferences and values of car-buying customers [46]. They consider these aspects in the initial design stage, rather than being constrained by them later.

ALTERNATIVE MATERIALS SYSTEMS

The three broad categories of materials under consideration by the automotive industry are steel, aluminum and polymer composites. While the results of the analysis may be used to compare any alternative system design using any material, it is helpful in the early stages of analysis to have some basic idea as to what the alternatives will be, so as to ensure that all materials advantages and disadvantages are captured when defining performance characteristics. Alternative designs generally fall into one of four categories: steel uni-body, aluminum intensive, space frame and hybrid.

STEEL UNI-BODY

The term uni-body refers to the design concept of integrating structural function into exterior body panels, as illustrated in Figure 2. This system includes internal and external components that are part of the structural load bearing system and also external components that are non-load bearing. This system is composed of approximately 300 stamped steel components which are welded and bolted together to form what is known as the "body in white".

Advantages of this system are relatively low operating costs, and the fact that this system and material represent the traditional approach to the design and manufacture of automobiles. Disadvantages of this system relative to the other alternatives are high capital cost requirements, poor design flexibility, poor corrosion resistance and weight.

ALUMINUM INTENSIVE SYSTEM

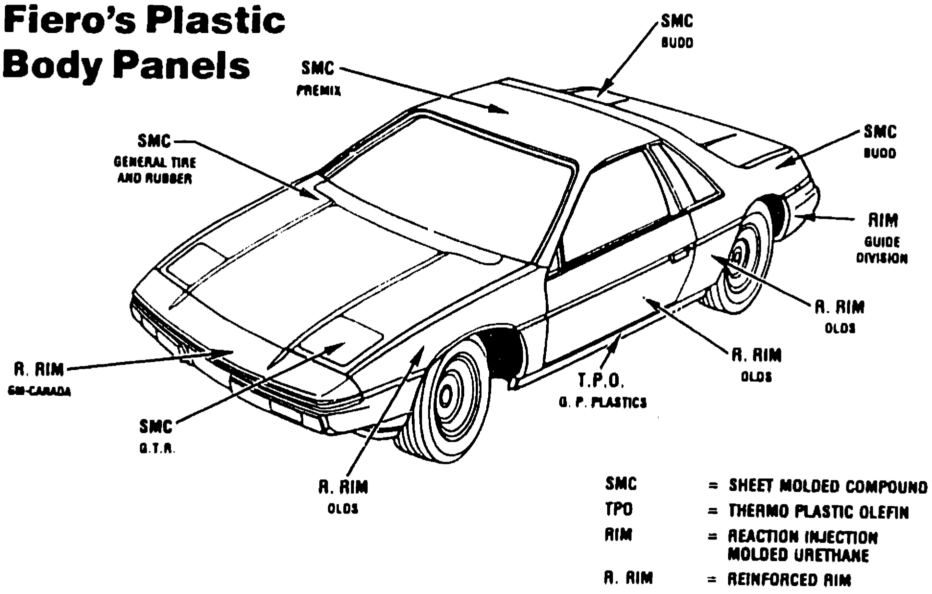
This system uses aluminum for both structural and non-structural components. A load bearing structural "frame" is composed of extruded aluminum tubes joined together by aluminum castings. The exterior body panels may be stamped from aluminum, steel, or polymer composite materials.

Advantages are weight savings, parts consolidation and low capital cost. Disadvantages are high materials cost, a greater degree of uncertainty as to the ultimate material cost, and technical problems with joining technologies.

STEEL FRAME WITH POLYMER COMPOSITE SKIN

This is the design concept used in the Pontiac Fiero, illustrated in Figure 3 [62]. The inner load bearing frame structure or "birdcage" is composed of stamped steel components welded together. The exterior body panels are referred to as "hang-ons", they are merely hung onto the structural frame, and fulfill no structural purpose in themselves.

Potential advantages are improved corrosion resistance, weight savings, lower capital costs and increased design and marketing flexibility. Lower tooling costs for the body panels allow a greater number of body styles may be offered each year, which can also be changed more often than those of a steel system. Disadvantages are higher material costs. Also, the actual weight savings may not be as dramatic as initially expected. This is because the structural function previously performed by a steel body panel is now transferred to the internal frame. Steel reinforcing components must be added.



Fiero's Plastic Body Panels

SMC = SHEET MOLDED COMPOUND
TPO = THERMO PLASTIC OLEFIN
RIM = REACTION INJECTION MOLDED URETHANE
R. RIM = REINFORCED RIM

Fiero's frame had 270 individual stampings and contained more than 600 lbs. of high-strength steel and galvanized HSS or mild steel.

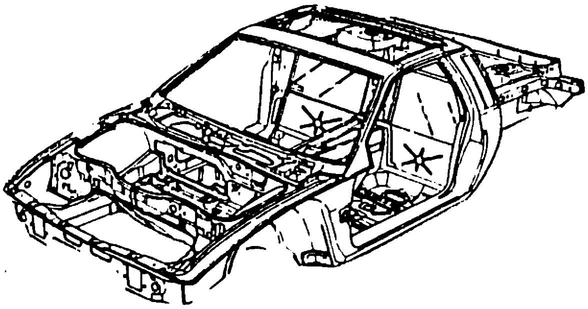


Figure 3. Space Frame Design - Pontiac Fiero

Source: 1984 Ward's Automotive Yearbook

HYBRID STEEL AND POLYMER COMPOSITE STRUCTURE AND BODY SKIN

Both steel and reinforced polymer composite materials are used in the load bearing structure and body skin panels. A variety of design concepts may be employed including the "space frame" concept. Another innovative concept which makes optimal use of polymer materials is that of a stamped steel "platform" on which a variety of structural composite "cage" structures and body skin systems may be placed. These details of these design concepts vary for each automaker, and are proprietary. One example is illustrated in Figure 4 [49].

These systems offer the greatest potential for realizing the advantages of polymer composite materials through redesign. Advantages include parts consolidation, weight savings, decreased capital costs, improved corrosion resistance and greater styling and marketing flexibility. Disadvantages are high materials cost and inexperience in the design of structural composites.

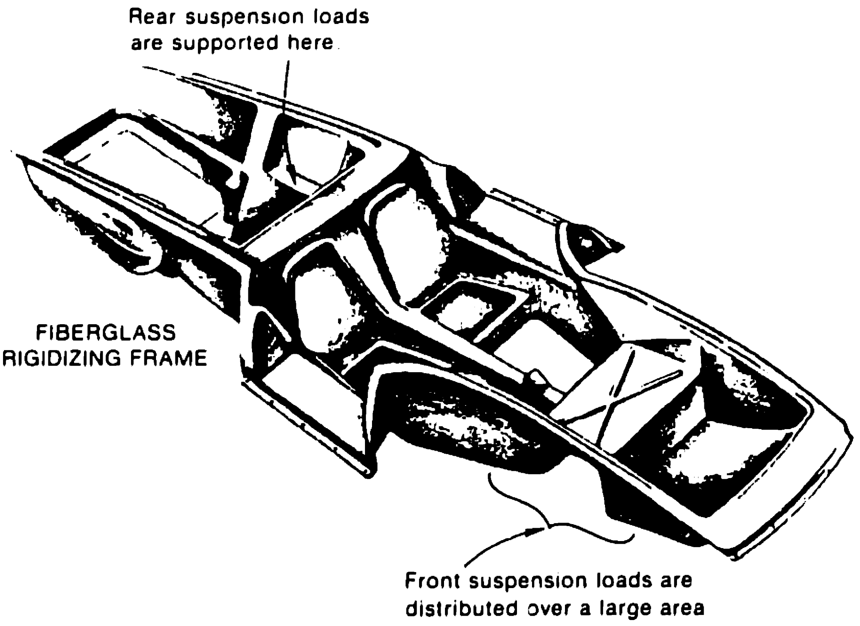


Figure 4. Hybrid Design

A polymer composite inner frame intended to replace steel frames. Steel reinforcing members are used to distribute loads at critical areas.

Source: K.W. Nelson, "Plastics in Vehicle Structures".

CHAPTER 3 - EXPANSION OF UTILITY ANALYSIS

Multiattribute utility analysis is a decision making tool especially useful for problems involving the consideration of multiple performance characteristics, seemingly incommensurate attributes, non-linearity of preference and uncertainty [37]. These are characteristics of the problem at hand. Although the existing methodology as applied in previous analyses of automotive components [21], [54] is insufficient in itself for a situation of this complexity, multiattribute utility analysis provides the basis for the development of a decision making tool appropriate to this problem. The expansion necessary for this application are described in this chapter. The following is a summary listing of the steps to be followed in this application. The first four steps were described in Chapter 2, Step 5 is described in Chapter 4, Step 6 is described in Chapter 5, Steps 7 and 8 in Chapter 3, and Steps 9 and 10 in Chapters 6 and 7. An example of use of the methodology to develop new alternatives is presented in Chapter 7.

STEPS IN APPLICATION

1. Define Problem
2. Define System
3. Identify Decision makers
4. Identify Alternatives
5. Delineate Subsystems
6. Determine Performance Characteristics for each subsystem
7. Develop Survey
8. Conduct Survey
   a. Define Attribute Ranges
   b. Determine Single Attribute Utility Functions
   c. Determine k scaling constants
   d. Derive multiattribute utility function
9. Apply Methodology to Actual Alternatives
   a. Develop alternatives
   b. Estimate attribute levels for each alternative
   c. Compute overall utility of each alternative
   d. Rank alternatives
   e. Quantify changes in attribute levels necessary for sub-optimal alternatives to become competitive
      1) Improvement in one or more attributes
      2) Acceptable tradeoffs between attributes
10. Redesign alternatives to achieve a set of attributes with higher overall utility, to approach a more optimal design.

Issues involved in the application of multiattribute utility analysis to a large system as opposed to an individual component are addressed. An approach is proposed which for the first time facilitates the application of this type of analysis to a complex, engineered system.

The approach is to divide the system into subsystems, each consisting of individual components with similar performance requirements. Multiattribute utility functions are assessed for each subsystem. A method for combining these utility functions of each subsystem to provide one expression for the overall utility of the entire system is presented.

DEFINITION OF SUBSYSTEMS

Multiattribute utility functions for individual engineered components such as bumpers [21] and turbocharger rotors [54] have been performed. In each case, one multiattribute utility function was derived for the individual component.

One of the first steps in the analysis is to define the component in terms of its performance requirements, or what it "does" rather than what it is named. It is essential that the performance characteristics are selected and defined in such as way as to capture all important advantages and disadvantages of each alternative material, and to prevent any bias towards or against any particular material. We seek to eliminate not only any institutionalized bias towards a traditional material that may exist, but also any "bandwagon" effect of favoring a new material simply because it is in vogue. The performance characteristics are not attributes of the raw material itself, such as density, or Young's modulus, but rather characteristics of how the material behaves in a designed system, such as total weight and stiffness. One might initially approach the automotive frame and skin system by attempting to assess utility functions for each individual component, then aggregating them in some way. However, this approach is neither feasible nor appropriate.

First, it would be prohibitively time consuming to assess multiattribute utility functions for each of the approximately 300 individual components of the system. Each assessment requires nearly an hour. Second, even if they could each be assessed and aggregated, the results would not be usable. Design concepts differ in the way they fulfill system functions such as crash-energy management and bearing of structural loads. So, performance requirements would vary for a particular component depending on the requirements placed on it by the design of the total system of which it was a part. Thus, several aspects of these assessed preference functions (including relevant performance characteristics, allowable range, degree of risk aversion, and scaling coefficients) would be design dependant. It would then be necessary to assess utility functions for each component for each design concept. Even if the enormous time requirements for such a set of assessments could be overcome, the results would not be useful for comparing the utility of two alternative design concepts. Also, it would not be possible to even estimate the utility of new and different design concepts, much less compare them to current systems.

To make the transition from direct substitution of individual components to system redesign to optimize materials' characteristics, one must think in terms of function on a large scale rather than the form of the individual component. To structure the analysis to facilitate creative redesign, the total system will be divided into subsystems which are delineated on the basis of function. Each subsystem will consist of a group of components which fulfill a particular function, each component having similar performance requirements. Subsystems will be defined such that conditions of preferential independance and utility independance are valid within each subsystem. Each component of each design alternative will fit into one and only one subsystem. However, since different design concepts fulfill system requirements in different ways, performance requirements for a particular component may vary depending on which design concept is used. Thus, a particular component may be one subsystem when used in Design Alternative A and another subsystem when used in Design Alternative B.

For example, the two basic design concepts are that of "uni-body" and "space frame" construction. In uni-body structures, both the internal and external components may fulfill load bearing functions. In the space frame design, all structural loads are borne by an internal skeleton-like frame, with the exterior body panels being referred to as "hang-ons", since they are merely attached to the structural frame for protective and aesthetic purposes. In a uni-body system the rear quarter panel is required to handle significant stress loads, whereas in a space frame design, it is not. Thus, a particular component such as a rear quarter panel of a uni-body design may be included in subsystem #6 described in Chapter 4 ("vertical external body panels below the splash line; load bearing") while the rear quarter panel of a space frame design may belong to subsystem # 7 ("vertical external body panels below the splash line; non-load bearing").

To avoid confusion, the term "frame" will include all those components which perform some load bearing function, regardless of whether they are interior or exterior components. The term "hang-on" will refer to components which perform no load bearing function, such as the front fender. The term "body skin" or "skin" will refer to all exterior surface components, such as the roof, hood and deck lid panels. A skin component will be considered part of the frame if it fulfills a structural load bearing function, and a hang-on if it does not.

By focusing on discrete subsystems which are defined on the basis of the function they fulfill, the analysis will remain applicable to the decision making problem even if new design concepts are developed. Any system which fulfills the same function as a traditional steel uni-body design, even if in a different form, may be analyzed.

AGGREGATION OF SUBSYSTEM UTILITY FUNCTIONS

For each subsystem, multiattribute utility functions are assessed which express the decision makers values and preference structure for sets of attributes. Now, these functions must be somehow combined in such a way as to express the total or overall utility of the entire system.

It would be inappropriate to express the overall utility simply as the sum of the utilities of the subsystems. Direct comparison of utility between subsystems is invalid. The utility functions for each subsystem are arbitrarily scaled 0 to 1, and since some subsystems may be much smaller than others, the relative importance of a small system would be exaggerated. The implication would be that a dollar saved in a relatively small subsystem such as "vertical body panels - load bearing" is worth more than a dollar saved in a relatively large subsystem such as "load bearing components in the passenger cage". One might approach this problem by assigning a weighting value to each subsystem on the basis of relative values for a single attribute. If the passenger cage, front and rear end subsystems each typically accounted for 15% of the capital cost and the external body panels subsystem accounted for 55%, one might multiply their subsystem utilities by 0.15, 0.15, 0.15 and 0.55, respectively, and sum to calculate overall utility. However, the relative attribute levels across subsystems varies depending on which attribute is chosen as the basis of comparison. The passenger cage may represent 15% of the capital cost, but 50% of the weight of the vehicle. Thus, relative subsystems weights may vary significantly if based on levels of a single attribute. Also, since these relative values are dependant on the design concept used, a weighting scheme appropriate to one design may not be applicable to another.

The issue then is how to evaluate the relative importance of the utility of each subsystem to the overall utility of the total system. The problem closely parallels issues involved in group decision making problems. In such a problem, a group of individuals, each with his own set of values and preferences, must select one system from a set of alternatives. The "group decision making problem" consists of how to go about defining criteria for the identification and selection of the "best" system. Extensive research has been performed in the area of economic analysis of social welfare functions. A variety of criteria for determining optimal social welfare have been explored, including the concept of "pareto optimality", whereby a situation exists such that it is not possible to increase the satisfaction of any individual without at the same time decreasing the satisfaction of another individual. Some approaches involve various methods of reaching a group consensus, including majority rule voting schemes, individual rankings of alternatives, and public vs. secret voting or ranking schemes. Other methods attempt to include considerations of equity or distribution of satisfaction by minimizing differences between most and least satisfied individuals, or minimize deviation from some mean level of satisfaction.

The current problem parallels a group decision problem if the "group" is defined as the entire structural frame and skin system, consisting of a number of individual subsystems. Each subsystem is viewed as an individual in the group.

Much of the research pertaining to aggregation of individual utility functions to derive a group utility function has focused on the problem incompatability of economic efficiency and equity. A very general interpretation of Arrow's Impossibility Theorem [3] is that given a set of seemingly reasonable conditions, there is no procedure for combining the rankings of alternatives by several members of a group into an overall group ranking that does not include comparison of preferences between individual members.

Kirkwood showed [41] that strictly "efficient" methods, ones which have pareto optimality or optimization of overall welfare as the sole objective are incompatible with methods which include considerations of equity.

Methods which require each member of the group to assign a priority ranking to each alternative to achieve a group consensus [14] provide an ordinal ranking of alternatives. Since the rankings are ordinal rather than cardinal and each members' ranking is given equal weight, no consideration of the magnitude of differences between the resulting welfare of individuals is possible.

Other methods which accomodate consideration of the magnitude of preferences but place equal weight on the preferences of each individual [44] address the problem of how to optimize total welfare of the group, but do not allow for considerations of equity regarding how that total welfare is distributed amoung individuals.

One type of approach to combining considerations of both efficiency and equity involves determining a solution which minimizes group regret via a weighted distance function [63]. The problem then becomes that of determining the appropriate point from which to measure posterior welfare (initial assets position, the greatest potential welfare had that individual been granted his first choice, or some median or average level of welfare) and how to assign the weighting values.

A delegation process for setting weighting values has been developed for problems where a weighted sum of individual utility functions is used to make group decisions [9] Group members designate weighing values to other group members from which a unique set of weights are derived.

Several heuristic approaches have been developed to address these problems. The use of anchored scales solves the problem of inconsistency between individual and group preferences [16]. Methods which include consideration of strength of preference and interpersonal comparison of preference address the problems posed by Arrow's Impossibility Theorem [8], [19], [28], [37] and appear to be applicable to this problem. While originally intended to solve problems of inter-personal comparisons of utility, the concepts appear to be applicable to the current problem of inter-system utility.

The theoretical problems regarding optimization of group utility are of interest. However, the problem we are currently dealing with is the complete lack of any systematic decision making methodology. Our goal is not an optimization algorithm but the development of a systematic decision making tool. The problems involved in the inefficiency of equity, while ethically troublesome in many cases, is really not applicable in the case of an engineered system. Issues of social justice are not at hand. Equity in this application is the distribution of satisfaction between the various groups of design engineers. While an engineer who specializes in passenger cage design may be less satisfied with system "A" than with system "B", it is difficult to interpret him as personally "suffering" as a result of the selection of system "B" because of its greater overall utility for the entire decision making group. In situations where a design engineer or group of design engineers makes materials selection decisions for all of the subsystems together as a whole, the issue of equity is further deanthropomorphized.

The entity responsible for weighing equity and efficiency considerations for the group is defined as the decision maker. The decision maker would be that person or group of people responsible for the final design and materials selection decisions for the entire system, taking into account the preferences of each individual. The individuals in this case is defined as the subsystems. A "benevolent dictator" is assumed, one who would select the system resulting in the greatest total "good" or utility for the entire group. She wants to make everyone happy. Such a decision maker has the best interests of each individual in mind; no malevolence or desire to make any individual suffer exists. Greater utility of the individual subsystems results in greater utility for the decision maker. The values and preferences for each individual subsystem are incorporated into the decision maker's own value and preference function.

The decision maker is a dictator in that her choice of the best system cannot be overridden by the protest of an individual. Each individual has input into the decision in terms of making his or her feelings, values and preferences known to the decision maker, but has not authority over the decision maker. We assume that the individual is capable of expressing preferences via the assessed multiattribute utility function, and assumine he is honest in expressing these preferences. The decision maker has sole responsibility and authority for making interpersonal comparisons of utility. The decision maker's preferences depend on the preferences of individuals, but preferences of individuals do not depend on preferences of others in the group or on those of the decision maker.

Being benevolent, the decision maker does incorporate the desires, preferences and values of each individual in her selection of "best" system. Although the decision maker would prefer that every individual be as satisfied as possible, the choices she faces are often not dominated by one alternative; in our case one alternative is not best in every attribute for every subsystem. Tradeoffs will have to be made. It may be necessary to make them not only between attributes but also between individuals subsystems.

The proposed approach is to aggregate subsystem utility functions via a weighted average. Strength of preference is reflected by the utility functions and inter"personal" comparison of preference is reflected by a weighting value assessed for each subsystem.

PROCEDURE

The procedure to assess utility functions and use the results to compare alternative systems is presented.

UTILITY FUNCTION ASSESSMENT

Utility functions for each of the subsystems were derived from information obtained in personally conducted surveys of automotive design engineers. The survey utilized the certainty equivalent method to obtain indifference statements to determine the single attribute utility functions and scaling constants. Some work regarding the effect of assessment technique on survey results has shown that results obtained using the "lottery equivalent" method differ from those obtained with the "certainty equivalent" method [17]. It is argued that in some cases the results obtained using the lottery equivalent method more closely reflect the decision maker's true preference structure, since the decision maker is inordinately influenced by the "certainty effect" [30], [59]. The argument is that most decision maker are usually faced with two uncertain situations, and is so unused to certain vs. uncertain situations that when faced with one during the survey, places inordinate value on the certain quantity. However, in this application the certainty equivalent method more closely approximates the scenario most commonly faced by the decision maker; a relatively "certain" situation posed by the traditional steel system vs. polymer composites whose ultimate performance characteristics are relatively uncertain.

Surveys were be performed both manually and with a computer aided survey program. Appendix B contains a copy of the manual survey form used in the interviews. The interactive computer program titled "ASSESS" used in several of the interviews was developed by Philippe Delquie [17]. This package facilitated the assessment procedure, reducing the time required to perform the survey. It was particularly useful in groups which included some bilingual members and some who were less fluent in English, since the program prompts can be written in another language, such as French or Italian. The surveys at Fiat Central Research and Peugeot were performed in this manner. An example of the output is included in Appendix D. An earlier computer aided assessment program, Multiattribute Utility Function Calculation and Assessment Package (MUFCAP), has also been developed [56].

The most efficient way to conduct either the manual or computerized assessment is to determine the relevant attributes beforehand, having already screened for insignificant and binary criteria, and aggregating performance characteristics where possible. The initial part of the survey then consists of determination of the appropriate ranges for each attribute. Then, the single attribute utility functions and scaling constant "k" values are assessed for each attribute, followed by testing for utility independance.

Some of the surveys were be conducted with individuals, others with a group. The assessment procedure should reflect as closely as possible the normal working procedure of the decision maker. If he normally works independantly, considering alternatives and making decisions on his own before recommending an alternative to a superior, then the survey is conducted only with him. If the normal working procedure is to work in a group, with discussion and debate before consensus is reached, then the survey is conducted in this manner, and survey responses are determined by group consensus. Responses to surveys previously performed [21] indicate homogeneity of response between members of a particular group of decision makers. For example, responses from the group of bumper design engineers were homogeneous, indicating that the utility function for each decision maker in the group was strategically equivalent; that is, given the same set of alternatives, each engineer would assign them the same ordinal ranking.

DERIVATION OF OVERALL UTILITY FUNCTION

Procedure

1. Define Attributes and Subsystems. The attributes relevant for each subsystem are defined, units specified and ranges determined.

   $i = 1 \ldots n$ attributes;

   1 = capital cost
   2 = variable cost
   3 = weight
   4 = design flexibility
   5 = corrosion resistance

   Define subsystems:

   $j = 1 \ldots m$ subsystems;

   1 = internal load bearing structural components
   2 = vertical exterior body panels above the splash line
   3 = vertical exterior body panels below the splash line
   4 = horizontal exterior body panels

2. Assess the single attribute utility functions for each subsystem.

   $U_i^j (x_i^j) = f (x_i^j)$

   = single attribute utility for attribute i in subsystem j

   x_i^j = amount of attribute i in subsystem j

3. Assess the scaling constants for each attribute for each subsystem.

   k_i^j = utility function scaling constant for attribute i in subsystem j

4. Calculate K for each subsystem j from relationship:

   $1 + K^j = \pi_{i=1}^{n} (1 + K^j k_i^j)$

   K^j = scaling constant for subsystem j

5. Derive multiattribute utility function for each subsystem. Multiplicative form:

   $U^j(x_1^j, x_2^j \ldots x_n^j) = f[(U_1^j(x_1^j), U_2^j(x_2^j) \ldots U_n^j(x_n^j)]$

   $K^j U^j(x_1^j, x_2^j, \ldots x_n^j) + 1 = \pi_{i=1}^{n} \quad [K^j k_i U_i^j(x_i^j) + 1]$

   K^j = scaling constant for subsystem j

6. Derive overall system utility as a function of multiattribute utility functions for each subsystem.

   $U (U^1, U^2, \ldots U^m) = f[U^1(x^1), U^2(x^2), \ldots U^m(x^m)]$

   U = overall utility of total system, consisting of m subsystems

   U^j = multiattribute utility of subsystem j

   x^j = set of attribute levels in subsystem j

   Approach is to derive a "group" utility function. "Individuals" in the group are each subsystem; the "group" is the total system.

   $U (x) = \Sigma_{j=1}^{m} W^j U^j(x)$

   W^j = assessed scaling constant for subsystem j

CHAPTER 4 - SUBSYSTEM DELINEATION

The basis for subsystem delineation is presented. Performance characteristics which distinguish subsystems are discussed, along with the initial exhaustive list of subsystems. Then, criteria for simplification of the exhaustive list to a more workable delineation are discussed.

DISTINGUISHING CHARACTERISTICS

Determination of relevant performance characteristics and delineation of subsystems is carried out after review of the technical literature, trade journals and conference proceedings [12], [13], [20], [25], [27], [51], [33], and extensive written and verbal communication with industry experts. Input from these experts is essential, since they are currently dealing with the very issues we are attempting to resolve. Information was obtained from both the automotive design engineers, materials engineers, and manufacturing engineers involved in the materials selection process, and from materials development researchers involved in marketing their product to the automotive industry. Appendix A contains a complete listing of the major sources consulted during the preliminary data gathering phase, and an example of survey letters used to obtain input. The companies consulted included:

Table 1. Major Companies Consulted in Preliminary Phase

Aluminum Company of America
Chrysler Corporation
Concept Analysis Corporation
E.I. DuPont Inc.
Ford Motor Company
General Electric Company
Inland Steel Company
Montedison

The subsystems are delineated as design engineers currently view them. The preliminary exhaustive delineation of subsystems is:

1. Internal load bearing components in front end
2. Internal load bearing components in passenger cage
3. Internal load bearing components in rear end
4. Vertical exterior panels above splash line; load bearing
5. Vertical exterior panels above splash line; non-load bearing
6. Vertical exterior panels below splash line; load bearing
7. Vertical exterior panels below splash line; non-load bearing
8. Horizontal exterior panels; load bearing;
9. Horizontal exterior panels; non-load bearing

Justifications for these delineations based on binary groupings is as follows:

LOAD BEARING VS. NON-LOAD BEARING

Non-load bearing components fulfill no structural functions. It is expected that load bearing components will have structural requirements such as torsional stiffness and bending strength included in their set of relevant performance characteristics, and that the non-load bearing components will not.

INTERNAL VS. EXTERNAL

For external body panel components, it is necessary to achieve a finished surface, usually painted. Internal components are not visible from the exterior, and surface finish quality is usually not important. It is expected that surface quality will be included as a performance characteristic for external components, but not for internal components. For some designs such as the space frame, there will be a direct correlation between physical location (internal vs. external) and structural function (load bearing vs. non-load bearing). For uni-body designs, this correlation will not hold.

FRONT END VS. PASS. CAGE VS. REAR END

While each of these sections bears structural load, their function in crash energy management varies. Any alternative must be designed to maintain the integrity of the passenger cage (Section B in Figure 5) during and immediately following impact, protecting the occupants [15]. However, this rigidity is neither necessary nor desirable for the front and rear end sections; these sections are designed to absorb the energy of a crash by buckling upon impact.

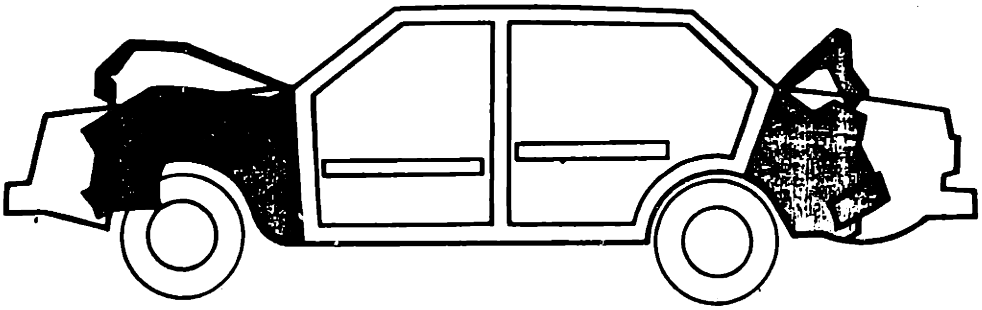


Figure 5. Crash Protection Diagram

The passenger cage is designed to maintain its integrity upon impact, while the front and rear ends are designed to absorb impact energy via buckling.

Source: Volvo

ABOVE VS. BELOW SPLASH LINE

The splash line is approximately one-third the distance from the ground to the roof of the vehicle. Increases in the use of road salt in recent years led to serious corrosion problems. Components below the splash line, including those on the underside of the vehicle, are subject to a much more corrosive environment than those above, due to spray from the road and the salt it contains. It is expected that the characteristics of corrosion resistance will be more highly valued for components below the splash line than for those above.

VERTICAL VS HORIZONTAL PANELS

Horizontal body panels include the hood, roof and deck (trunk) lid, and the major requirement is stiffness. Horizontal panels are subject to greater environmental stress due to more direct exposure to ultraviolet radiation. Vertical panels include the front and rear fenders and doors, and do not have to be particularly rigid or strong, as illustrated in Figure 6 [39].

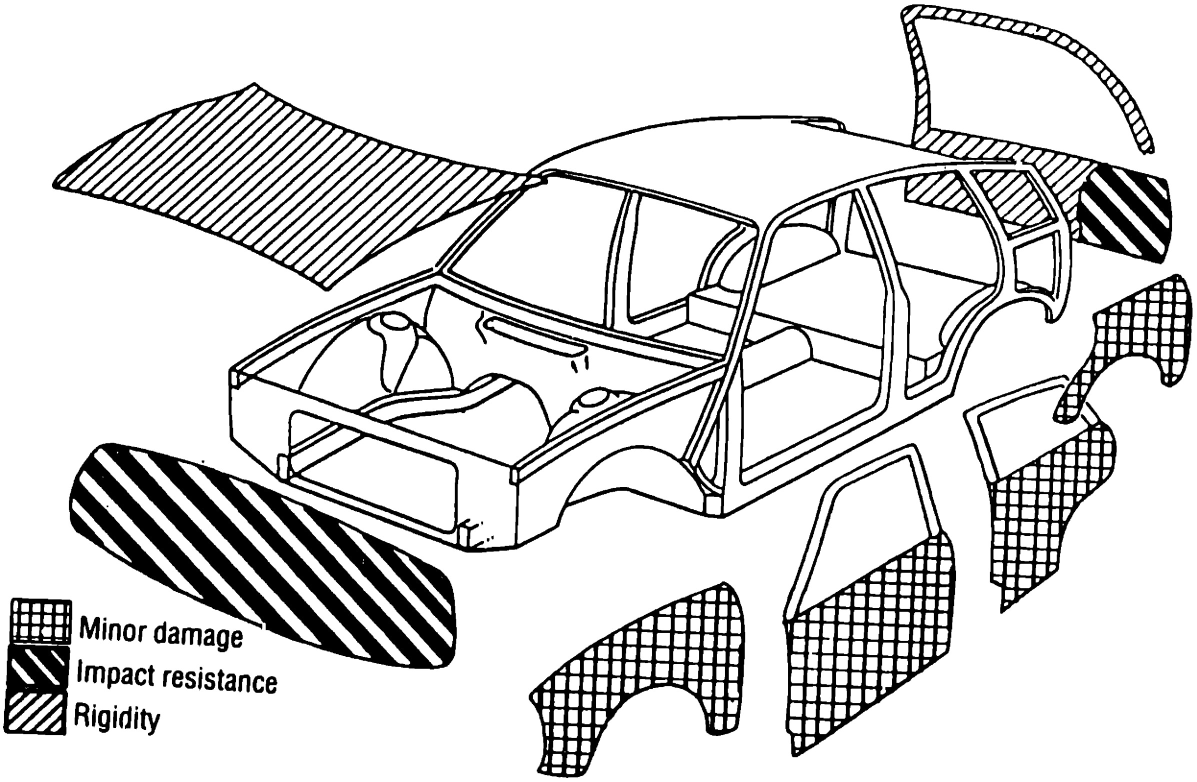


Figure 6. Body Panel Requirements

Source: D. Kewley, Society of Automotive Engineers, Technical Paper Number 850103

SIMPLIFICATION

The approach taken to define performance characteristics and system subgroups is that of development of an initial exhaustive list which includes all input offered by the sources consulted, followed by simplification to a more workable set of subsystems and performance characteristics. Quantitative methods may be used [10], but were not necessary in this case. This approach is intended to prevent an item from being overlooked in the initial assessment.

Delineation of subsystems is done in conjunction with definition of performance characteristics. As performance characteristics and subsystems are being determined, components are grouped into subsystems with similar performance requirements. The goal is to define the performance characteristics and subsystems in such a way as to accurately reflect the performance functions and exploit conditions of preferential and utility independance to minimize the number of preference statements required in the assessment procedure. The exhaustive enumeration of performance characteristics and subsystems is simplified by the elimination of attributes which are binary, insignificant or aggregable for a particular subsystem.

BINARY

Binary performance requirements are those which MUST be met at a specified level in order for the system to be acceptable, but for which there is no value to the decision maker in exceeding. For example, "temperature resistance" is a binary requirement in that a specific temperature level experienced by the component during the manufacturing and/or operating processes must be tolerated. The component is unacceptable if it cannot withstand this temperature, but the decision maker is not willing to pay (in terms of sacrificing in other areas of performance such as cost or weight) in order to achieve the ability to withstand temperatures significantly higher than those experienced during its manufacture or operation.

INSIGNIFICANT

These are characteristics that are considered in the decision making process, but whose contribution to overall utility of the system is so small and/or varies so little between systems as to lend it inconsequential in relation to other characteristics. For example, while static yield resistance mentioned as being considered by design engineers, it is not necessary to consider tradeoffs which might be made in order achieve a certain level of static yield resistance. The reason is that the characteristic of buckling resistance is more constraining; if a component or subsystem meets the buckling resistance requirement, the static yield requirement is met and surpassed [11].

AGGREGABLE

Several attributes may be commensurate, and may be converted to a common metric. For example, many of the benefits of "parts consolidation" are expressed in assembly cost savings. Ting describes criteria for aggregation of attributes for multiattribute utility analyses. The necessary and sufficient condition for a set of attributes to be aggregable is that their rates of substitution be independant of the levels of other attributes [58].

The remaining relevant characteristics are those which are considered by the design engineer and which he has the freedom, willingness, responsibility and authority to trade performance levels off against each other over a definable range.

The analysis is simplified where possible by the aggregation of subsystems into larger subsystems. Subsystems which are distinguished only by attributes that are later identified as binary for that subsystem are consolidated with another subsystem with similar performance requirements. This, while the distinction between exterior panels above the splash line and below the splash line is important in determining whether a specific corrosion resistance requirement will be met, this distinction does not need to be included in the subsystem definition if corrosion resistance is a binary performance requirement. Criteria for the aggregation of objectives and measures of effectiveness are that the resulting attributes should form a complete set, be non-overlapping, meaningful and quantifiable via measurement or estimation. Attributes may be aggregated if the conditions of preferential independance and constant rates of substitution hold [7].

CHAPTER 5 - PERFORMANCE CHARACTERISTICS

This chapter discusses the performance characteristics. Using criteria discussed in previous chapters, we define those attributes which are relevant, significant and non-binary. Other attributes which were mentioned by the sources are discussed.

Table 2. Exhaustive List of Performance Characteristics

- Capital Cost
- Operating Cost
- Weight
- Fatigue, service life
- Styling Flexibility
- Drag Resistance
- Fuel Economy
- Response Time
- Corrosion Resistance
- Surface Finish
- Temperature Resistance
- Quality
- Parts Consolidation

Structural Considerations

- Torsional Stiffness
- Bending Strength
- Vibration Damping
- Dent Resistance
- Yield Resistance
- Anisotropy
- Buckling Resistance
- Oil Canning

RELEVANT ATTRIBUTES

After elimination of binary, insignificant and aggregable attributes, the revised listing of relevant and negotiable performance characteristics includes capital cost, operating cost, weight, design flexibility and corrosion resistance.

CAPITAL COST

This includes costs for new facilities ("brick and mortar"), tooling and equipment for both component production and assembly. The process of stamping sheet steel into components requires large investments in tooling and machinery. Large production volumes allow this expense to be spread over a great number of components. The existing production and marketing structure which consists of very large production volumes of a relatively few number of models which change incrementally over periods of several years came to be as a result of these high tooling and machinery costs.

The economics of polymer composites and some aluminum processing technologies are the inverse of steel; relatively low capital investment required for tooling and machinery coupled with relatively high material costs. The cost benefits of reinforced polymer composites over steel are realized with low production volumes of a greater variety of body styles which change more frequently. In order to be more competitive in the international automobile market [2] the trend is away from very large production volumes with a small number of slowly changing body styles towards shorter production runs, a greater number of body styles and more frequent styling changes. The differentiation between capital and operating cost reflects this trend.

The attributes of parts consolidation and quality are reflected in this attribute. Also aggregated into this attribute are the costs for special equipment to achieve a Low Profile, Class A surface finish on polymer composite components. Since the time frame under which this group of decision makers is operating is not in the near future, existing physical plant facilities were not considered. New production facilities for each of the alternative systems was assumed. A more detailed discussion of these attributes follows.

OPERATING COST

This includes materials, energy, labor, assembly and other variable or piece costs. Like capital cost, it also reflects attributes of parts consolidation and quality. This attribute is not to be confused with the cost to the consumer of operating the vehicle over its lifetime. Steel often offers lower materials costs than aluminum or polymer composite materials.

WEIGHT

Attributes of fuel economy, engine performance and weight savings have been aggregated into one attribute of weight. The benefits of weight reduction are primarily improved fuel economy and/or increased performance [26], [45]. The use to which weight reduction is put, improved fuel economy or increased performance or some combination of the two, is determined by the design engineer. Aluminum and polymer composite materials offer the potential for weight savings over steel. Weight savings as high as 50% have been estimated when comparing polymer composite to steel components [52].

Weight reduction in one component may allow weight reduction in other components. This effect is called the weight compounding effect, and is often included as a factor in weight reduction analyses [60]. Thus, in some situations a pound reduction in one component may result in several pounds weight reduction for the entire system. However, since we are analyzing a very large and complex system, specifically for the purpose of capturing benefits of redesign, we will take weight reductions at face value, and not multiply to approximate the compounding effect. This will be reflected in the total weights of the redesigned systems.

CORROSION RESISTANCE

Plastic materials generally have superior corrosion resistant properties to metals, although metals may be treated (coated with zinc, for example) in order to achieve some standard criterion, such as the 5/10 year warranty against surface and rust-through corrosion [18], [35]. One might argue that the differences between materials for this characteristic may be reflected in rust proofing treatment costs or warranty costs for less corrosion resistant materials. This characteristics would then be viewed as binary if each system must meet the same specific 5/10 year criteria, and no value is perceived in going beyond it. However, several groups expressed a willingness to pay for corrosion resistance beyond what is available with steel, and also think of it as an attribute separate from cost.

DESIGN FLEXIBILITY

This attribute captures many of the important differences between traditionally designed systems and newer systems. This characteristic has been raised, particularly by proponents of plastic materials, as significant. Along with "quality", it is difficult to define but in fact does seem to be considered. Aspects of this flexibility include styling, marketing and manufacturing considerations, and are discussed below. It should be pointed out that these characteristics represent the potential of a material; it is up to the design engineer to take advantage of them. Ultimate flexibility of a materials system design is a function not only of the material itself, but also of the skill of the design engineer and the efficiency of the manufacturing system.

The way that this aggregation of attributes has been quantified is in the number of body styles which can be placed on a common platform. The concept of offering 2 or 3 body styles on a common frame has been used extensively for some time, but the trend is to increase the number of body styles being offered. A popular design concept is that of a common platform on which several body styles can be mounted. The platform or structural frame is usually steel, with the body panels being plastic or a mix of plastic of steel. Different body types might include 2-door, 4-door, station wagon, sport coupe, hatchback, luxury, and personal car models. Thus, the design engineer can realize both the economies of scale for capital intensive steel stamping equipment for the common platform, and the design flexibility benefits of polymer composites.

- Manufacturing Economics - Manufacturing and marketing trends towards systems with shorter production runs and lower production volumes create the desirability of systems with a lower proportion of component cost accruable to tooling or capital investment costs. This proportion is much greater for metal forming processes than for plastics forming processes. Polymer and aluminum materials differ in processing economics; the tooling and machine cost is much lower than that for steel, while materials costs may be greater or equal. The amounts of time and capital expenditure required for model change are decreased, while processing flexibility is increased. This makes shorter production runs cost effective and allows for shorter product turnaround times.

- Styling Flexibility - Polymer composite materials and processes offer the potential for greater flexibility in shaping the outward appearance of the automobile due to flow properties of the material. This design flexibility from more formable plastic materials is valued both from the point of view of a greater range of shapes possible in individual models and from the greater variety of model options possible within a single family [42].

- Drag Resistance - The coefficient of drag of a painted plastic surface is not significantly different from that of a painted steel surface. However, certain materials and/or forming processes may provide more flexibility in the design of surface shapes with more aerodynamically efficient profiles. This results in greater fuel efficiency. It has been estimated that a 3% reduction in drag results in a 1% increase in fuel efficiency.

- Marketing Flexibility Offering a greater number of body styles allows auto companies to appeal to a greater number of market sectors and increase sales volumes.

- Anisotropy - Polymer composite materials offer greater control over the degree of anisotropy in a component than metals. This factor allows for greater flexibility in design of structural components. Several polymer processing technilogies such as resin transfer molding (RTM) permit the placement of reinforcing fibers only where they are needed, resulting in more efficient use of costly fibers.

- Compliance with Regulations - With a design concept which utilizes a common crash management structure and standard engine systems, it becomes unnecessary to resubmit each new model for testing for compliance with federal impact and emissions regulations if only the skin is changed. Thus, one benefit of a greater number of models per common platform is time savings and decreased testing costs.

OTHER ATTRIBUTES

These attributes have been raised in preliminary discussions with design engineers and materials marketing interests as important in the consideration of material alternatives. However, since they are either binary, insignificant or aggregable to other attributes, it is not necessary to include them as seperate attributes in the multiattribute utility function.

- Paintability/Surface Finish - It is more expensive to obtain a "Low Profile - Class A" painted surface finish on most plastic materials than on steel [40]. The cost of painting is included in the assembly cost, and differences between materials will be reflected there.

- Parts Consolidation - Capital and operating costs will reflect savings incurred in component production and vehicle assembly due to the consolidation of a large number of parts into one component.

- Temperature Resistance - This is a binary characteristics in that specific operating temperatures must be endured by each component. Temperature extremes may be experienced either during operation of the vehicle, as for components near the engine compartment, or during the manufacture and assembly of the component itself. Body panels coated in a traditional paint bake oven must be capable of withstanding temperatures of up to 400 degrees farenheit [48] Many polymer materials are not capable of withstanding these temperatures [61], although new painting systems are being developed which reduce temperature requirements.

- Quality - The characteristic of "quality" as being one separate and distinct from all of the above performance characteristics has been mentioned by automotive design engineers and materials promoters as a characteristic that is considered in the decision making process. Intuitively, one might assume that "quality" is simply another expression for "utility". However, this interpretation is denied by those who claim to consider it separately in their decision making process.

In describing aspects of quality, engineers listed such considerations as "fit and finish", part reject rate, process controllability, and ability to maintain consistency. It was determined that one aspect of this characteristic is binary. Either a system possesses a level of quality that is acceptable, or it does not. Systems with unacceptable levels of quality may be brought "up to spec" by improving processing technology, process control, using more costly materials, etc. Thus, within the threshold of acceptability, quality is reflected in capital and operating costs.

- Fatigue - This characteristic is measured by service life, and is binary. The required number of cycles is predetermined.

- Recyclability - It would be prohibitively expensive if not technically infeasible to recycle polymer composite intensive automobiles. In contrast, 70% of the steel used in automobiles today is recycled [6]. While many engineers in the industry are aware of the potential problems this may cause, the actual effects are so uncertain and in the distant future that this aspect is not considered.

- Risk - This has been raised by several individuals as an attribute that must be considered in the decision making process, both by design engineers and materials marketing interests. It is heartening to note that there is an awareness that this is a factor. However, a major benefit of the utility analysis approach is that the riskiness or uncertainty of alternatives and the decision makers attitude towards risk is inherent in the analysis. It is not appropriate tin this case to consider risk as an attribute in itself. Rather, the decision maker's attitude toward risk or uncertainty as to in the outcome, or level to which attribute levels are achieved, is reflected in the shape and degree of curvature of the single attribute utility functions.

- Structural Requirements - Structural performance evaluation is performed in practice by achieving compliance with industry standard criteria verified by prescribed testing procedures [36]. Systems are designed meet specific performance criteria in the areas of vibration frequency, torsional stiffness, etc. A deck lid study [47] provides an example of how structural characteristics are usually dealt with in materials substitution problems. High strength steel, aluminum and polymer composites were considered as alternatives to conventional steel for a deck lid. Oil canning resistance, or panel stiffness, is defined as the concentrated load applied normal to the panel surface, which is necessary to produce unit deflection in the direction of the load. Panel stiffness is a function of both the design and the material itself. Since changing the shape of the deck was not possible since it had to fit within an existing system, several of the alternative designs required the addition of internal reinforcing panels and/or gauge increases in order to meet load requirements. Therefore, in this application for this set of decision makers, structural characteristics can be viewed as binary. The concept of radical redesign to optimize alternative materials'characteristics to the point that these basic structural aspects are "played with" or varied over a certain range and traded off against one another is still probably 10 to 20 years in the future.

CHAPTER 6 - RESULTS AND ANALYSIS

This chapter illustrates how the results of utility analysis may be used by design engineers to compare and select material systems and by materials interests to market their product. The methodology was applied to automotive design engineers from companies in the United States and Europe. The companies surveyed are Chrysler, Ford, Fiat, Peugeot and Renault. Appendix C contains a complete listing of survey participants, names, locations, and date of survey.

DETERMINE THE BEST SYSTEM

As discussed earlier, when decision makers are faced with several alternative systems, each system may be represented as bundles of seemingly incommensurate attributes. The "best" choice is not always clear. The choices faced by the groups surveyed illustrate this point.

Table 3 lists the alternative systems available to Fiat2 and the attribute levels they possess. As can be seen from the table, the units of measurement used for each attribute vary, capital cost being measured in percent change and design flexibility being measured in number of bodies per platform, for example. Another complicating factor is that of the five attributes under consideration, two are a "good" and three are a "bad". More is always preferred to less for the "goods" of design flexibility (measured in number of body styles per common platform) and corrosion resistance (measured in number of years); for each, a higher value is always preferred to lower value. The converse holds for capital cost (measured in total dollars, lire, francs or percent change from the current value), operating cost (measured in dollars, lire or francs per vehicle or percent change from the current value) and weight (measured in pounds, kilos or percent change from the current value); less (or negative values for percent change) is always preferred to more.

Faced with this confusing array of attributes, the decision maker might initially normalize each to a common scale, such as "percentage of the range over which I am able and willing to consider or make tradeoffs against each attribute". This would allow the direct comparison of relative levels of attributes. The least desirable level of any attribute (the "worst" end of the range as defined by the respondant) is represented by "0% of range" and the most desirable level (the "best" end of the range as defined by the respondant) by "100% of range". A discussion of the criteria for defining these ranges appears later in this chapter. For "goods", 0% represents the lowest possible quantitative value, such as 5 years for corrosion resistance; for "bads", 0% represents the highest quantitative value, such as 30% increase in capital cost. In the following discussion, the terms "highest" and "lowest" will consistently be used to refer

Table 3. FIAT 2

ALTERNATIVE SYSTEMS AND CORRESPONDING ATTRIBUTE LEVELS

Design	Capital Cost in Percent Change from Current Value	Piece Cost in Percent Change from Current Value	Weight in Percent Change from Current Value	Design Flexibility in Number of Bodies per Platform	Corrosion Resistance in Years
Steel Uni-Body	0	0	0	2	4.5
Steel Frame; PC Skin	- 10 %	+ 60 %	- 30 %	8	8
Steel Frame; Steel & PC Skin	- 10 %	+ 50 %	- 20 %	7	7

to relative levels of attributes rather than their actual quantitative value. "Higher" will always be preferred to "lower". An attempt will also be made to use the phrase "best" or "ranks highest" rather than simply "highest" to further avoid confusion.

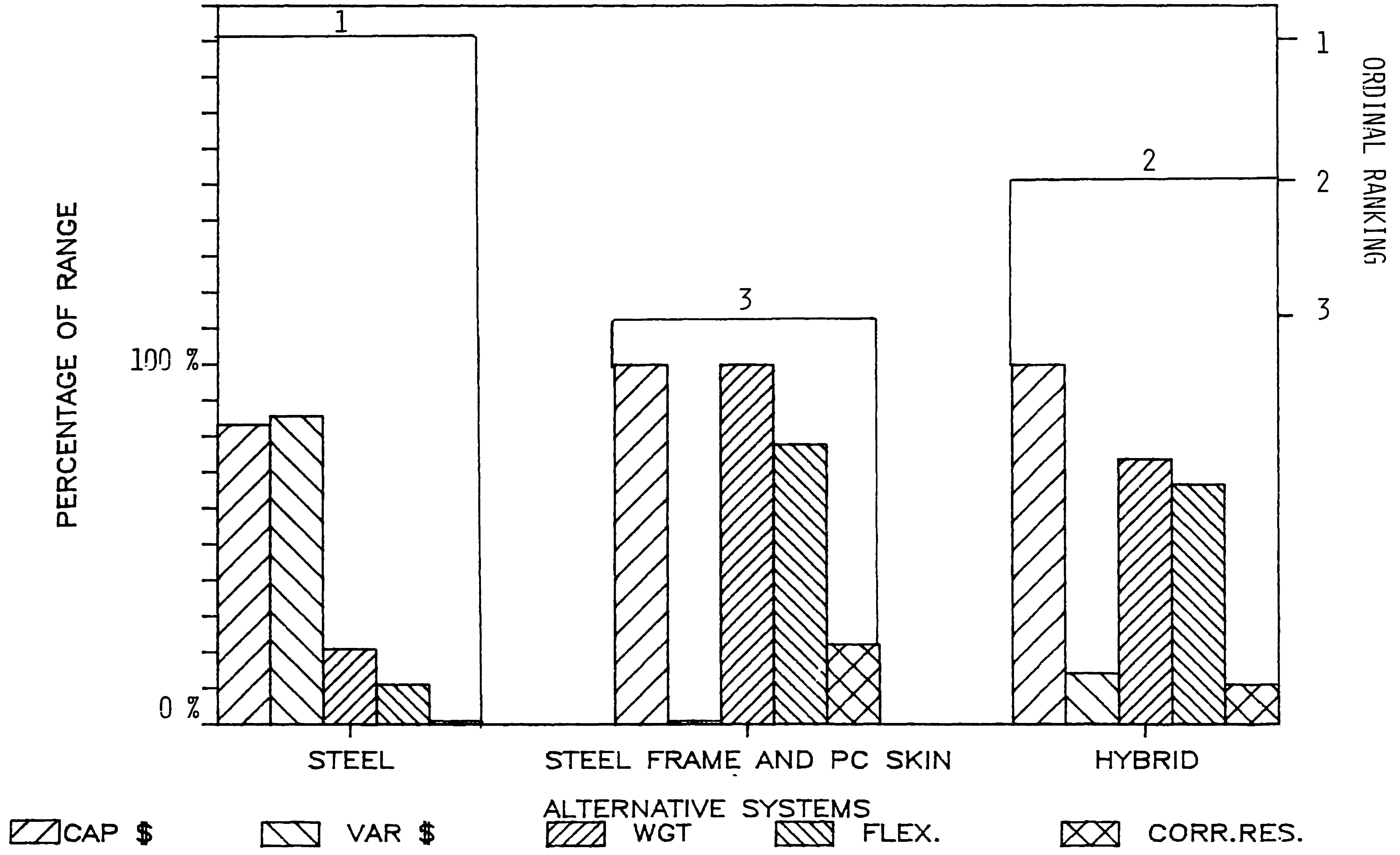
In this chapter, we illustrate that except in cases where one alternative dominates all the others in each attribute, this decision making approach (the direct comparison of relative attribute levels) is inadequate at best and misleading at worst, and that utility analysis may be used to identify optimal alternatives and quantify tradeoffs necessary to improve the desirability of sub-optimal alternatives.

Figures 7-12 illustrate the relative levels of each attribute for each alternative for each auto maker, and the corresponding overall utility rankings. The alternatives being considered by each auto maker are not necessarily of the same design in each category. For example, the steel uni-body considered by Ford is their steel uni-body design, the steel uni-body considered by Fiat is the Fiat uni-body design. The "Hybrid" alternative represents each auto maker's approach to making maximum use of polymer composite materials. Some auto makers are considering designs which incorporate steel and polymer composite materials in both the frame and skin; others only in the frame with an all polymer composite skin. Design details are proprietary. A reasonable assumption is that the alternative in each category has been designed with the interests of the particular auto maker in mind. So, although the attribute levels for designs may vary between automakers, each represents the state-of-the-art design in each category for each company.

Figure 7.

ATTRIBUTE LEVELS AND ORDINAL RANKING

ALTERNATIVES FOR FIAT #2



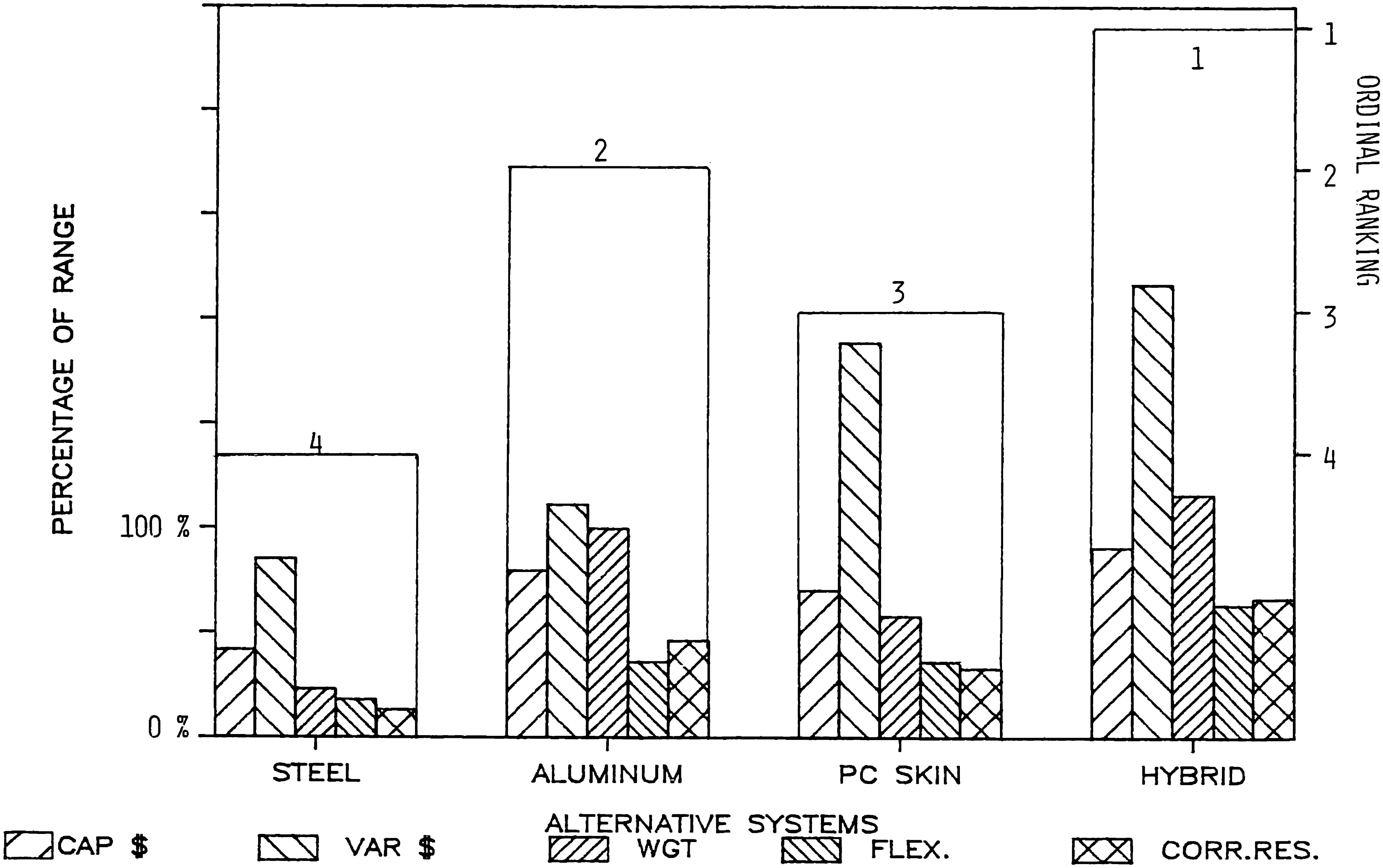
The results for Fiat2 demonstrate the benefit of utility analysis in determining which system has the greatest value to the decision maker in a situation where one alternative does not dominate the others in all of the attributes. A cursory evaluation of relative attribute levels of each alternative in Table 3 and Figure 7 may lead one to the conclusion that Alternative #2 is the most desirable system, when in fact it is the least desirable. Alternative #1 ranks lowest in all the attributes except for piece cost, where it ranks highest. Of the three alternatives, Alternative #2 offers the best capital cost, weight, design flexibility and corrosion resistance, and ranks worst only in piece cost. Alternative #3 ties for highest in capital cost, and falls midway between the other two alternatives in all the other attribute levels. Since Alternative #2 ranks highest in all but one of the attributes, one might expect that its overall utility would be highest. One would also expect that its utility would at least be higher than that of Alternative #1, whose levels for all but one attribute rank the worst of all three alternatives. This is not the case. In fact, the overall utility of Alternative #2 is the LOWEST of the three alternatives, and the overall utility of Alternative #1 is the HIGHEST. This is another example of a system offering performance the decision maker has expressed interest in (two attributes at their best levels), but at an unacceptable price (barely tolerable piece cost).

An examination of the relative attribute levels for each of the alternatives faced by Chrysler in Table 4 and Figure 8 leads to the straightforward identification of the best and worst alternatives. Of the four alternatives, System #1, the steel uni-body, offers the least desirable levels of each of the five attributes. System #4, consisting of a steel and polymer composite structural frame and polymer composite skin design (details are proprietary), ranks highest in each of the five attributes. Not suprisingly, the overall utility of this system is highest, and the overall utility of System #1 is the lowest. In such a situation where one alternative clearly dominates the others, the use of utility analysis as a decision making tool by the design engineer is unnecessary. However, it is very useful in determining how the dominated alternatives can be improved in order to become competitive, by quantifying tradeoffs the decision maker is willing to make. This is discussed in the next section.

FIGURE 8.

ATTRIBUTE LEVELS AND ORDINAL RANKING

ALTERNATIVES FOR CHRYSLER



Although the decision problem faced by Ford is not as complex in that only three rather than five attributes are considered. identification of the best system is not as clear cut. As listed in Table 5 and illustrated in Figure 9, each of the three alternatives ranks highest in one and only one attribute. Alternative #1 offers the most desirable variable cost level, but the least desirable capital cost and weight. Alternative #2 offers the best capital cost, but is mid-range in operating cost and weight. Alternative #3 is the lightest system, but has the worst operating cost level. Utility analysis results show that Alternative #2 has the highest overall utility, while that of #3 is lowest. In terms of performance tradeoffs, Alternative #3 essentially offers a significant weight savings, but at too high an operating cost increase to successfully compete with heavier systems.

Table 4. CHRYSLER

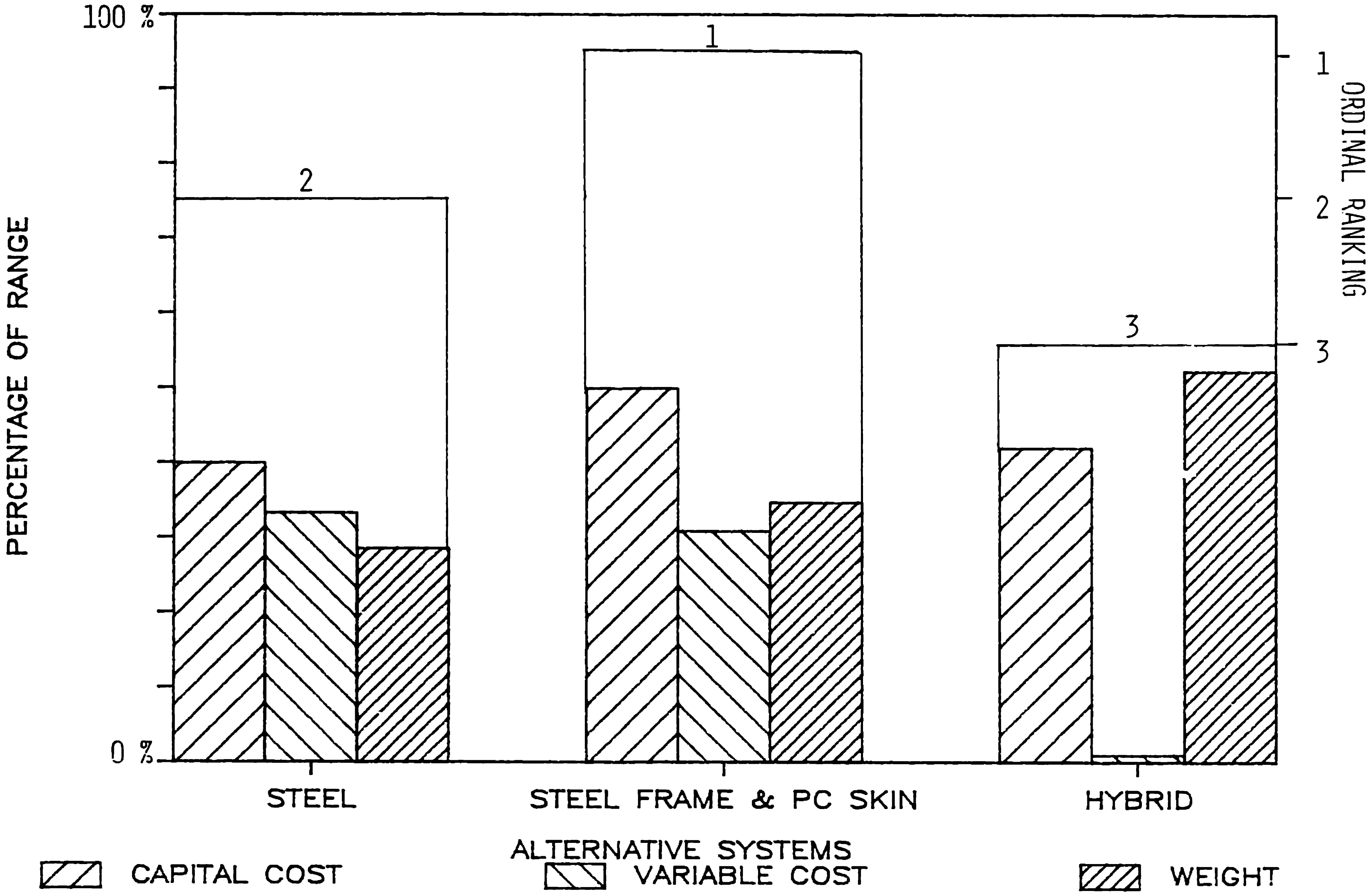
ALTERNATIVE SYSTEMS AND CORRESPONDING ATTRIBUTE LEVELS

Design	Capital Cost in $ Million	Piece Cost in $ Dollars per Vehicle	Weight in pounds	Design Flexibility in Number of Bodies per Platform	Corrosion Resistance in Years
Steel Uni-Body	525	625	550	3	7
Aluminum Intensive Vehicle	364	580	385	5	12
Steel Frame; Polymer Composite Skin	404	446	475	5	10
Steel & PC Frame; PC Skin	318	398	350	8	15

FIGURE 9

ATTRIBUTE LEVELS AND ORDINAL RANKING

ALTERNATIVES FOR FORD



The alternatives considered by Fiat1 are similar to those of Chrysler in that Alternative #2 offers the most desirable levels for each of the five attributes, as can be seen in Table 6 and Figure 10. Not surprisingly, it also has the highest overall utility. Alternative #1 has the worst levels of each attribute except for operating cost, where it is mid-range among the three alternatives. Its overall utility is lowest.

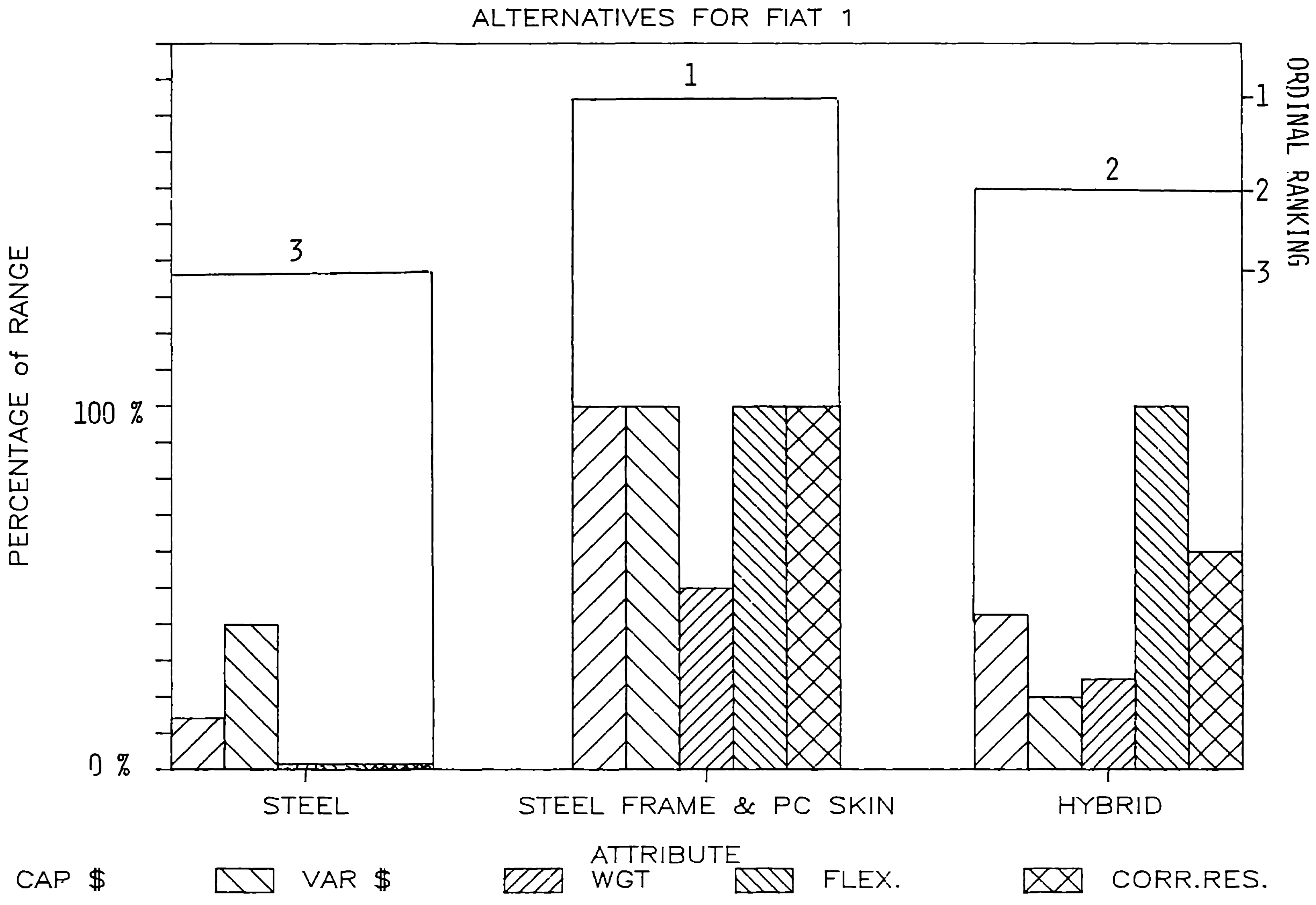
Table 5. FORD

ALTERNATIVE SYSTEMS AND CORRESPONDING ATTRIBUTE LEVELS

Design	Capital Cost in Percent Change from Current Value	Piece Cost in Percent Change from Current Value	Weight in pounds
Steel Uni-Body	0 %	0 %	3000
Steel Frame; Polymer Composite Skin	- 5 %	+ 1.1 %	2957
Polymer Composite Frame and Skin	- 1 %	+ 15 %	2834

Figure 10.

ATTRIBUTE LEVELS AND ORDINAL RANKING



Comparing the results of Fiat2 with those of Peugeot, we see that faced with a similar set of alternatives, the two sets of decision makers may rationally differ in their selection of the "best" system. The sets of attributes represented by Alternatives #1 and #2 faced by both auto makers are very similar. Alternative #1 ranks lowest in all attributes except operating cost, in which it ranks highest, and Alternative #2 ranks highest in all attributes except operating cost, in which it ranks lowest. Table 7 lists the alternatives and attribute levels being considered by Peugeot. For Peugeot, Alternative #2 has the highest utility, and would be selected over Alternative #1, as illustrated in Figure 11. Fiat2, on the other hand, would choose Alternative #1, whose utility for Fiat2 is highest, over Alternative #2, whose utility is lowest.

Table 6. FIAT 1

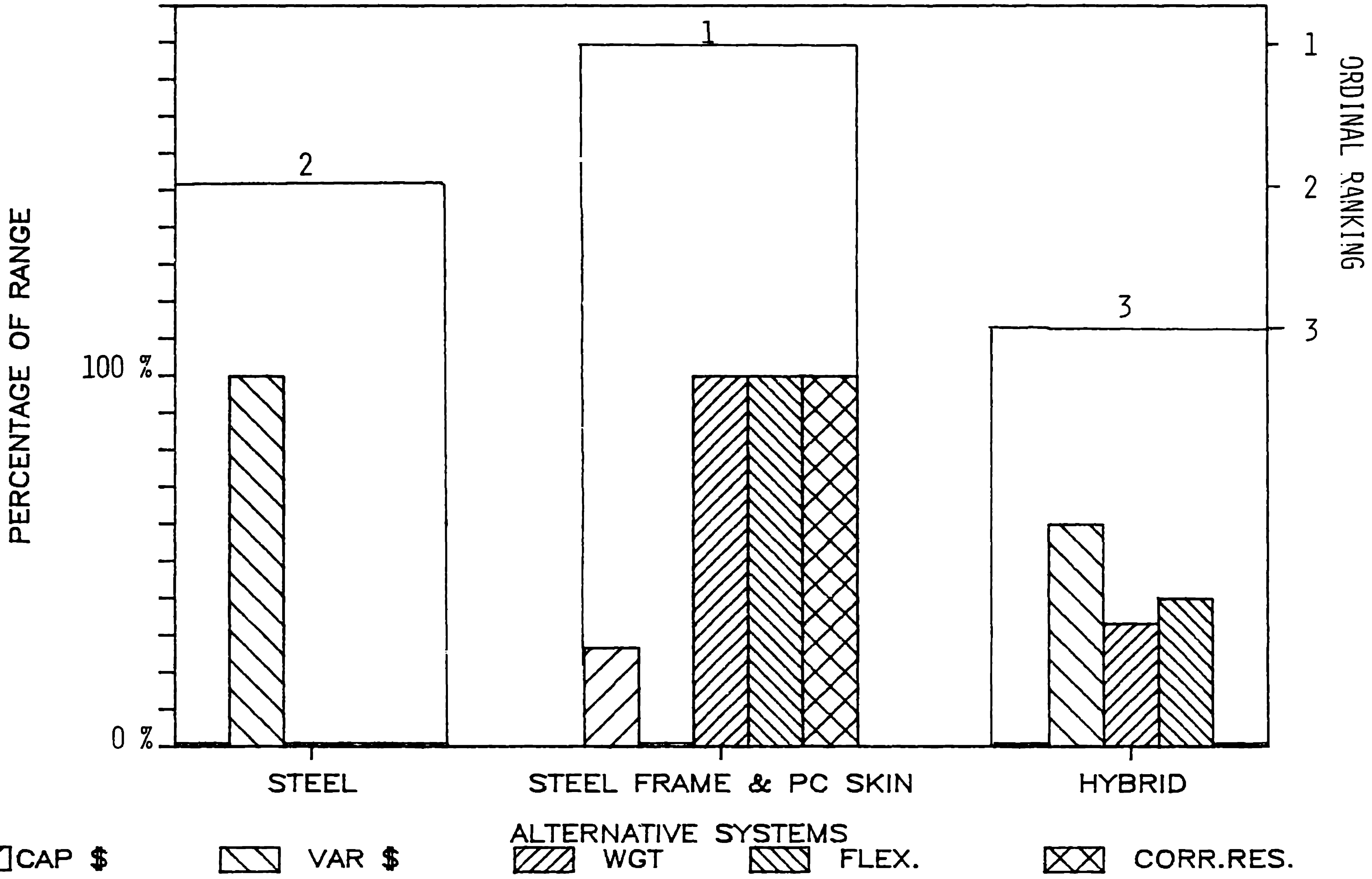
ALTERNATIVE SYSTEMS AND CORRESPONDING ATTRIBUTE LEVELS

Design	Capital Cost in Percent change from Current Value	Piece Cost in Percent change from Current Value	Weight in Percent change from Current Value	Design Flexibility in Number of Bodies per Platform	Corrosion Resistance in Years
Steel Uni-Body	0 %	0 %	0 %	3	5
Steel Frame; PC Skin	- 30 %	- 15 %	- 5 %	10	10
Steel Frame; Steel & PC Skin	- 10 %	+ 5 %	- 2.5 %	10	8

Figure 11.

ATTRIBUTE LEVELS AND ORDINAL RANKING

ALTERNATIVES FOR PEUGEOT



The results for Renault are also interesting. Table 8 and Figure 12 list and illustrate the relative attribute levels and ordinal ranking of alternatives faced by Renault. Alternative #1 ranks lowest in all attributes except operating cost, where it ranks highest, similar to Alternative #1 for Fiat2 and Peugeot. Alternative #2 ranks midway in capital cost, operating cost and weight, and ties with Alternative #3 for highest in design flexibility and corrosion resistance. Alternative #3 is similar to Alternative #2 for Fiat2 and Peugeot ranking highest in all attributes except operating cost, in which it ranks lowest. Again, one might expect that Alternative #3 would have the highest overall utility, when in fact it has the lowest. The most desirable system is Alternative #2.

Table 7. PEUGEOT

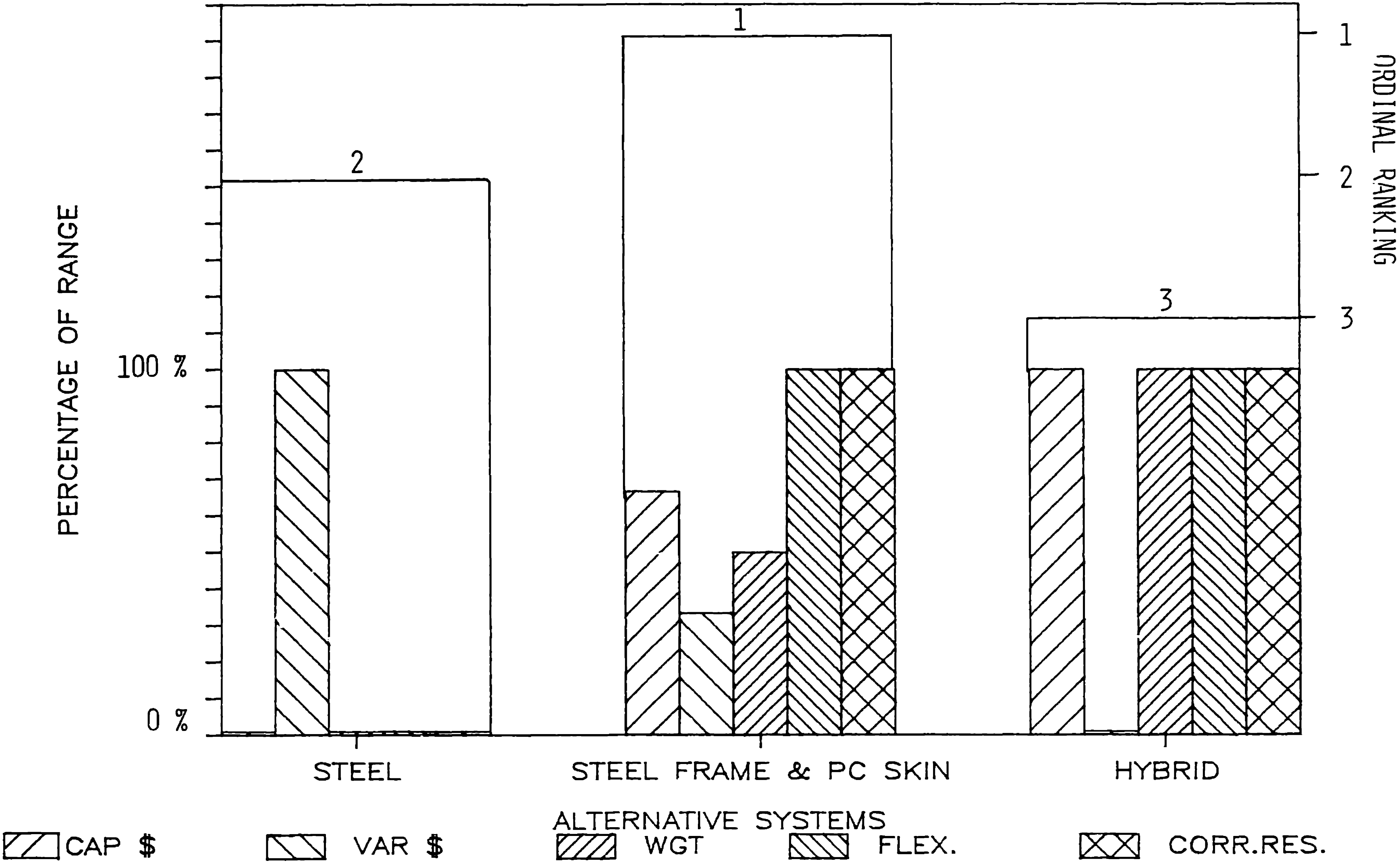
ALTERNATIVE SYSTEMS AND CORRESPONDING ATTRIBUTE LEVELS

Design	Capital Cost in Francs 1,000	Piece Cost in Francs per Vehicle	Weight in kilos	Design Flexibility in Number of Bodies per Platform	Corrosion Resistance in Years
Steel Uni-Body	2000	5000	900	1	5
Steel Frame, PC Skin	1600	10000	600	6	15
Steel Frame, Steel & PC Skin	2000	7000	800	3	5

FIGURE 12.

ATTRIBUTE LEVELS AND ORDINAL RANKING

ALTERNATIVES FOR RENAULT



Summarizing, the overall utility or desirability of a system depends not only on its performance characteristics but also on whose utility is being considered. Faced with similar sets of alternatives, Fiat2, Peugeot and Renault would not necessarily choose the same system. Alternative #1, the steel uni-body system, is similar for each automaker in that it offers the most desirable level of operating cost and the least desirable levels of each of the other attributes. For Fiat2, this alternative is the best choice, and for Peugeot and Renault it ranks second. Alternative #2 for both Fiat2 and Peugeot and Alternative #3 for Renault each offer the least desirable operating cost level and the most desirable levels of each oth the other attributes. This alternative is the worst choice for Fiat2 and Renault, and the best choice for Peugeot. Table 9 summarizes these results. As we have seen, a examination oi relative attribute levels alone is insufficient to determine which alternative offers the greatest utility to a decision maker. These normalized representations convey relative levels of attributes for each alternative within the specified range, but not the non-linearity of preference, the relative preference for attributes, nor the quantification of trade-offs under uncertainty.

UNCERTAINTY

Two aspects of an alternative design contribute to its overall desirability; the estimated attribute levels and the uncertainty

Table 8. RENAULT

ALTERNATIVE SYSTEMS AND CORRESPONDING ATTRIBUTE LEVELS

Design	Capital Cost in Billion Francs	Piece Cost in Francs per Vehicle	Weight in kilos	Design Flexibility in Number of Bodies per Platform	Corrosion Resistance in Years
Steel Uni-Body	3	30	500	1	5
Steel Frame; PC Skin	2	40	425	5	15
Steel & PC Frame; PC Skin	1.5	45	350	5	15

(or probability distribution of the outcome) involved in those estimates. This analysis has been based on the assumption of no uncertainty as to the attribute levels of the alternatives.

Utility analysis may be used to quantify the effect of uncertainty as to ultimate attribute levels on the overall utility of each alternative. For risk averse decision makers, the greater uncertainty involved in systems utilizing polymer composite or aluminum materials may result in their overall utility being diminished. If the uncertainty is significant, it may result in a reversal of the relative desirability of steel vs. polymer composite systems.

Table 9.

Ordinal Ranking for Alternative Designs for each Company

DESIGN	Chrysler	Ford	Fiat1	Fiat2	Peugeot	Renault
Steel Uni-body	4	2	3	1	2	2
AIV	2	nc	nc	nc	nc	nc
Steel Frame, PC skin	3	1	1	3	1	1
Hybrid	1	3	2	2	3	3

1 = Best 4 = Worst nc = not considered

For example, of the set of alternatives available Ford, the steel frame and polymer composite system has the highest overall utility and would be chosen over the steel system if attribute levels are known with certainty. However, if the operating cost estimates were uncertain due to unstable material prices, and it were estimated that there was a 50% chance that the actual operating cost would be 10% greater than that for steel and a 50% chance that it would be 10% less than that for steel, (rather than a certain 1.1% operating cost increase over steel for certain), the overall utility of the steel frame and polymer composite skin system would from a value greater than that for steel to a value less than that for steel.

Various methods for assessing judgemental or subjective probability estimates of ultimate attribute levels have been used [4], [29]. The fractile method is easily applied [53], and if applicable in cases where mutial probabilistic independance properties hold.

TRADEOFFS

The results of utility analysis may also be used to determine how a system that does not rank "best" in terms of highest utility can be improved in order to become more competitive. It is possible to quantify the tradeoffs between performance characteristics that the decision maker is willing to make. This information may be used by either the automotive design engineer to further improve the value or utility of a system design he or she wishes to pursue, or by materials or component suppliers to make their system more desirable when compared with the competition.

Quantification of these tradeoffs may be made within the defined range of attribute values. During the survey the respondants were asked to define these ranges, based on their own estimates of the upper and lower values of attribute levels that they anticipated they would be faced with or offered. The initial response for an attribute such as cost would normally be " 0 cost to infinite cost ". This response was refined by asking the decision maker to temper his estimate of the lower limit to that below which they could not tolerate going, despite highly desirable levels of other attributes. The upper limit was tempered to an optimistic yet realistic estimate of performance levels that alternative systems potentially offer AND that they would be interested in. "Interest" is defined as the willingness to pay in terms of performance in another attribute in order to achieve the upper limit.

For example, plastics potentially offer extremely high levels of corrosion resistance. Some estimates are as high as 50 years. However, other constraints such as the designed service life of the vehicle (10-15 years) limit the value of a 50 year corrosion resistance guarantee. Say a decision maker places an upper limit of 12 years on corrosion resistance. He may be willing to pay in terms of operating cost to improve corrosion resistance from 5 to 10 years. Under the impression that corrosion resistance is valued limitlessly, a materials supplier may develop a system offering a 50 year corrosion-free guarantee. The tradeoff required to achieve this level of corrosion resistance is increased processing costs in order to ensure quality control at the fiber-resin interface. Without such control, wicking of moisture by the fibers may occur, causing the equivalent of "corrosion" in polymer composites. The materials supplier is disappointed that his system is not selected.

Utility analysis in this case helps identify areas in which an alternative may improve its competitive position. When attribute levels are greater than the upper limit of the defined range, the single attribute utility level for each of these values is one. The decision maker is not "interested" in improving corrosion resistance to greater than 12 years. That is, any level of corrosion resistance above 12 years has equal value to him. He is not willing to "pay" in terms of any other attribute in order to go from, say, 15 to 50 years, since both values are outside the range. In a sense, beyond the defined range the attribute is a binary characteristic; below the minimum range the system is unacceptable and above it the decision maker is indifferent to changes.

Essentially, this system offers performance at a level the decision maker is not interested in, at a price he is unwilling to pay. In order to make this system more attractive to the auto industry and competitive with the other alternatives, utility analysis makes clear that the materials supplier would do well to improve the performance level of one of the other attributes such as operating cost, while decreasing the level of corrosion resistance offered. By allowing performance to fall to the upper limit of the range for corrosion resistance, 12 years, the supplier loses nothing in terms of that attribute's contribution to the overall utility of the system, and possibly gains some slack with which to improve the levels of other attributes.

This could be done in this example by eliminating the quality control necessary to achieve the 50 year corrosion resistance, thereby decreasing operating costs.

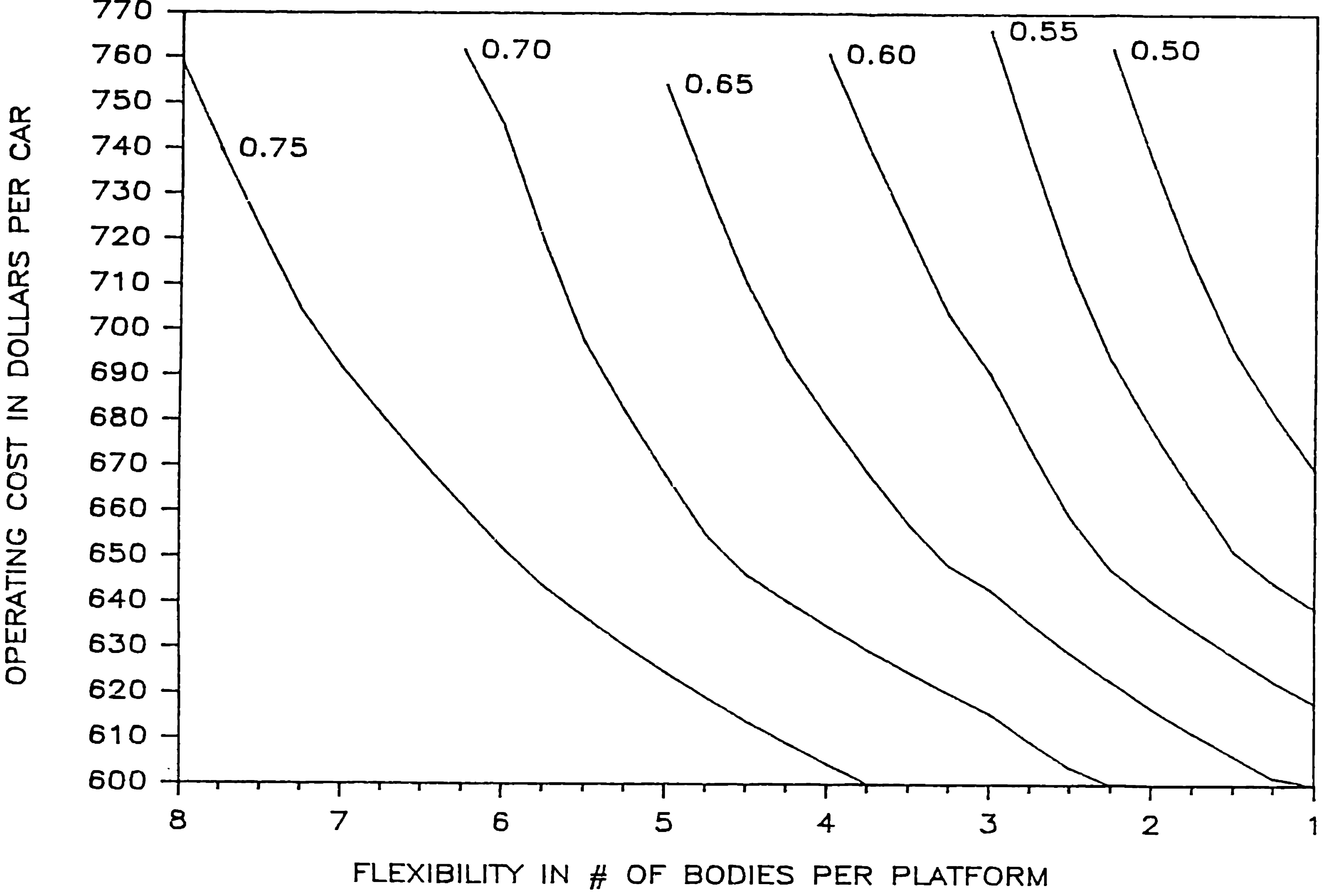
When attribute levels are within the defined range, utility analysis may be used to quantify the tradeoffs the decision maker is willing to make. Many advanced materials alternatives offer improved levels of performance in one or more attributes, but at an increased price. Decision makers are often interested in the advantages of a new material, but are not prepared to pay the price. Decreases in weight may be obtained by using polymer composite materials, but the material cost itself is usually higher than that for steel. The results of utility analysis may be used to determine not only which performance characteristics the decision maker is willing to tradeoff, but also to quantify those tradeoffs. The tradeoff can be quantified by determining the slope of the iso-utility curve with the two characteristics of interest as the axes. Since the iso-utility curves are not linear, the slope of the curve depends on where on the curve you are. The proper location at which to determine the slope is the "current assets" position, or the position at which the system currently in use falls. To quantify the tradeoffs between attributes that the decision maker is willing to make, determine the slope of the iso-utility curve for the current system.

Figure 13 illustrates how iso-utility curves may be used. For purposes of illustration, assume we are comparing two systems that have identical capital costs of 525 million dollars, weights of 500 lbs and 10 years of corrosion resistance. System A has operating costs (materials, energy and labor) of $690 per vehicle and includes 7 possible body styles per common platform. These body styles may be a 2-door, 4-door, station wagon, etc. System B has operating costs of $625 per vehicle and 5 bodies per platform, while System C has operating costs of $645 per vehicle and 3 possible body styles.

Figure 13.

ISO—UTILITY CURVES

CAP = 525, WGT = 500, CORR.RES. = 10



The iso-utility curves represent combinations of system attributes which have equal utility or value-in-use to the decision maker. For example the decision maker would be indifferent between System A and System B. The slope of the curves are a measure of the cost/performance trade-offs that the decision maker has expressed a willingness to make. Notice that these trade-offs are not linear; the amount of trade-off depends on the what position the decision maker is currently in.

Comparing System A with System C, one sees that System A is preferred with its higher utility of 0.75 compared with 0.65 for System C. For System C to become competitive with System A, one would seek to make changes in its attribute levels which would increase its utility to 0.75. For example, increasing the number of bodies per platfrom from 3 to 5 and decreasing operating costs to $625 per vehicle would suffice. If the number of body styles were increased to 6, an operating cost increase from $645 to $650 would be tolerated.

Comparing the results for Ford and Renault, we see that these tradeoffs differ. We first note that the engineers at Renault consider all five attributes, whereas Ford engineers consider only three attributes; capital cost, variable cost and weight. For each, Alternative #2 has a higher utility than Alternative #1. The capital cost decrease necessary to make Alternative #1 competitive with Alternative #2 is 6% for Ford and 1.7% for

Renault. Alternative #1 could also be made competitive at Renault by increasing the number of body styles from 1 to 2, while making no improvements in capital cost.

Table 10 lists the tradeoffs that decision makers are willing to make if faced with alternatives to their current assets position, the traditional steel uni-body design. The specific tradeoffs selected were based on the types of tradeoffs they will most likely face given the current material alternatives. Operating cost increases are most often the price to be paid when considering aluminum or polymer composite alternatives to steel. Benefits of these materials are weight reduction, decreased capital cost, increased design flexibility and improved corrosion resistance in the case of polymers. Design concepts which incorporate common steel structures and a great number of body styles may do so at the cost of overall system weight in some of the styles.

ATTRIBUTES AND RANGES

The most basic differences in decision making environments begin with the selection of the performance characteristics themselves. Two different groups of automotive design engineers may differ in the set of performance characteristics which are relevant to them. Quite a bit is learned about a decision making environment in the initial process of determining which

Table 10. Tradeoffs from Current Assets Position

Tradeoffs Tolerated	CHRYSLER	FORD	FIAT 1	FIAT 2	PEUGEOT	RENAULT
Operating Cost Increase per 1% Decrease in Capital Cost	0.04%	0.90%	0.39%	1.80%	1.29%	0.70%
Operating Cost Increase per 1% Weight Reduction	0.46%	0.93%	0.33%	0.05%	3.10%	0.40%
Operating Cost Increase per 1 Additional Body Style	3.24%	0.00%	1.23%	1.45%	2.14%	1.93%
Operating Cost increase per 1 Year Add'l Corrosion Resistance	0.14%	0.00%	4.81%	1.15%	6.54%	0.73%
Weight Increase per 1 Additional Body Style	5.92%	0.00%	0.00%	1.90%	0.00%	0.00%

attributes the decision maker is concerned with, interested in, and which they have the flexibility to "play around" with. The fewer the number of attributes, the more limited the environment and the less able they are to exploit fully new material properties. For example, the group surveyed at Ford became involved in materials design and selection relatively late in the design concept development stage. Decisions as to number of years of corrosion resistance and number of bodies per platform had already been made by the time they become involved. These engineers are involved in problems with a shorter time frame than the other groups. Their decision making environment is more constrained. This group considered only three attributes, rather than five in their decision making process.

The other groups were each able to consider five attributes. However, all the structural characteristics were viewed as binary; specific testing criteria already in place continue to be used. These testing criteria were developed when only steel was considered as an alternative. Testing criteria developed for one material present a bias for that material.

If a decision maker were able or willing to look at radical design change to optimize materials characteristics, and were not constrained by existing structural testing criteria, relevant performance characteristics would likely include some of the structural characteristics such as torsional stiffness along with cost, weight etc.

Determination of the range over which the decision maker is willing and able to trade performance characteristics off against each other, also tells a great deal about the decision making environment. The single attribute utility for all attribute levels at or better than the upper limit of the defined range is 1. An alternative with an attribute level less than the lower limit of the defined range is unacceptable. Alternatives which offer, say, weight savings greater than the upper limit of the defined range and operating costs which are worse than the lower limit of the defined range are in effect offering performance the decision maker is not interested in at a price he is not willing or able to pay. Thus, the greater the range, the greater the freedom and flexibility the design engineer has to sacrifice in one area in order to achieve in another. Table 11 includes the attributes, ranges, and units of measurement for each auto maker.

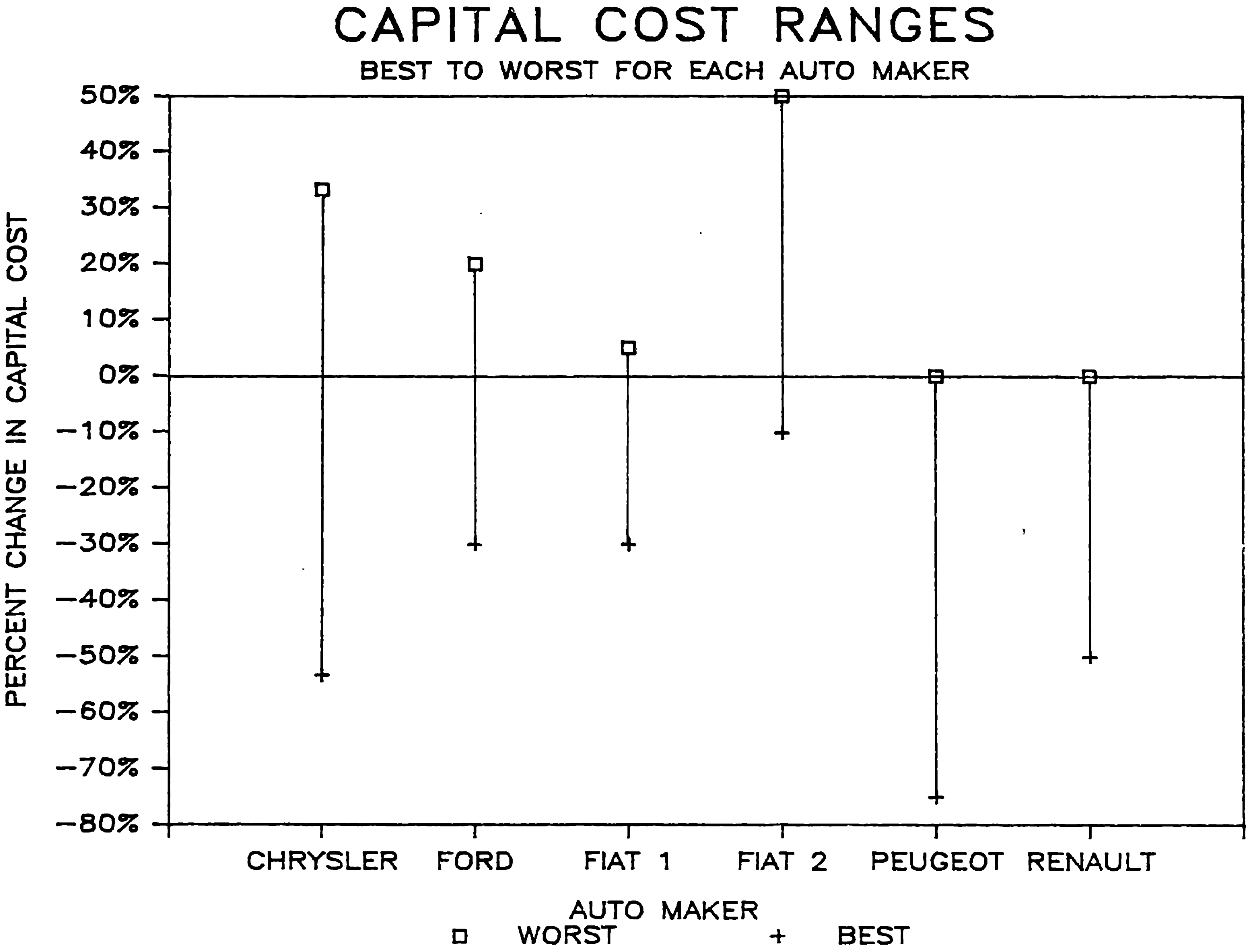
Figure 14 illustrates the significant differences in range over which capital cost is considered. Similar figures for the other four attributes are included in Appendix G. In comparing these figures, differences between companies in attribute ranges provide a quantitative comparison of their interest in improving performance levels of attributes and of their tolerance for less and less desirable levels of attributes.

Table 11. Attribute Ranges for Companies Surveyed

	CHRYSLER	FORD	FIAT 1	FIAT 2	FIAT 3	PEUGEOT	RENAULT
Capital Cost							
Worst	700	+20	+ 5	+50	1,200	2,000	3
Best	280	-30	-30	-10	800	500	1.5
units	Million Dollars	% Change	% Change	% Change	Billion Lira	Thousand Francs	Billion Francs
Operating Cost							
Worst	773	+15	+10	+60	400	10,000	45,000
Best	600	-30	-15	-10	300	5,000	30,000
units	Dollars per Vehicle	% Change	% Change	% Change	Thousand Lira/ Vehicle	Francs per Vehicle	Francs per Vehicle
Weight							
Worst	600	3200	0	+ 8	110	900	500
Best	385	2500	-10	-30	90	600	350
units	lbs	lbs	%	%		kilos	
Design Flexibilty							
Worst	1		3	1	2	1	1
Best	12	na	10	10	5	6	5
units		Number of Bodies per Common Platform					
Corrosion Resistance							
Worst	5	na	5	6	7	5	5
Best	20		10	15	15	15	15
units				Years			

Ff = French francs
bl = billion

Figure 14.


CAPITAL COST RANGES
BEST TO WORST FOR EACH AUTO MAKER
PERCENT CHANGE IN CAPITAL COST
50%
40%
30%
20%
10%
0%
−10%
−20%
−30%
−40%
−50%
−60%
−70%
−80%
CHRYSLER
FORD
FIAT 1
FIAT 2
PEUGEOT
RENAULT
AUTO MAKER
□ WORST
+ BEST

- Ford considers capital cost and weight over a range that is midway amoung the auto makers. In operating cost, it will tolerate only up to a 15% increase, and is looking for as much as a 30% decrease.

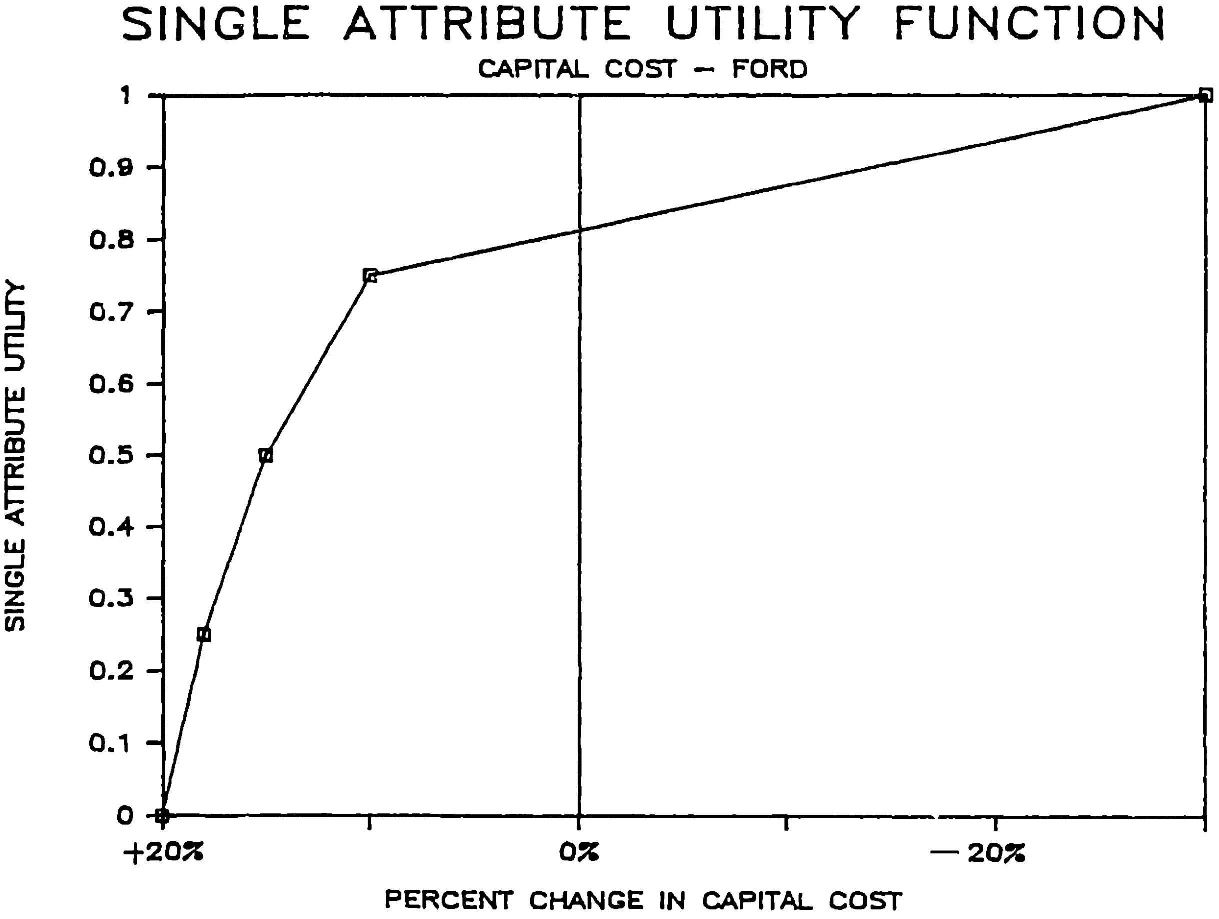
- Fiat1 considers the smallest ranges of all the auto makers surveyed for each of the attributes except design flexibility.

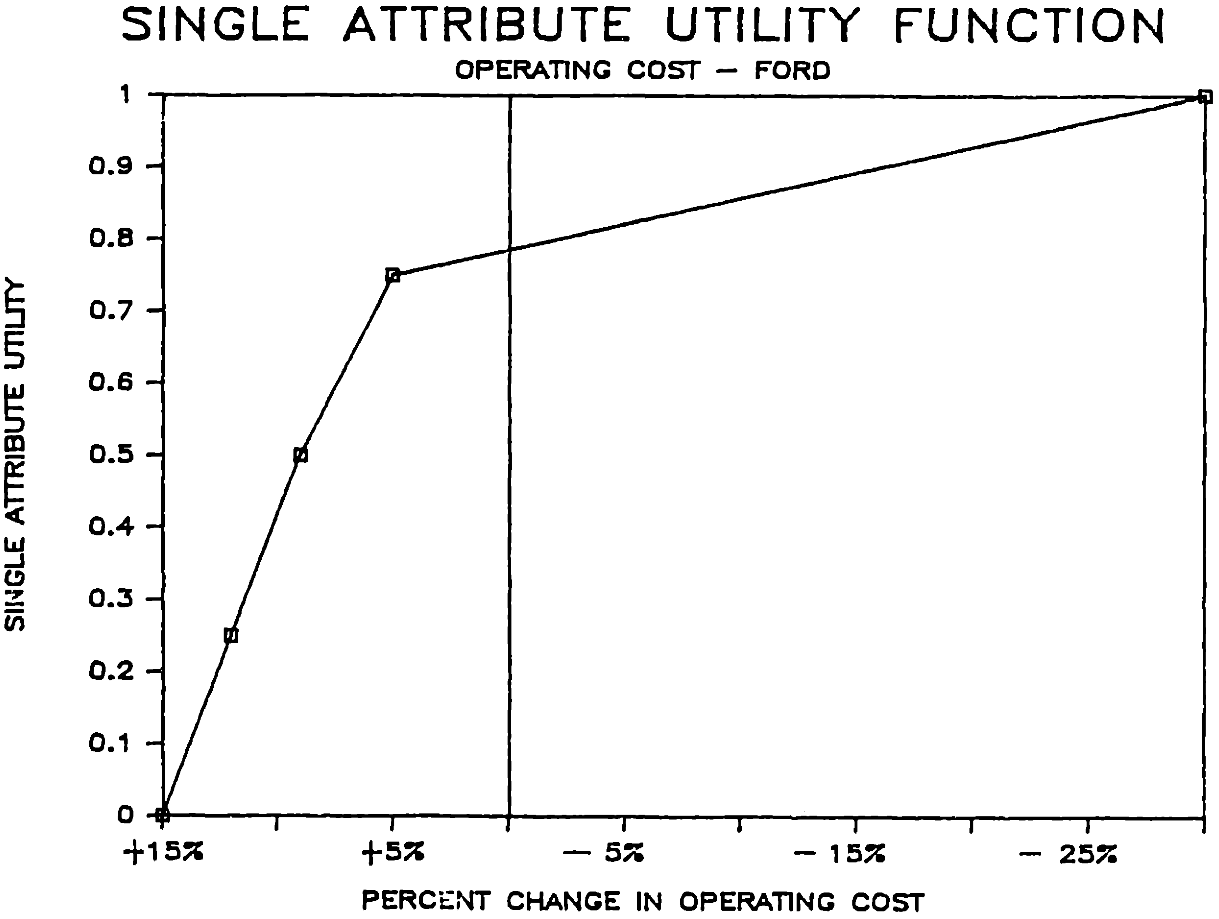
- Peugeot and Renault engineers will not tolerate any increase in capital cost or weight. Peugeot may be willing to accept as high as a 100% increase in operating cost, while Renault will accept only up to a 50% increase.

DEGREE OF RISK AVERSION

In Figures 15.1-15.33 (all are located in Appendix C) are plotted the single attribute utility functions for each attribute for each automaker. Each plot conveys information as to the decision maker's preference structure for one attribute in isolation, independant of the levels of other attributes. The single attribute utility functions reflect the decision makers' attitudes towards risk for each attribute. Comparing the general shape of these functions, differences in the type and degree of risk aversion can be observed. Linear functions express "risk neutrality". As we've plotted them, concave functions express risk aversion for "bads" of capital cost, operating cost and weight and convex functions express risk preference. The converse holds for the "goods" of design flexibility and corrosion resistance. This information may be used by materials' interests in improving the competitive position of their product. Where a decision maker is risk averse, an alternative may be improved not only by improving attribute levels but also by decreasing the degree of uncertainty involved in the estimate of that attribute level, such as providing more reliable cost estimates or guaranteed price quotes. One may also use the plots to compare relative degrees of risk aversion. Some notable observations:

FIGURE 15.


SINGLE ATTRIBUTE UTILITY FUNCTION
CAPITAL COST – FORD
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
+20%
0%
– 20%
PERCENT CHANGE IN CAPITAL COST


SINGLE ATTRIBUTE UTILITY FUNCTION
OPERATING COST – FORD
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
+15%
+5%
– 5%
– 15%
– 25%
PERCENT CHANGE IN OPERATING COST

- Capital cost - with the exception of Fiat2 and Chrysler, each auto maker is risk averse to roughly the same degree. Fiat2 is risk neutral. Chrysler is risk positive.

- Operating cost - each auto maker risk averse to roughly the same degree, Fiat 3 and Renault slightly S-shaped. Chrysler slightly risk positive.

- Weight - each auto maker risk averse, Fiat1 risk positive.

- Design flexibility - each auto maker risk averse except Fiat1

- Corrosion resistance - each auto maker except Chrysler and Fiat3 (whose curves are S-shaped) are risk averse. Fiat3 is mildy risk positive until 9 years, mildly risk averse after; or risk neutral throughout. Chrysler is risk averse until 12 years, risk positive after.

S-shaped curves represent situations where risk aversion is demonstrated in the region below the current assets position, and risk positiveness in the region above the current assets position. Thus, there is great value to the decision maker in doing extremely well in an attribute; one more unit at the upper end of the scale increases his utility by a greater amount than one more unit if his current position is at the lower end of the scale. From a managerial or personal viewpoint, the explanation offered by those interviewed in a related survey of bumper engineers is that doing exceptionally well in one attribute (even if other attributes suffer slightly for it) would tend to serve the function of providing recognition for unusual engineering skill rather than for simply being able to "get the job done".

From a risk perspective, if the currents assets position is relatively high, the decision maker becomes more willing to gamble to make further gains. The potential gains from "winning" a gamble are perceived to be greater than "losing" that same amount. If the current assets level is relatively low, the decision maker becomes risk averse, and is less willing to take a gamble and risk further loss.

CHAPTER 7 - CURRENT AND POTENTIAL APPLICATIONS

EXAMPLE OF STEPS IN APPLICATION

The steps involved in the procedure for using the results of the assessment to compare alternative designs and as a design aid in developing new alternatives is summarized, using the example of the results for Fiat 2 to illustrate.

1. Determine performance characteristics which are relevant and negotiable for the decision maker. In this case they are capital cost, operating cost, weight, design flexibility and corrosion resistance.

2. Conduct the utility assessment survey using either the manual survey forms included in Appendix B or the interactive computerized assessment program titled "Assess".

3. Input utility survey results to spreadsheet. This analysis was facilitated by development of a Lotus 1-2-3 spreadsheet program. Required inputs to the program are the data from the utility surveys; data points which determine the single attribute utility functions, and the attribute scaling constants. The multiattribute utility function scaling constant K derived from the survey results, and estimated attribute levels for each alternative design are also

entered. The model may then be used to calculate overall utility of each alternative and to quantify tradeoffs. An example of the entire spreadsheet, including inputs and results is included in Figure 16.

4. Develop alternatives which satisfy the system definition. That is, the set of components which fulfill the same function as a structural frame and body skin. In this case the alternatives are the steel uni-body system, the steel frame and polymer composite skin system, and a steel and polymer composite hybrid system of proprietary design.

5. Estimate the expected levels of performance for each attribute for each alternative. Total manufacture and assembly cost may be estimated by using cost estimation models developed in the Materials Systems Laboratory. These production processes include steel stamping, aluminum extrusion and casting, a variety of polymer composite forming processes, and the assembly process. The models may be used to estimate materials, labor, tooling, utilities, capital and overhead costs of manufacturing each component and assembling them. Cost estimates may also be obtained directly from the auto companies.

Figure 16. Spreadsheet for Fiat2 - Input/Output Page

```
          A         B        C         D        E         F
1    Fiat; Di Carlo
2    S.A.Util.Cap.Cost Oper.CostWeight   Flexib.  Corr.Res.
3           0      0.5      0.5      0.08        1         6
4        0.25     0.35      0.5      0.05        2         7
5         0.5     0.25     0.38     -0.05        4         8
6        0.75      0.1     0.28      -0.1      5.5        10
7           1     -0.1     -0.1      -0.3       10        15
8
9                                                          Kc =          0.95
10             Single Attribute Levels as a Function       Ko =          0.92
11   Input     of Single Attribute Utility                 Kw =          0.03
12   S.A. U    Cap.Cost Oper.CostWeight   Flexib.  Corr.Res.Kf =          0.35
13                                                         Kr =          0.18
14          1     -0.1     -0.1      -0.3       10        15
15                                                         K =        -0.9978
16             Single Attribute Utility Levels as a Function
17             of Single Attribute Levels
18             Cap.Cost Oper.CostWeight   Flexib.  Corr.Res.
19   Input         280      600       385       12        20
20   Calc.U          0        0         0        1         1
21                       Input Attribute Levels &          Overall Utility
22             Resulting Single Attribute Utility Levels   for
23
24   Design    Cap.Cost Var.Cost Weight   Flex.    Corr.     Fiat;
25                                                 Resist.   Di Carlo
26   Steel           0        0         0        2       4.5
27   Uni-Body     0.88     0.93      0.38     0.25      0.00   0.9802
28
29   Steel
30   Frame;       -0.1      0.6      -0.3        8         8
31   PC Skin      1.00     0.00      1.00     0.89      0.50   0.9704
32
33   Steel
34   Frame;       -0.1      0.5      -0.2        7         7
35   Steel &      1.00     0.25      0.88     0.83      0.25   0.9757
36   PC Skin
37
38          4     -0.1      0.5      -0.2        7         7
39                1.00     0.25      0.88     0.83      0.25   0.9757
40
```

Attribute levels for Fiat 2 alternatives were indicated in Table 3. In cells B26..F38 of the spreadsheet, input each of the five attribute levels each alternative, as indicated in Figure 16. Cells B38..F38 are available for a fourth alternative. The values indicated directly below the input attibute levels are an intermediate calculation made by the spreadsheet in estimating overall utility. It is the single attribute utility value for that attribute.

6. Compute the overall utility of each alternative system. After attribute levels have been entered for each alternative, recalculate the spreadsheet. The resulting overall utility values appear in cells G27..G39.

7. To determine which system is "best", compare the overall utility of alternative systems. Ranking is based on overall utility; those with higher utility are preferred to those of lower utility. The steel uni-body design ranks highest, followed by the hybrid design, with the steel frame and polymer composite skin system ranking lowest.

8. Determine how to improve alternatives which do not rank #1. Neither the ordinal ranking nor the overall utility gives an indication of how much better the first choice alternative is compared to the second, the second to the third, etc. To obtain a quantification of how much lower ranking alterna-

tives must be improved in order to become competitive with the highest ranking system, we determine sensitivity of ordinal ranking to changes in attribute levels. To do this, we enter new values for the attribute levels in the spreadsheet in cells B26..F38 until the overall utility of the alternative matches or exceeds that of the first choice system.

To compare the improvement in one attribute that is necessary to alter the rankings, we determine the decrease in operating cost necessary to make Alternatives #2 and #3 equally desirable with Alternative #1. Inputing smaller and smaller percent increases in operating cost in cells C30 and C34, we determine that Alternative #2 must bring its operating cost down from 60% greater than the steel alternative to 45.9% greater. In other terms, the space frame and polymer composite skin system must decrease its operating cost by 9% to become competitive with steel. Alternative #3 must bring its operating cost down from 50% greater than the steel alternative to 43.2% greater. This represents a 4.5% operating cost decrease necessary to become competitive with steel.

Unfortunately, improvement in one area of performance is often achieved only at the expense of decreased performance in another area. In such cases, utility analysis may be used to identify attributes the decision maker would be willing to trade off against each other, and also to quantify this tradeoff. Thus, it is possible to specify combinations of attribute improvements and deprovements which each alternative must make in order to achieve the same overall utility.

In this case, the required 9% and 4.5% decreases in operating cost necessary to increase the utility of Alternatives #2 and #3 to that of Alternative #1 may not be feasible. Inputing combinations of operating cost and design flexibility levels into cells C30 and E30 for Alternative #2 and cells C34 and E34 for Alternative #3, we determine that Alternative #2 would be competitive with Alternative #1 if operating cost is decreased from 60% to 48% greater than the steel alternative (or only a 7.5% rather than a 9% operating cost decrease) if there is also an increase in design flexibility from 8 to 10 body styles per platform. Alternative #3 would become competitive with an operating cost decrease from 50% to 46.2% greater than the steel alternative (or a 2.5% rather than a 4.5% operating cost decrease) along with an increase in design flexibility from 7 to 10 body styles per platform. This information is then incorporated into the redesign effort in making Alternatives #2 and #3 competitive with Alternative #1.

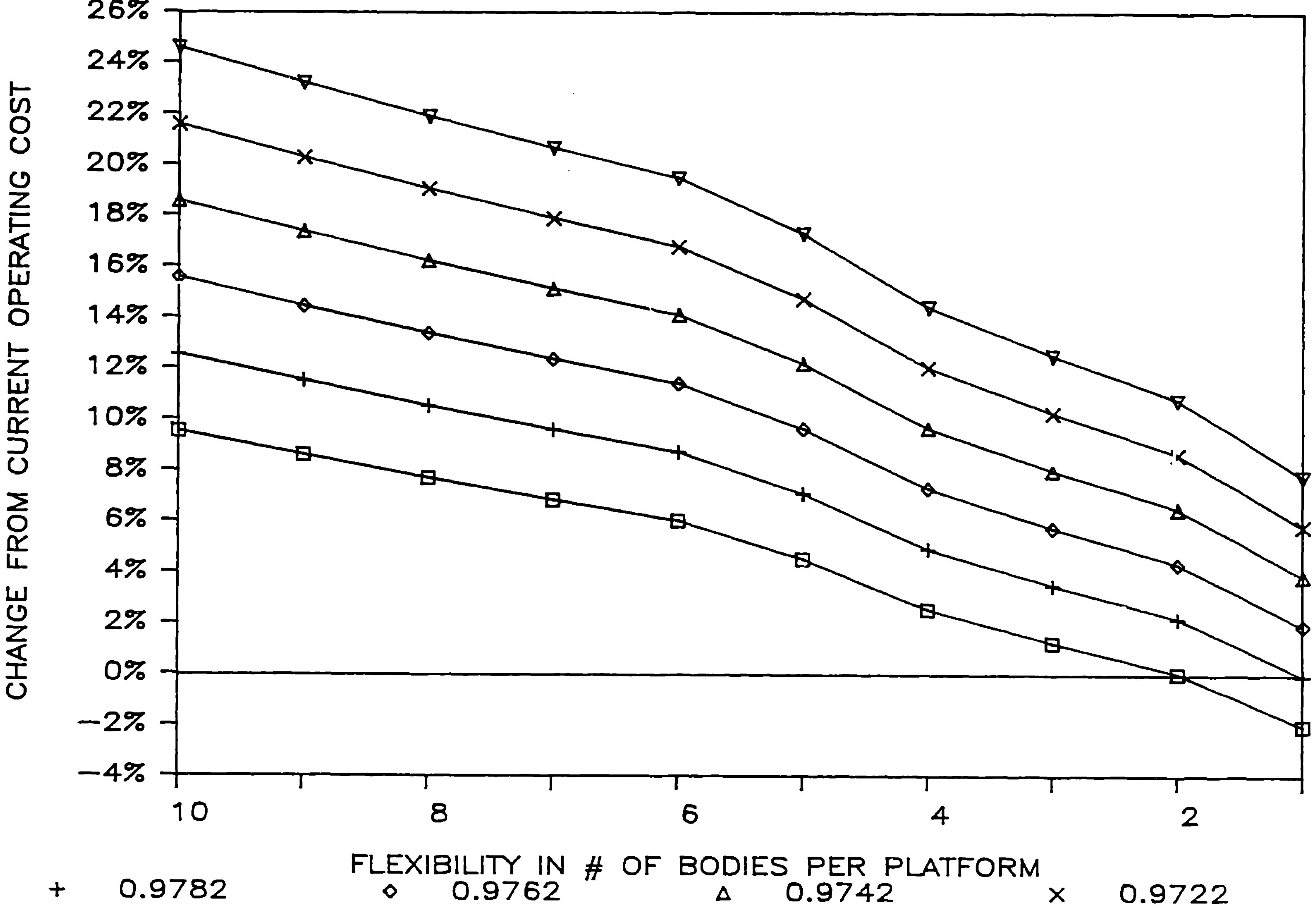
9. Determine tolerable changes in current design. To compare the relative desirability of changes in a design that has currently the highest overall utility, use the iso-utility curves to determine the marginal tradeoffs between attributes. The tradeoff is determined by the slope of the iso-utility curve on which the alternative lies, as illustrated in Figure 17. In this case the decision maker is willing to tolerate a 1.45% increase in operating cost in order to gain 1 more body style per platform for the steel system.

10. Use results to direct research and development efforts. Identify areas of performance in which progress or innovation would be useful vs. those where it would be a dead end. In this case, research into polymer chemistry and processing technologies which would increase corrosion resistance from 15 to 25 years would not be profitable in terms of making the system more desirable to automotive design engineers at Fiat 2, since the limit of the range over which they are willing to pay for performance in this area is 15 years.

Figure 17.

ISO–UTILITY CURVES FOR FIAT 2

CAP. COST = 0, WGT = 0, CORR.RES. = 4.5



RELATION TO OTHER "EXPERT SYSTEMS"

In this section, the relationships between utility analysis and other design tools such as data bases, knowledge based expert sytems, finite element analysis and computer aided design (CAD) systems are discussed. The benefits of applying utility analysis as a complement to these tools are discussed.

As we have seen from this application, even engineers in advanced design groups approach materials selection and design problems by direct substitution of one material for another on an individual component by component basis in an existing design. Minor changes such as gauge increases are made to allow for the physical differences between materials. Comparisons betweeen materials systems are then made on the basis of only one or two attributes such as cost and weight. The "new" material often loses this contest since the component for which it is being considered was designed to optimize the characteristics of the material for which it and the entire system to which it belongs was originally designed. New materials are expected to bear the same load distributions and respond with the same deflection within the same design envelope as the old material in the same size and shape, and to do so lighter and cheaper than steel. This approach does not put the design engineer in a position to redesign systems in order to fully optimize new materials' characteristics. Part of the reason for this is that the analytic tools available to these engineers are inadequate for this task.

Several types of analytic tools may be used by design engineers, made possible by the availability of high speed computation equipment. Extensive development of materials property data bases has occurred [32], [55]. These data bases provide easy access to materials properties necessary for design, provide information on a wide range of materials and are easily updated.

Knowledge based expert systems are another analytic tool available to the design engineer. Such systems attempt to model the large set of heuristics that experts have come to utilize as a result of many years of experience in domain specific types of problems [57]. Many knowledge based expert systems are rule based; sets of rules are embodied in if/then statements extracted from experts in the field. Such statements incoporate the extensive experience of experts, and consolidate all aspects of their experience which now influences their judgement. These include both technical and non-technical aspects which are a result of that person's total educational, technical, personal and subjective experiences. Through a complete cataloging of the cause and effect relationships used by experts, these systems describe how professionals think about a problem and develop a solution. By linking sets of rules and cause and effect relationships, they capture the expert's approach to problems in a holistic manner.

CAD systems are another design tool. Such systems provide for graphics capabilities to quickly configure the geometry of a component or an entire system of components. Advanced systems allow linking between CAD files and finite element analysis models to determine how a particular system design behaves and performs under a specified set of loads and stresses. Several systems have been developed, including those for polymer composite materials [23]. Such systems greatly speed up the design process, allowing the design engineer to make design changes and quickly determine the effect of these changes on the way the system responds to loads and stresses it will be subject to and to determine whether the system still meets performance criteria.

Multiattribute utility analysis takes up where data bases, knowledge based expert systems, CAD systems and finite element analysis leave off. All four of these tools serve to greatly speed up the inference process, and help engineers develop designs that meet functional criteria. However, none of these systems alone or in combination provides the design engineer with direction as to ways in which a design may be optimized. The engineer must rely on his or her own intuition and expert technical judgement to determine whether a design which meets essential performance characteristics may be improved, or how it may be improved. Comparing the relative desirability of two alternative designs which perform equally in all respects except that one is superior in one characteristic such as cost is straightforward. The comparison becomes difficult when no alternative dominates the others in all areas of performance. One design may be less expensive, but another may be more corrosion resistant.

What differentiates a "good design" from a "bad design"? Excluding designs which are unacceptable because of failure to meet minimal performance criteria (the structure cannot support itself, or survive a 5 mile per hour impact), we are left with a set of alternative acceptable designs, some of which may be better than others. Good designs are efficient designs. Minimum functional requirements are satisfied or are exceeded using available resources in the most efficient manner possible. There is no waste in terms of consuming more resources than is necessary. "Bad" design may meet functional requirements (the automotive frame and skin system may survive testing as specified by the Federal Motor Vehicle Safety Standards), but in a way that is not pareto optimal. It may be possible to improve performance in one area without decreasing performance in another. Both types of design "get the job done", but to design well is not simply to specify beam widths and lengths to meet testing criteria, but to do so in such as way as to minimize the expenditure of resources and to maximize the overall value or utility of the entire system by designing to achieve the optimum combination of attributes.

Utility analysis does not embody the technical rules which govern structural design. Rather, it enables the design engineer to identify which of a set of acceptable alternatives is superior, and also provides direction on how to optimize that design. Once designs are developed using data bases, expert systems, CAD systems and finite element analysis to the point that essential performance criteria are satisfied, utility analysis may be used to determine how to modify a design to offer the bundle of negotiable attributes that optimizes overall utility.

Utility analysis used in conjunction with and as a complement to these systems would allow the clear distinction between objective and subjective considerations. Objective considerations are those which can be categorized as purely "technical". Objective rules describe the universal physical relationships between materials properties such as modulus of elasticity and design parameters such as cross-sectional area and length of members to determine physical response such as deflection under load. Subjective considerations may vary between individuals, and include such considerations as the relative values placed on attributes of a design such as weight, cost and uncertainty. The use of the term "subjective" is not to imply that these considerations are not as valid or as important as the objective technical ones. They are equally important. The distinction is that subjective considerations may vary between individuals and over time. Since the rules which embody subjective judgements along with technical considerations, an expert system developed with input from design engineers at Ford may not be applicable to another company such as Fiat. No unique solution to a problem is easily accomodated.

By identifying and separating objective from subjective considerations, it is possible to achieve better, more efficient designs. Subjective judgements and assumptions embodied in the rules but which may not be applicable to a particular set of decision makers or situation may be separated from the objective judgements, preventing unnecessary constraints from being met.

The traditional approach to dealing with subjective considerations such as uncertainty involves the use of safety factors (ie. calculate width necessary to meet beam stiffness requirements to three significant figures, then multiply by a safety factor of two), or uncertainty ranges. These types of crude but necessary and useful rules of thumb may be embodied in the knowledge base reflected in the if-then relationships without the expert or modeller being aware of them. The rules reflect technical relationships but may also include assumptions regarding appropriate safety factors and degree of risk aversion.

Utility analysis quantifies the effect of uncertainty and the decision makers unique attitude towards that uncertainty. These affect how attribute levels are valued in isolation, in relation to other attributes and as contributing to the overall value of whole system.

Utility analysis incorporates consideration of incommensurate attributes, quantifies the tradeoffs decision makers are willing to make between them, and allows for non-linearity of these tradeoffs, or situations where the actual tradeoff tolerated depends on the decision maker's current assets position. Some expert systems use weighting schemes which assume constant rates of substitution between attributes. This means that the engineers would be willing to pay the same dollar amount for one pound removed from a very heavy system and for one pound removed from a very light system, which is often not the case.

Combining utility analysis with data bases, expert systems, CAD systems and finite element analysis and clarifying the distinction between objective and subjective considerations reflects a traditional engineering or reductionist approach to problems; dividing the problem into components, analyzing each component, then assembling them back together for a solution. This approach provides for a method by which engineers may improve on the design process itself, avoiding the pitfalls of relying solely on a model which automates a design process which may be inefficient. Rather than utilizing computer capabilities to solve problems in the traditional manner with greater speed, this approach provides for a problem solving approach which would not have been possible without computer capabilities. Such an approach holds great potential for the development of superior solutions.

CHAPTER 8 - CONCLUSIONS AND RECOMMENDATIONS

- Results of Application - The preferences and values of seven different sets of automotive decision makers responsible for materials selection decisions for the structural frame and body skin system have been assessed. Performance characteristics which are both relevant and negotiable are capital cost, operating cost, weight, design flexibility and corrosion resistance. Decision making environments differ, resulting in no universally correct answer to the question of which material is best for this system. Different decision makers rationally choose different alternatives, based on the economic, institutional, manufacturing, and engineering constraints specific to their situation. Given similar sets of alternatives, the steel uni-body remains the best choice for Fiat2, while the steel frame and polymer composite skin system is the best system for Ford, Fiat1, Peugeot and Renault. For Chrysler, the best alternative is the hybrid system.

- Usefulness of Multiattribute Utility Analysis - It was initially thought that the utility analysis methodology may too cumbersome and time consuming a decision making tool to be practicably applied to a problem of this complexity. The results of this set of applications have proved that this is not the case. We have learned that utility analysis is an appropriate decision making tool in situations involving choices between alternatives of which none clearly dominates in every aspect of performance. Thus, faced with a confusing array of alternatives, the decision maker can use utility analysis to identify and select the best system.

Utility analysis is also useful in quantifying performance tradeoffs the decision maker is willing to make. This feature can be exploited to determine how a sub-optimal alternative may be improved in order to become competitive with the chosen system. This procedure is useful both in situations where one alternative dominates the others in all performance requirements, and in situations where choices are not as clear cut.

- Recommendations - The methodology did not facilitate redesign to optimize material characteristics, primarily because the decision makers are not yet in a position to do so. The initial approach was to model an existing environment where this type of redesign was being carried out. At the beginning of the study, it was realized that some designers might be further along than others in the switch from direct substitution of isolated components to redesign of entire systems. It was expected that should an assessment be performed at a company just in the process of developing a new redesign approach that participating in the assessment procedure itself would be helpful in structuring their approach to the problem in a systems analytic way.

Thus, it was hoped that the methodology of defining subsystems in terms of performance characteristics would in itself facilitate redesign where this was not already occuring. The process of going through the assessment procedure and analyzing the results was expected to aid the design engineer in developing new design alternatives. Although subsystems were delineated on the basis of functional requirements which could provide the basis for redesign, it was determined that many of these structural performance characteristics were still being viewed as binary. As a result, distinctions which led to the exhaustive subsystem delineation were not necessary.

If the analyst worked closely with design engineers in developing an approach to the process of redesign to optimize materials' characteristics based on functional requirements, it would be appropriate to view this application of utility analysis not just as a decision making tool but also as a design aid. The original hypothesis was that a decision making tool was needed to help automotive design engineers sort out and select the best from a set of alternative material designs, each offering a confusing array of incommensurate attributes. The result of this application is that a tool is needed not only to sort out the existing alternatives, but also to help develop new ones. We have seen that the existing materials design and selection process is suboptimal in terms of not fully utilizing any materials' capabilities. The application of utility analysis as both a decision making tool and as a design aid to optimize materials' characteristics has great potential.

APPENDIX A - PRELIMINARY INPUT

PRELIMINARY INPUT SOURCES

Aluminum Company of America
Alcoa Center, PA

Roger Haddon, Project Manager
Aluminum Intensive
Vehicle Program

Barry Bixler, Design

Ron McClure
Technology Planning

Chrysler Corporation
Detroit, MI 48288

J.J. Bazzetta
Chassis & Final Manufacturing

M.A. Bowen, Manager
Product Engineering & Design
Liberty II

Roger Hakio

J.P. Hinckly, Manager
Manufacturing Planning & Eng.
Project Liberty

Ed Lesniak

Ed Maier
Body Design Specialist

T.T. Pierce
Body-in-White Specialist

Drew Ragan
Advanced Stuctures

Ron Traficante
Tom Treece
Bob Wilkerson

Concept Analysis Corporation
Pat Glance
Corporate Director
Plymouth, MI 48170

E.I. DuPont Inc.
Wilmington, DE 19898
Dave Agnew
Bill Anderson
M.L. Sheer

Ford Motor Company
Dearborn, MI 48124

Sandra Laatsch
Engineering Div./Planning

Chris Magee
Director
Vehicle Concepts Research

Joe Williams
Supervisor
Vehicle Engineering Dept.

General Electric Company
Mr. Raymond Naar
1285 Boston Avenue
Bridgeport, CT 06601-2385

Inland Steel Company
30 West Monroe Street
Chicago, IL 60603

Bernie Levy
Steve Smith
Brian Sok
Roy Platz

Montedison
Ing. Giancarlo Beretta
Foro Buonaparte
31-20121 Milano, Italy

SAMPLE REQUEST FOR INPUT

July 31, 1985

Ms. Sandra Laatsch
Ford Motor Company
Engineering Division/Planning
3056 Rouge Office Building
3001 Miller Road
Dearborn, MI 48124

Dear Ms. Laatsch,

Thank you for the information you provided us regarding materials substitution at Ford. As we discussed, our research group has developed a method to aid design engineers in the materials selection process. In order to deal with the complex problems involved in comparing fundamentally different materials such as steel and plastics, the method focuses on performance characteristics, rather than abstract materials properties. This approach also allows the design engineer to take maximum advantage of new materials, rather than being forced to operate within the constraints dictated by the existing system. The enclosed research summary you requested should clarify things.

At this point, we need input on a questionnaire we are developing. Its purpose is to gather data to determine how automotive engineers value materials characteristics for structural-load-bearing frame and body skin systems. The major categories of materials under consideration are steel, aluminum and polymer composites. The questionnaire will be given to automotive design engineers involved in the system design and materials selection process. An example question is attached, to illustrate the form of the questionnaire.

It would be very helpful to us if you and/or your design engineers could provide some feedback by completing and returning the attached preliminary list of performance characteristics. Remember that there are no right or wrong answers; what we are after is your approach to the problem. We need your input in order to insure that we accomplish five things in devising the questionnaire:

1. Include all pertinent performance characteristics such that both advantages and disadvantages of each material are captured.

2. Express the performance characteristics in terms that are meaningful and significant to the decision maker.

3. Define the characteristics and the units in which they are expressed such that there is no built in bias towards any particular material.

4. Identify "binary" performance criteria, which must be satisfied at some specific minimum level, but to which there is minimal value in exceeding.

5. In the interests of efficiency, to eliminate repetitive or insignificant characteristics from further consideration.

Another issue that we need your thoughts on is the tentative breakdown of systems within the structural frame and body skin systems. The performance tradeoff questions will apply to a category of components. Note that in the example, the question refers to an "internal load-bearing structural member". We wish to define categories such that all components in a category have similar performance requirements, so that a material is not eliminated from consideration for use in a fender simply because it is unacceptable for use in a floor pan. Our preliminary breakdown is:

1. Internal load-bearing structural members. These components are not part of the external body skin system. The inner side sill is an example.

2. External load-bearing structural members. The rear quarter panel in a uni-body is an example.

3. External non-load bearing components. The front fender in a space frame is an example.

Do you think the categories are too broad? For example, do you think that a further breakdown into systems such as "front end internal load bearing members" or even individual components is necessary? Do you think it is necessary to have separate categories for different performance characteristics such as "below splash line" and "above splash line" for corrosion resistance? What further breakdown would you suggest, if any?

We very much appreciate your efforts in assisting us. I will call you later next week to see if you have any questions and to get your general reaction to this material. My phone number is

617-253-4333.

Sincerely,

Deborah L. Thurston

Relevance Scale for Performance Characteristics

1. Essential; a specific minimum or maximum standard must be met or the system is unacceptable, and there is minimal value to exceeding the standard.
2. Very important; should definitely be included.
3. Important; should be included.
4. Marginal; may be excluded.
5. Not important; should be excluded. It is either insignificant or is already measured through another performance characteristic.

Example Question

You know that an internal load bearing component, when made of the traditional material, exhibits average vibration damping. A new material under consideration for use in the component will cost, weigh and perform exactly the same in all respects as the traditional material except for vibration damping. Test results indicate that there is a probability p that the vibration damping of the component using the new material will be improved by 10%. However, there is also a probability of 1-p that the vibration damping will be decreased by 10%. For example, if the probability of improved vibration damping is 70%, the probability of decreased vibration damping is 30%. What is the lowest

probability p that would lead you to select the new material?

Performance Criteria

for Internal Load Bearing Structural Members

Structural Function	Relevance 1 to 5 Scale	Unit or Method of Measurement	Average Value Observed	Maximum Value Allowed	Minimum Value Allowed
Bending Stiffness					
Torsional Stiffness					
Buckling Resistance					
Dynamic Yield Resistance					
Static Yield Resistance					
Temperature Resistance					
Vibration Damping					
Fatigue					
Corrosion Resistance					
Design Flexibility; anisotropy					
Weight			---	---	---
Cost of Production*			---	---	---
Other					

* Includes materials, labor, tooling, utilities, capital, and overhead for forming, assembly and finishing processes

Performance Criteria

for External Non-Load Bearing Structural Members

Structural Function	Relevance 1 to 5 Scale	Unit or Method of Measurement	Average Value Observed	Maximum Value Allowed	Minimum Value Allowed
Oil Canning Resistance					
Buckling Resistance					
Yield Resistance					
Vibration Damping					
Temperature Resistance					
Fatigue; service life					
Corrosion Resistance					
Styling Flex.; appearance, drag coeff.					
Weight			---	---	---
Cost of Production*			---	---	---
Other					

* Includes materials, labor, tooling, utilities, capital, and overhead for forming, assembly and finishing processes

Performance Criteria
for External Load Bearing Structural Members

Structural Function	Relevance 1 to 5 Scale	Unit or Method of Measurement	Average Value Observed	Maximum Value Allowed	Minimum Value Allowed
Bending Stiffness					
Torsional Stiffness					
Oil Canning Resistance					
Buckling Resistance					
Dynamic Yield Resistance					
Static Yield Resistance					
Vibration Damping					
Temperature Resistance					
Fatigue; service life					
Corrosion Resistance					
Styling Flex.; appearance, drag coeff.					
Weight		pounds			
Cost of Production*		dollars			
Other					

* Includes materials, labor, tooling, utilities, capital, and overhead for forming, assembly and finishing processes

APPENDIX B - UTILITY SURVEY FORMS

MANUAL SURVEY FORMS

The following forms are examples of the ones used in the assessment procedure. One single attribute form and one scaling constant form must be completed for each attribute for each subsystem. Scaling constants for each subsystem must also be assessed. Preferential and utility independance conditions must be tested. The empty plots are used to quickly sketch the single attribute utility functions during the survey.

OPERATING COST for NON-STRUCTURAL COMPONENTS; SINGLE ATTRIBUTE

(Operating cost for certain) vs. Lottery

```
                          ______ (Co min)
              0.5    /
                    /
(Co)     vs.       /
                   \
              0.5   \
                     \______ (Co max)
```

Which do you prefer?		
Co	Co	Lottery
Co max____		X
Co1_______		
Co2_______		
Co3_______		
Co4_______		
Co min____	X	

At which level of Co are you indifferent?____________

```
                          ______ (Co min)
             0.75    /
                    /
(Co)     vs.       /
                   \
             0.25   \
                     \______ (Co max)
```

Which do you prefer?		
Co	Co	Lottery
Co max____		X
Co1_______		
Co2_______		
Co3_______		
Co4_______		
Co min____	X	

At which level of Co are you indifferent?____________

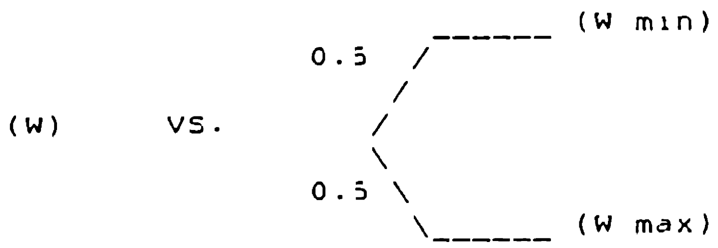
```
                          ______ (Co min)
             0.25    /
                    /
(Co)     vs.       /
                   \
             0.75   \
                     \______ (Co max)
```

Which do you prefer?		
Co	Co	Lottery
Co max____		X
Co1_______		
Co2_______		
Co3_______		
Co4_______		
Co min____	X	

At which level of Co are you indifferent?____________

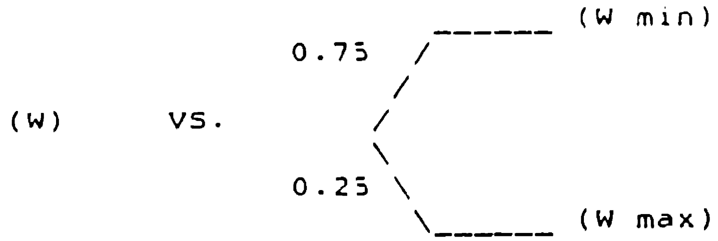
WEIGHT for STRUCTURAL COMPONENTS; SINGLE ATTRIBUTE

(Weight for certain) vs. Lottery



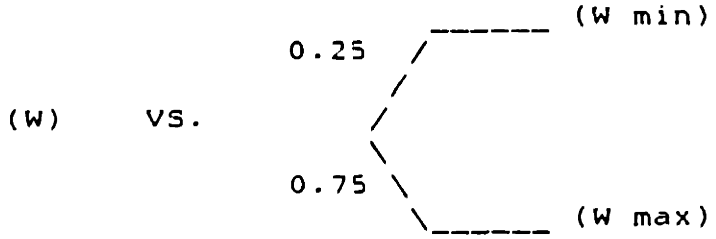
Which do you prefer?		
W	W	Lottery
W max____		X
W1 ______		
W2________		
W3________		
W4________		
W min____	X	

At which level of W are you indifferent?_____________



Which do you prefer?		
W	W	Lottery
W max____		X
W1 ______		
W2________		
W3________		
W4________		
W min____	X	

At which level of W are you indifferent?_____________

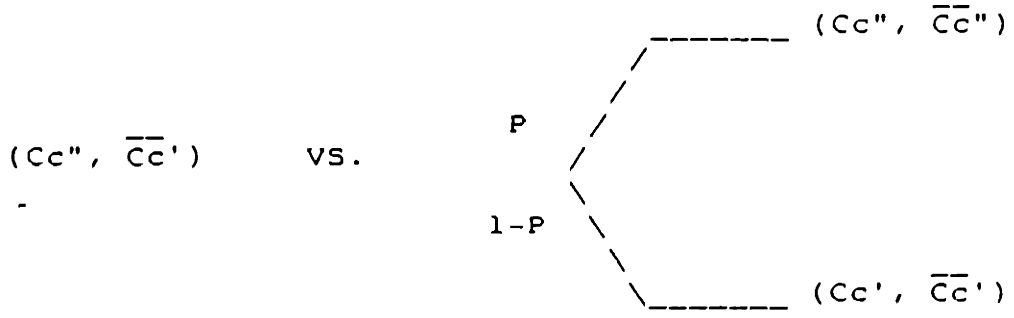


Which do you prefer?		
W	W	Lottery
W max____		X
W1 ______		
W2________		
W3________		
W4________		
W min____	X	

At which level of W are you indifferent?_____________

CAPITAL COST for NON-STRUCTURAL COMPONENTS; SCALING CONSTANT Kcc

Current System VS. New System



Which do you prefer?

P	Current System	New System
0%	X	
10%		
20%		
30%		
40%		
50%		
60%		
70%		
80%		
90%		
100%		X

At which level of P are you indifferent?____________

Cc" = best possible level of capital cost
Cc' = worst possible level of capital cost
$\overline{Cc}$" = best levels of all other attributes besides capital cost
$\overline{Cc}$' = worst levels of all other attributes besides capital cost

RESISTANCE to CORROSION for NON-STRUCTURAL COMPONENTS;

SCALING CONSTANT Kr

Current System VS. New System

```
                                        _______ (R", R̄")
                                       /
                               P      /
(R", R̄')        VS.                  /
                                     \
                              1-P     \
                                       \_______ (R', R̄')
```

Which do you prefer?

P	Current System	New System
0 %	X	
10%		
20%		
30%		
40%		
50%		
60%		
70%		
80%		
90%		
100%		X

At which level of P are you indifferent?____________

R" = best possible level of resistance to corrosion
R' = worst possible level of resistance to corrosion
$\bar{R}$" = best levels of all other attributes
$\bar{R}$' = worst levels of all other attributes

PREFERENTIAL INDEPENDANCE

WF PI C

Do preferences between alternatives remain the same even when cost changes?

(COST, WEIGHT, FLEXIBILITY) VS. (COST, WEIGHT, FLEXIBILITY)

(1000, W1, F1) VS. (1000, W2, F2)
(100, W1, F1) VS. (100, W2, F2)

(1000, W2, F2) VS. (1000, W3, F3)
(100, W2, F2) VS. (100, W3, F3)

(1000, W3, F3) VS. (1000, W1, F1)
(100, W3, F3) VS. (100, W1, F1)

CF PI W

Do preferences between alternatives remain the same even when weight changes?

(COST, WEIGHT, FLEXIBILITY) VS. (COST, WEIGHT, FLEXIBILITY)

(C1, 1000, F1) VS. (C2, 1000, F2)
(C1, 100, F1) VS. (C2, 100, F2)

(C2, 1000, F2) VS. (C3, 1000, F3)
(C2, 100, F2) VS. (C3, 100, F3)

(C3, 1000, F3) VS. (C1, 1000, F1)
(C3, 100, F3) VS. (C1, 100, F1)

CW PI F

Do preferences between alternatives remain the same even when flexibility changes?

(COST, WEIGHT, FLEXIBILITY) VS. (COST, WEIGHT, FLEXIBILITY)

(C1, W1, 5) VS. (C2, W2, 5)
(C1, W1, 1) VS. (C2, W2, 1)

(C2, W2, 5) VS. (C3, W3, 5)
(C2, W2, 1) VS. (C3, W3, 1)

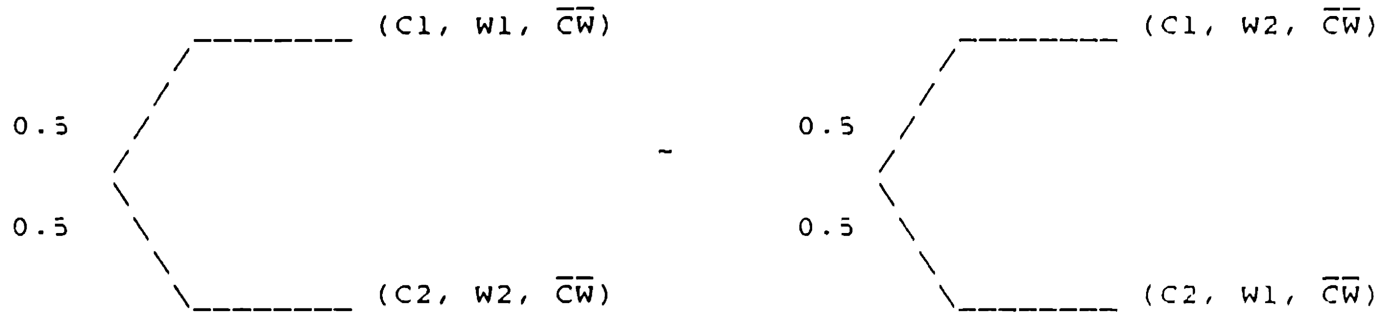
(C3, W3, 5) VS. (C1, W1, 5)
(C3, W3, 1) VS. (C1, W1, 1)

UTILITY INDEPENDENCE

(ATTRIBUTE A, OTHER ATTRIBUTES)   VS.   LOTTERY

```
                                               ______ (X1, OA1)
                                    0.5   /
                                         /
(CE, OA1)            VS.                /
                                        \
                                    0.5  \
                                          \______ (X2, OA1)



                                               ______ (X1, OA2)
                                    0.5   /
                                         /
(CE, OA2)            VS.                /
                                        \
                                    0.5  \
                                          \______ (X1, OA2)



                                               ______ (X1, OA3)
                                    0.5   /
                                         /
(CE, OA3)            VS.                /
                                        \
                                    0.5  \
                                          \______ (X2, OA3)
```

NON-STRUCTURAL COMPONENTS; ADDITIVE INDEPENDENCE



TOTAL SYSTEM; ADDITIVE INDEPENDENCE

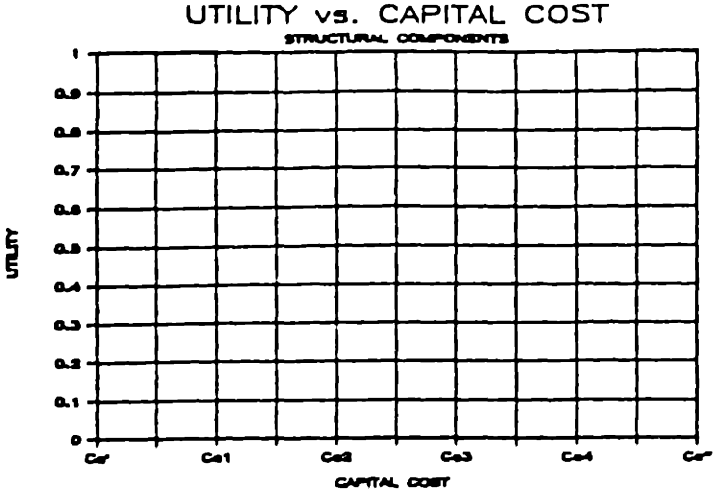
Are you indifferent between these two lotteries?

```
             _______  (S1, N1)                         _______  (S1, N2)
            /                                         /
 0.5       /                               0.5       /
          /                          ~              /
          \                                         \
 0.5       \                               0.5       \
            \_______  (S2, N2)                        \________  (S2, N1)
```

```
             _______                                   _______
            /                                         /
 0.5       /                               0.5       /
          /                          ~              /
          \                                         \
 0.5       \                               0.5       \
            \_______                                  \________
```

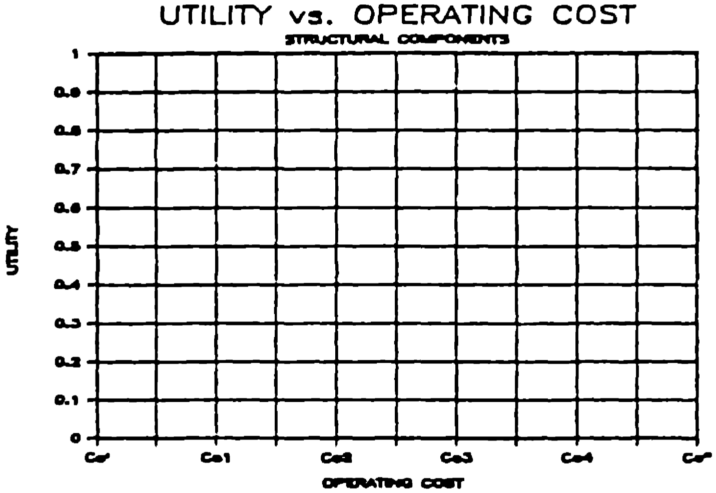
S = structural, load bearing components

N = non-structural components



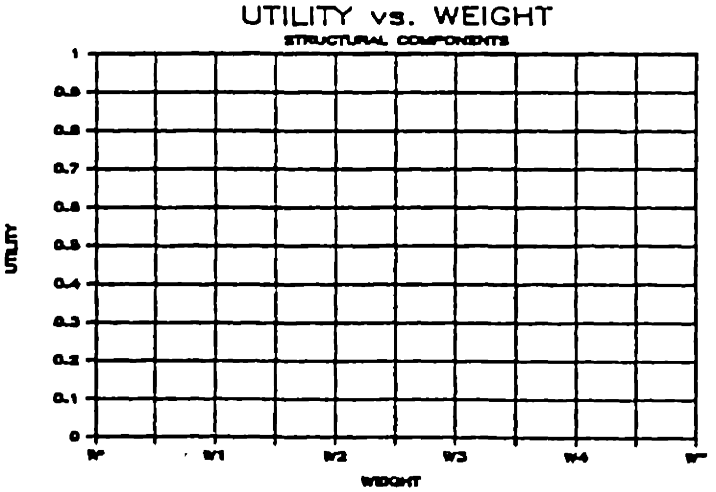
UTILITY vs. CAPITAL COST

STRUCTURAL COMPONENTS



UTILITY vs. OPERATING COST

STRUCTURAL COMPONENTS



UTILITY vs. WEIGHT

STRUCTURAL COMPONENTS

INPUT FILE FOR "ASSESS"

The following table is an example of the input information file required to run the "ASSESS" program. The surveyor enters data based on input from the subjects. Names of the relevant attributes are input in the first column, and the upper and lower ranges over which each attribute is considered are entered into the second and third columns. In the fourth column, a "y" for "yes" indicates that the attribute is a "good"; in the quantification units specified, more is preferred to less. An "n" for "no" indicates that less is preferred to more. The number of points to be assessed for the single attribute utility function is entered in column five. The method by which the assessment procedure and bracketing techniques are performed is entered in the last column. Methods #1 and #2 assess points on the single attribute utility function as indifference points between a quantity for certain (or "certainty equivalent") and a lottery. In the bracketing procedure used to obtain these indifference points, the certainty equivalent is varied in Method #1 and the probabilities assigned to the outcomes of the lottery are varied in Method #2. Method #3 obtains indifference points between two lotteries, varying the probabilities of the outcomes of one of the lotteries in the bracketing procedure.

```
#_of_attributes:  5

methods: 1 - certainty equivalent, constant p
         2 - certainty equivalent, varying p
         3 - lottery equivalent
         4 - probability equivalent

ATTR  UNIT          UPPER       LOWER   DESIRE   # OF PTS   METHOD
-------------------------------------------------------------------

1    CAPITAL         700         280      N         4          1

2    OPERATING       773         600      N         4          1

3    WEIGHT          600         385      N         4          1

4    FLEXIBILITY      12           1      Y         4          1

5    CORROSION        20           5      Y         4          1
```

APPENDIX C - UTILITY SURVEY DATA

SURVEY PARTICIPANTS

Company	Location	Name	Date of Survey
Chrysler	Pontiac, MI	Ed Maier	2/27/86
Ford	Dearborn, MI	W. Joe Williams Roy Bonnett Chris Morris	2/28/86
Fiat #1	Turin, Italy	Paulo Odone	9/8/86
Fiat #2	Turin, Italy	Salvatore DiCarlo	9/8/86
Fiat #3	Orbassano, Italy	Massimo Castagna Sante Quaranta Fenoglio Lepore	9/9/86
Peugeot	Paris, France	Jean-Jacques Lanfranchini Maurice Girard Courmier Madec	9/11/86
Renault	Paris, France	Michael Costes	9/12/86

* Survey performed with ASSESS, interactive computer assessment package.

ORIGINAL SURVEY DATA

Chrysler Corporation

Single Attribute Utility	Capital Cost	Operating Cost	Weight	Design Flexib.	Corrosion Resistance
0	700	773	600	1	5
0.25	400	700	580	3	7
0.5	320	650	500	6	12
0.75	300	625	425	11	18
1	280	600	385	12	20
Scaling Constant k	0.3	0.4	0.7	0.95	0.1

Ford Motor Company

Single Attribute Utility	Capital Cost	Operating Cost	Weight
0	0.20	0.15	3200
0.25	0.18	0.12	3125
0.5	0.15	0.09	3100
0.75	0.10	0.05	3040
1	-0.30	-0.30	2500
Scaling Constant k	0.9	0.9	0.9

Fiat 1

Single Attribute Utility	Capital Cost	Operating Cost	Weight	Design Flexib.	Corrosion Resistance
0	0.05	0.10	0.00	3	5
0.25	0.04	0.05	-0.04	5	5.5
0.5	-0.02	-0.02	-0.08	6	6
0.75	-0.05	-0.05	-0.09	8	8
1	-0.30	-0.15	-0.10	10	10
Scaling Constant k	0.4	0.7	0.3	0.5	0.55

Fiat 2

Single Attribute Utility	Capital Cost	Operating Cost	Weight	Design Flexib.	Corrosion Resistance
0	0.5	0.6	0.08	1	6
0.25	0.35	0.5	0.05	2	7
0.5	0.25	0.38	-0.05	4	8
0.75	0.1	0.28	-0.1	5.5	10
1	-0.1	-0.1	-0.3	10	15
Scaling Constant k	0.95	0.92	0.03	0.35	0.18

Fiat 3 Central Research

Single Attribute Utility	Capital Cost	Operating Cost	Weight	Design Flexib.	Corrosion Resistance
0	1200	400	110	2	7
0.25	990	365	102	3	9
0.5	950	345	99	4	11
0..75	900	320	94		12
1	800	300	90	5	15
Scaling Constant k	0.15	0.15	0.05	0.90	0.90

Peugeot

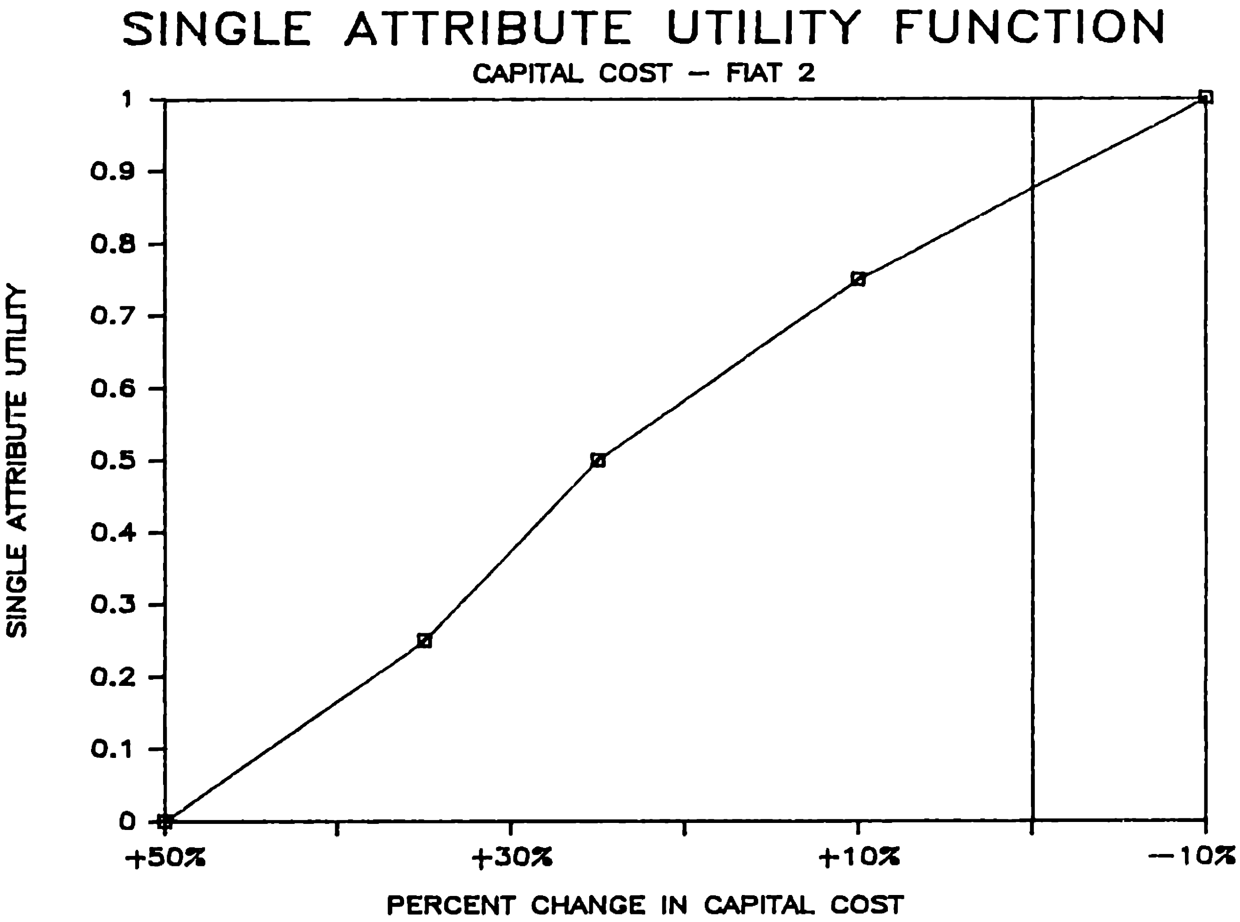
Single Attribute Utility	Capital Cost	Operating Cost	Weight	Design Flexib.	Corrosion Resistance
0	2000	10000	900	1	5
0.25	1800	7500	850	2	8
0.5	1500	6700	750	3	10
0.75	1200	6000	700	5	12
1	500	5000	600	6	15
Scaling Constant k	0.30	0.35	0.40	0.05	0.45

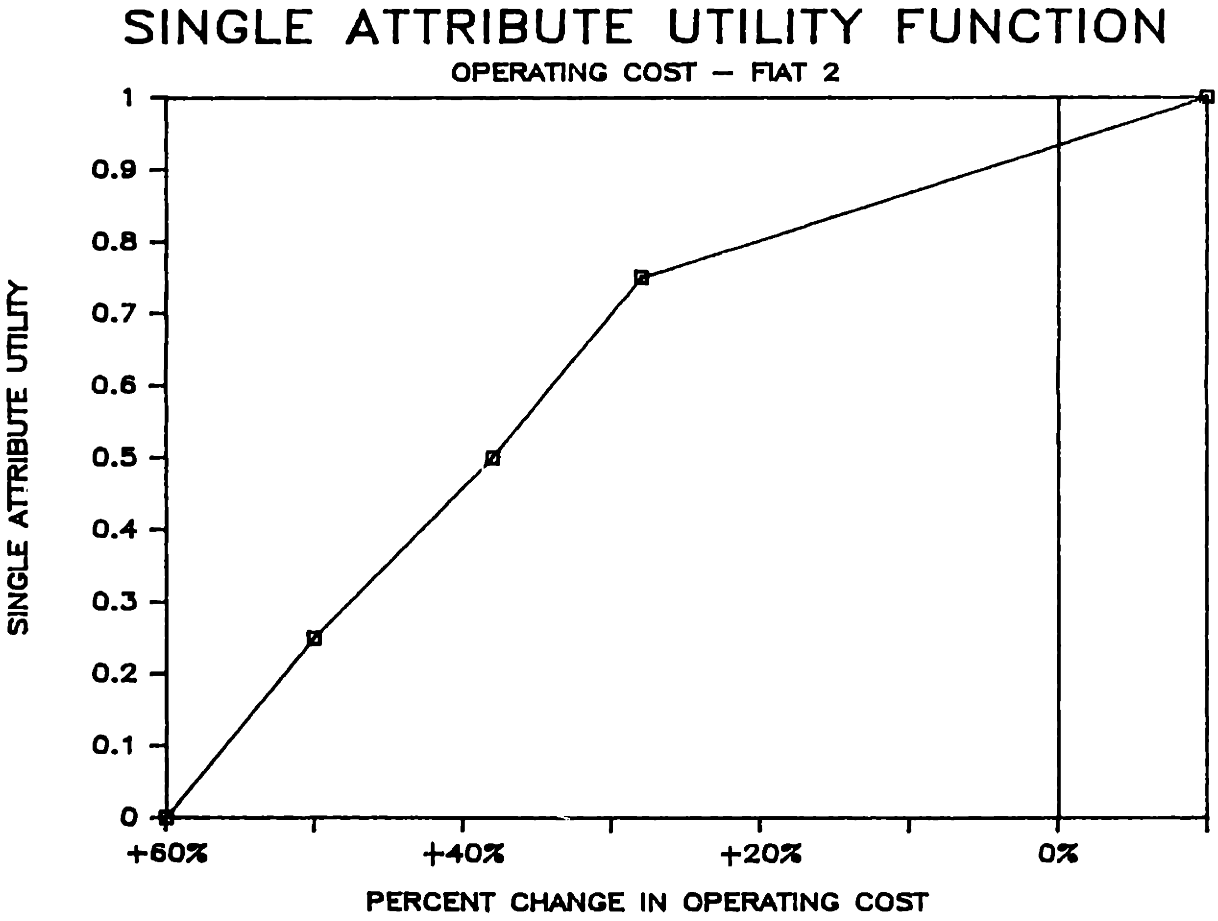
Renault

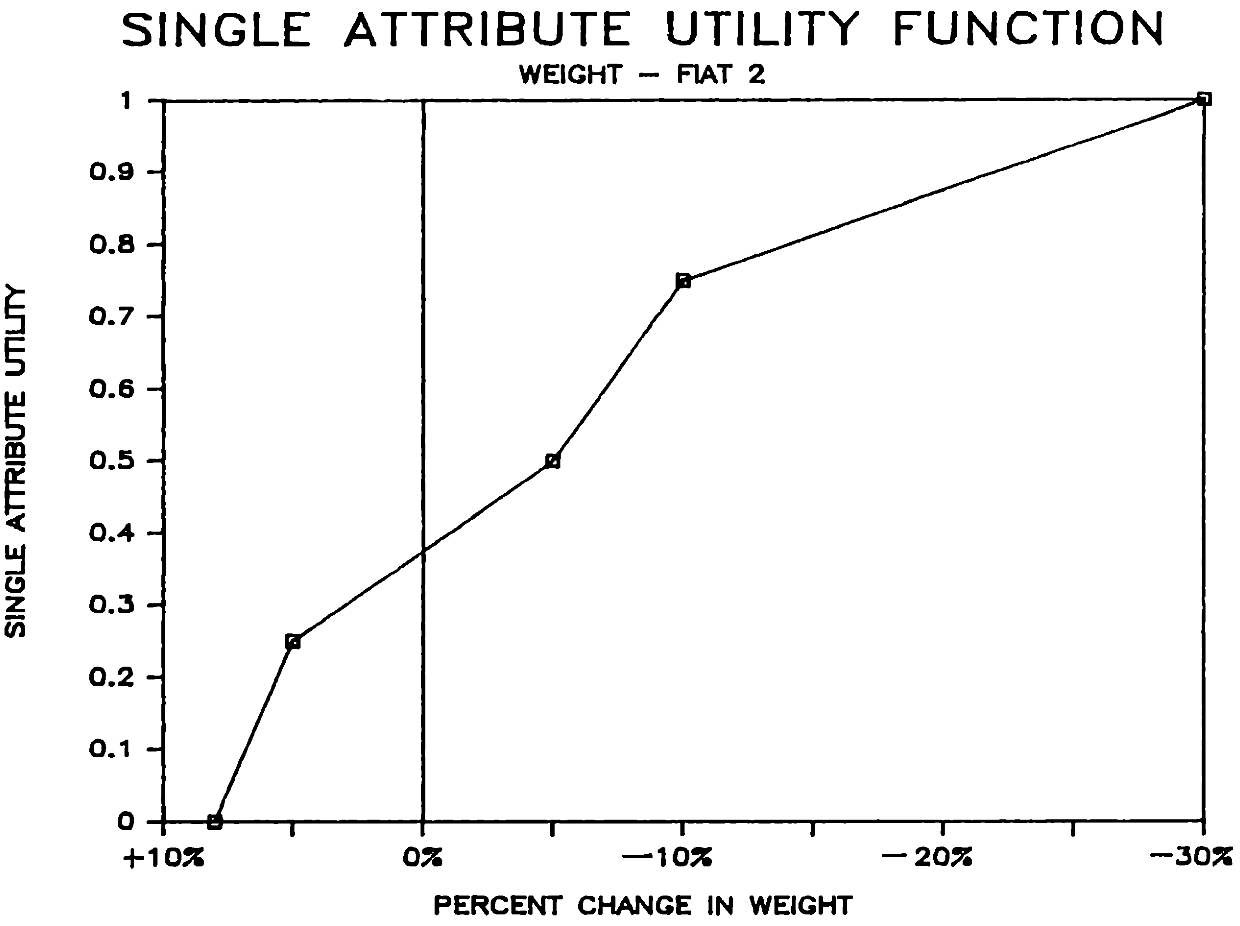
Single Attribute Utility	Capital Cost	Operating Cost	Weight	Design Flexib.	Corrosion Resistance
0	3.00	45	500	1	5
0.25	2.90	41	480	1.5	6
0.5	2.80	40	468	2	7
0.75	2.60	38	450	3	9
1	1.50	30	350	5	15
Scaling Constant k	0.58	0.9	0.45	0.25	0.20

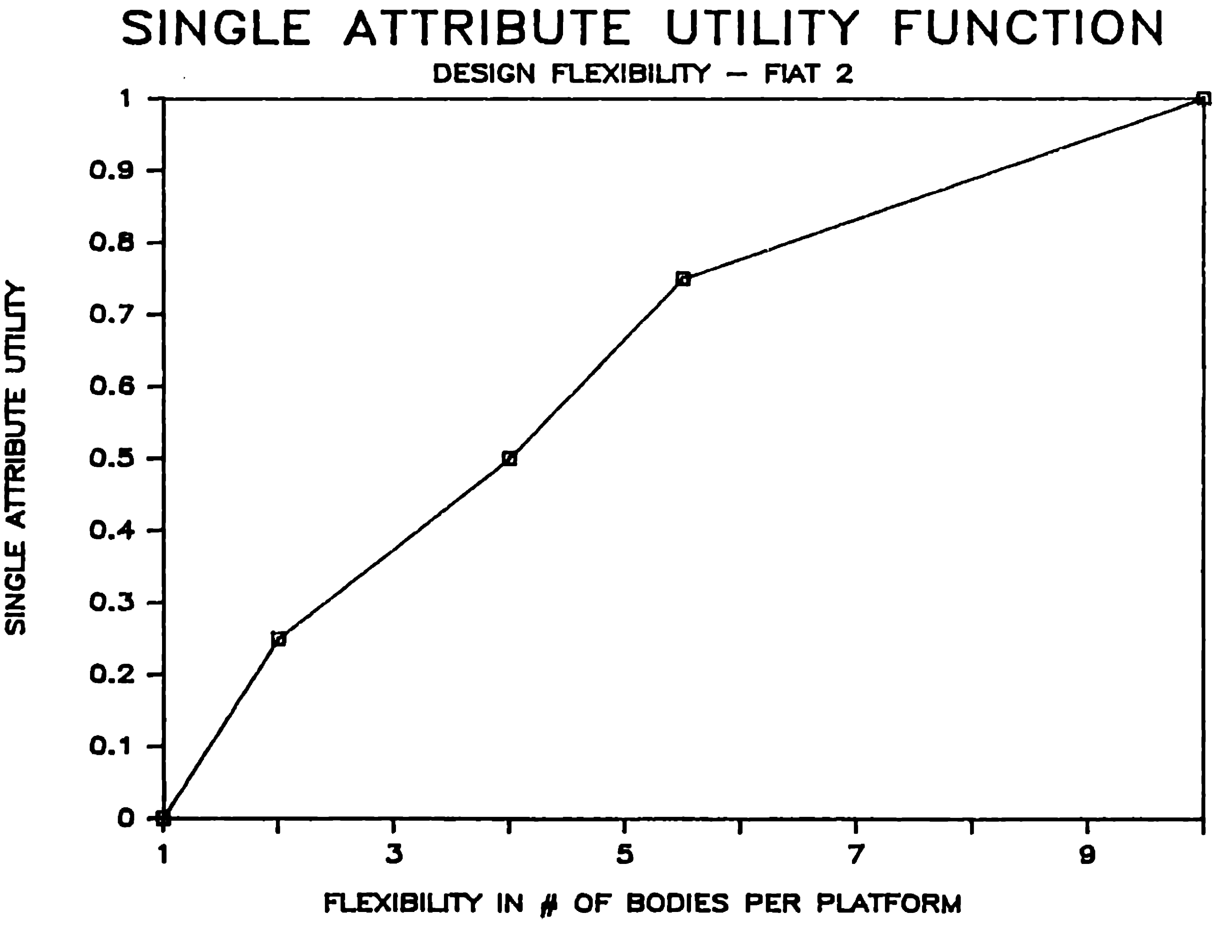
SINGLE ATTRIBUTE UTILITY FUNCTIONS

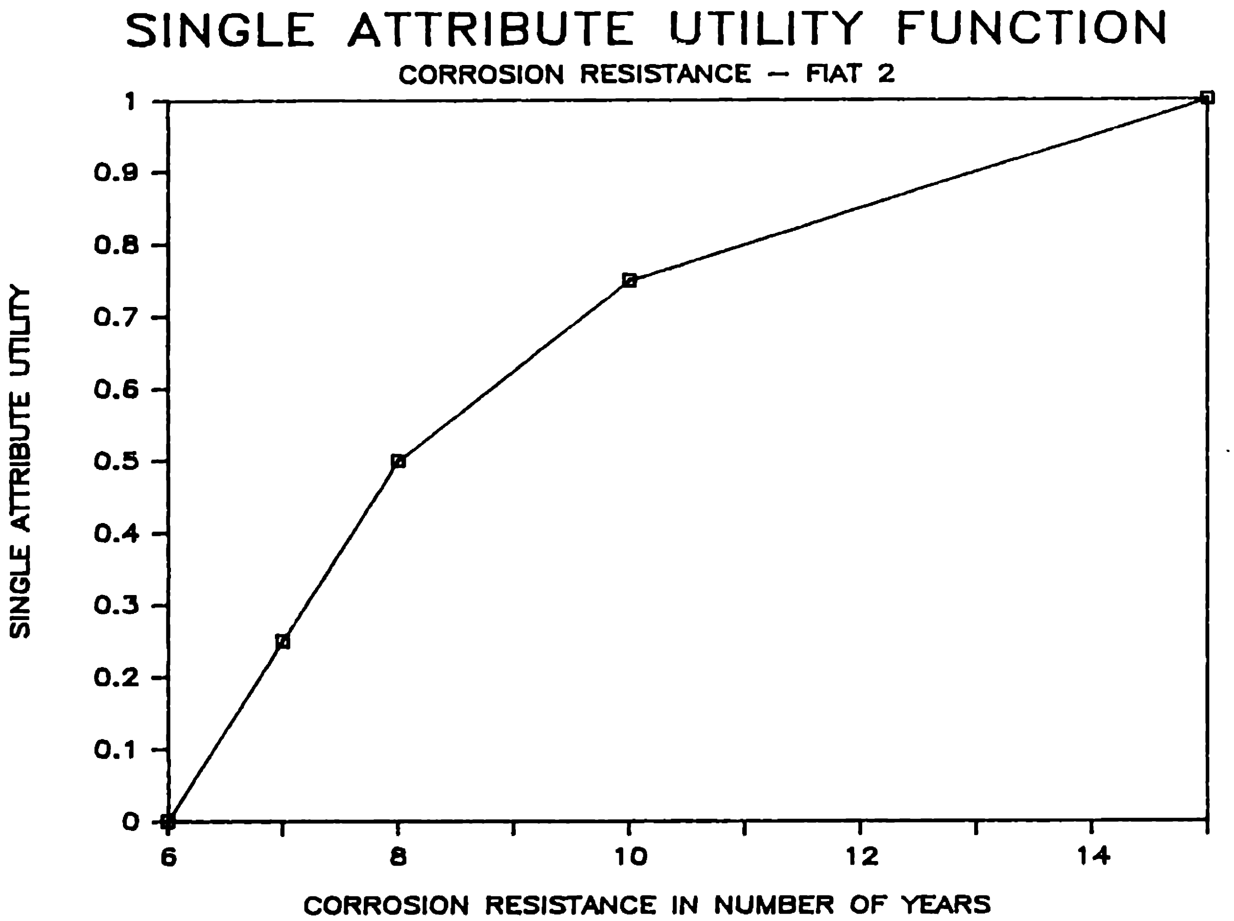
The following plots are single attribute utility functions for each attribute for each company.


SINGLE ATTRIBUTE UTILITY FUNCTION
CAPITAL COST – FIAT 2
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
+50%
+30%
+10%
−10%
PERCENT CHANGE IN CAPITAL COST


SINGLE ATTRIBUTE UTILITY FUNCTION
OPERATING COST – FIAT 2
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
+60%
+40%
+20%
0%
PERCENT CHANGE IN OPERATING COST

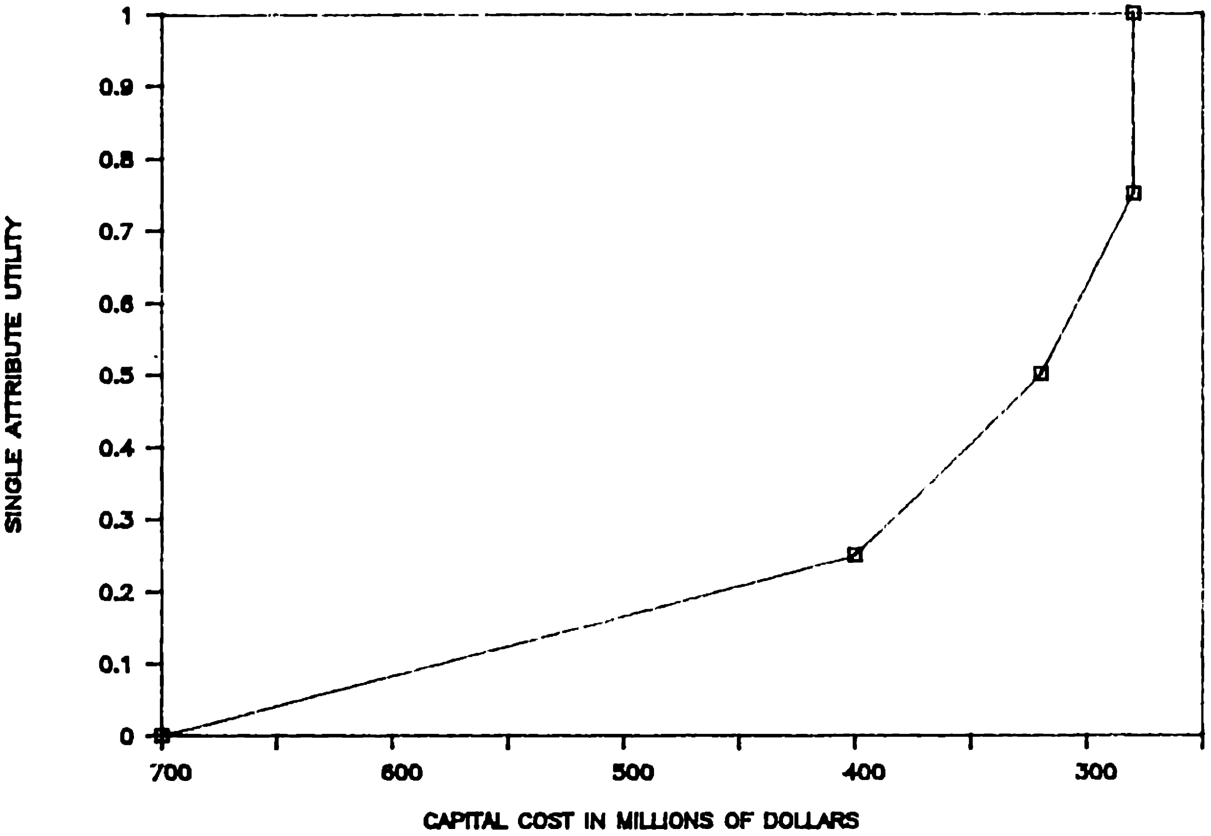

SINGLE ATTRIBUTE UTILITY FUNCTION
WEIGHT – FIAT 2
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
+10%
0%
–10%
–20%
–30%
PERCENT CHANGE IN WEIGHT


SINGLE ATTRIBUTE UTILITY FUNCTION
DESIGN FLEXIBILITY – FIAT 2
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
3
5
7
9
FLEXIBILITY IN # OF BODIES PER PLATFORM


SINGLE ATTRIBUTE UTILITY FUNCTION
CORROSION RESISTANCE – FIAT 2
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
6
8
10
12
14
CORROSION RESISTANCE IN NUMBER OF YEARS

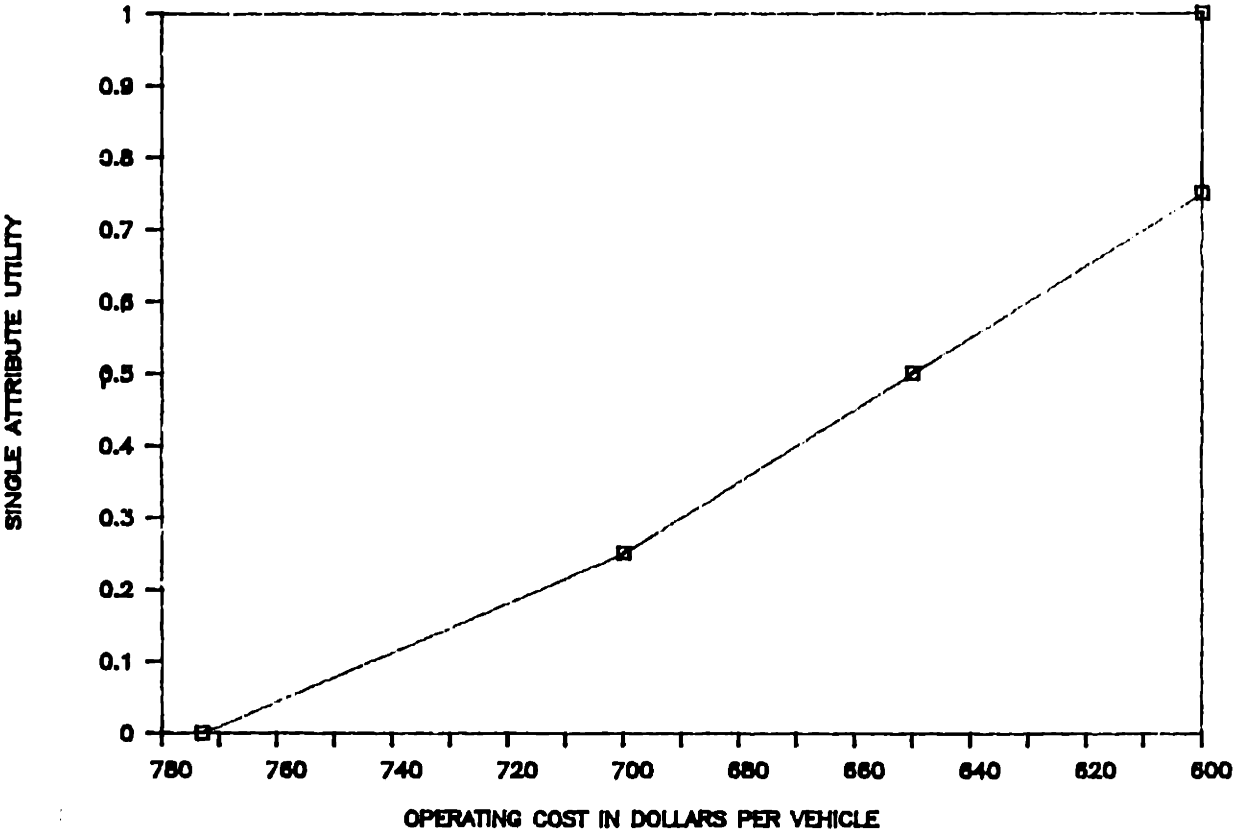
SINGLE ATTRIBUTE UTILITY FUNCTION

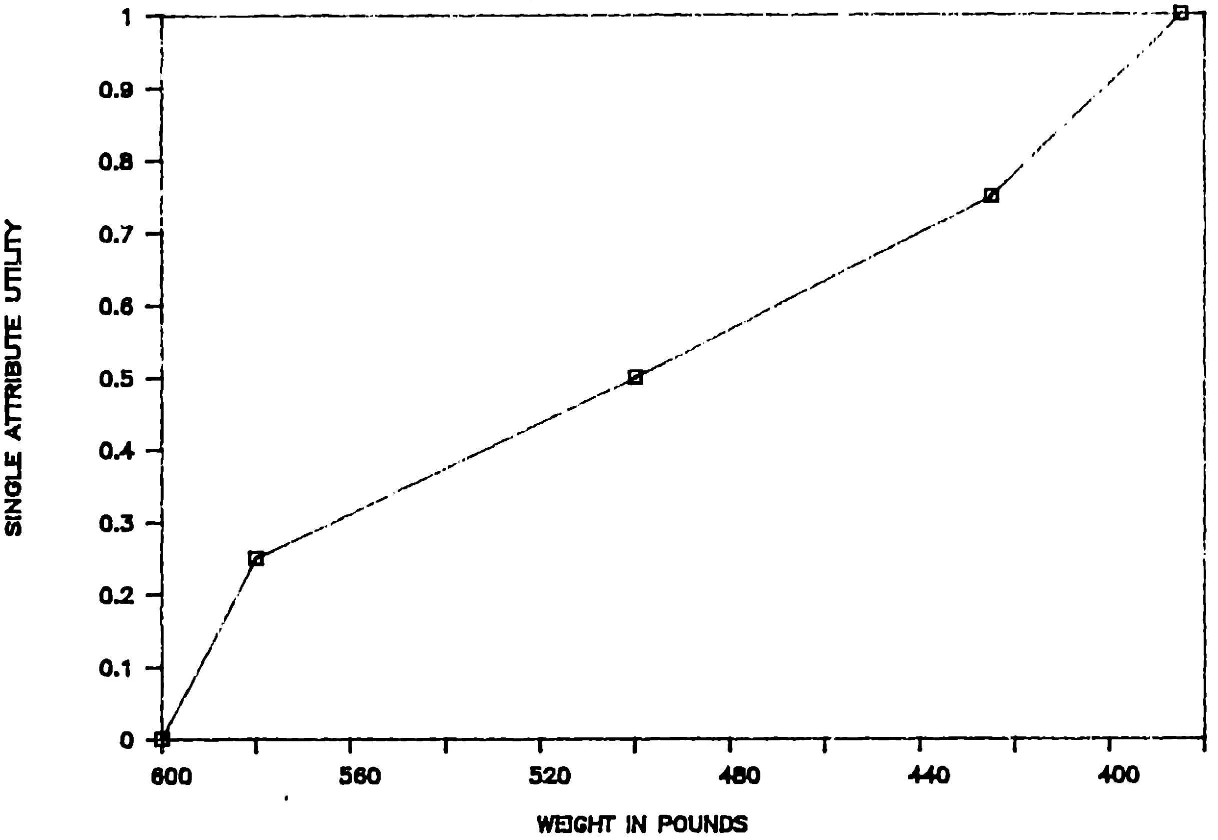
CAPITAL COST – CHRYSLER



SINGLE ATTRIBUTE UTILITY FUNCTION

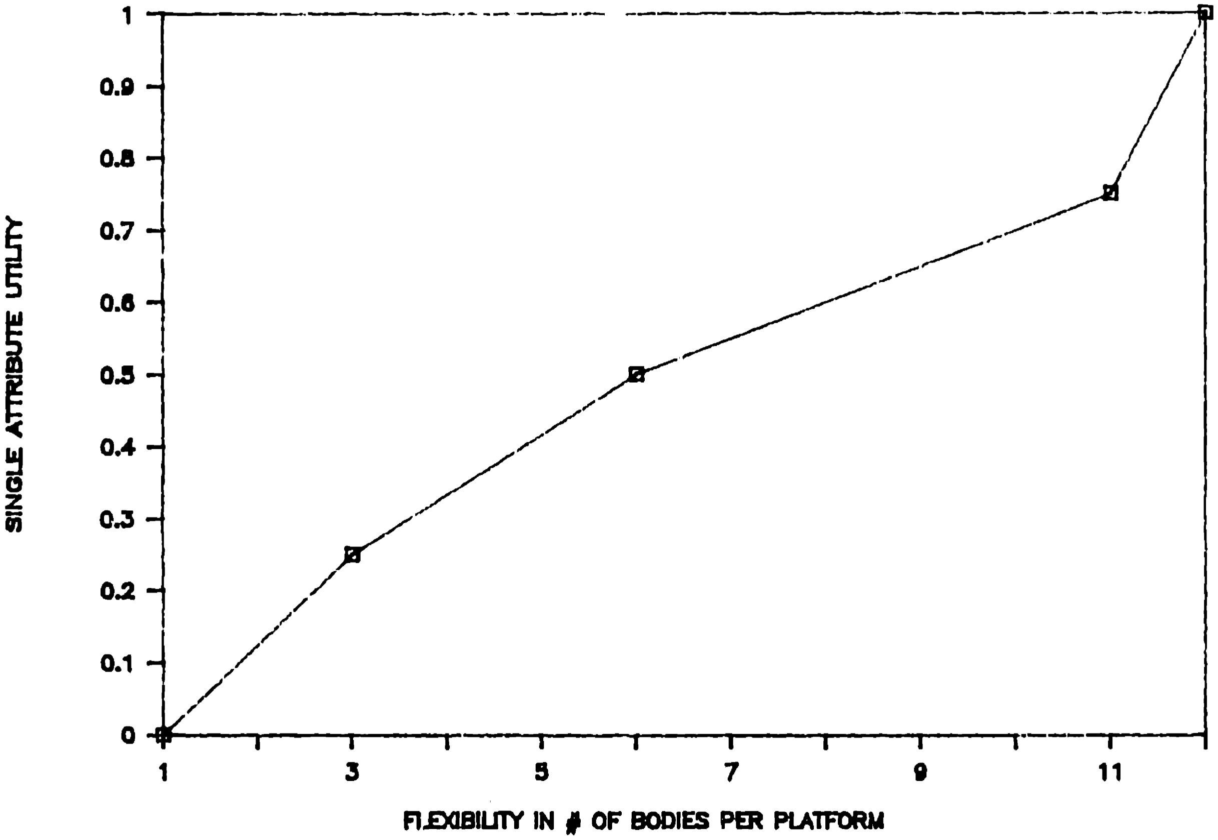
OPERATING COST – CHRYSLER





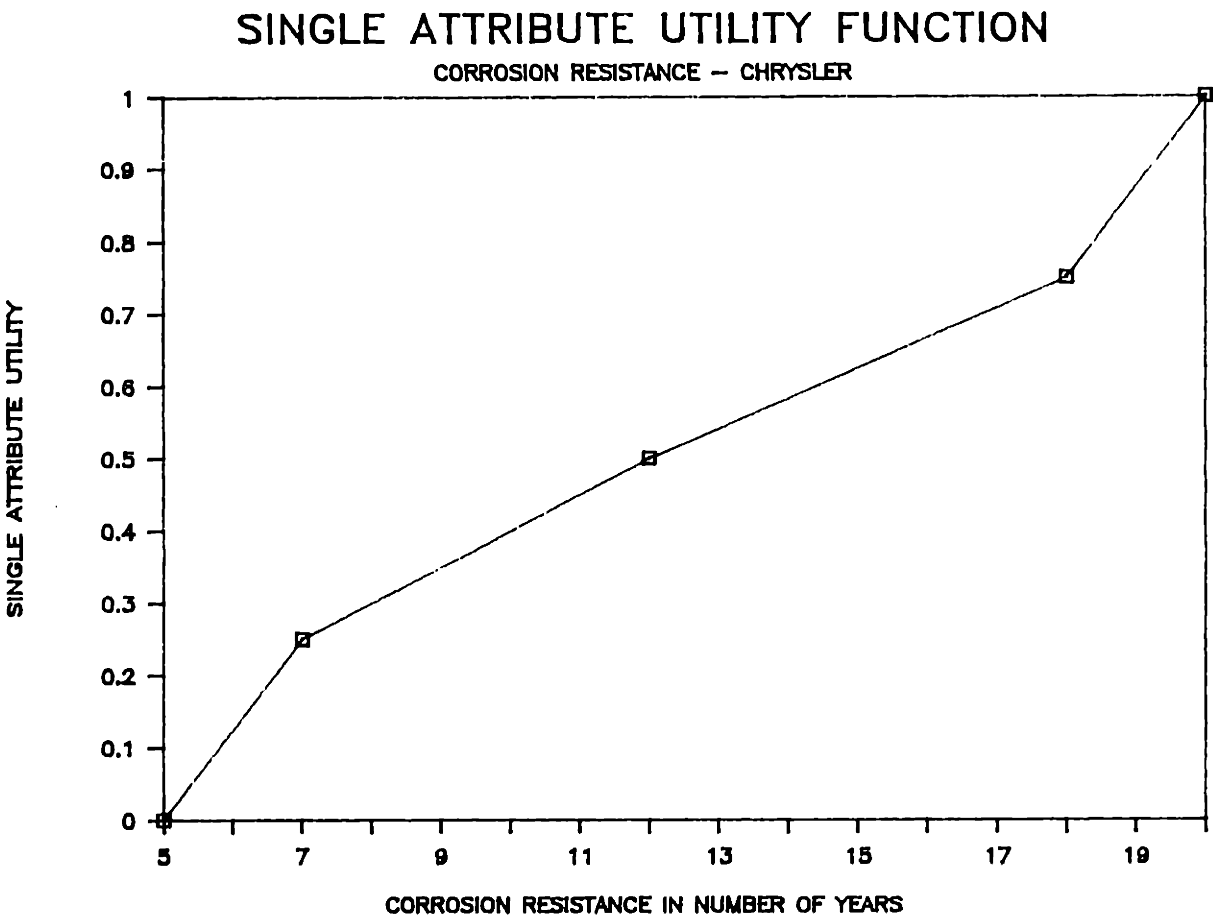
SINGLE ATTRIBUTE UTILITY FUNCTION

WEIGHT — CHRYSLER

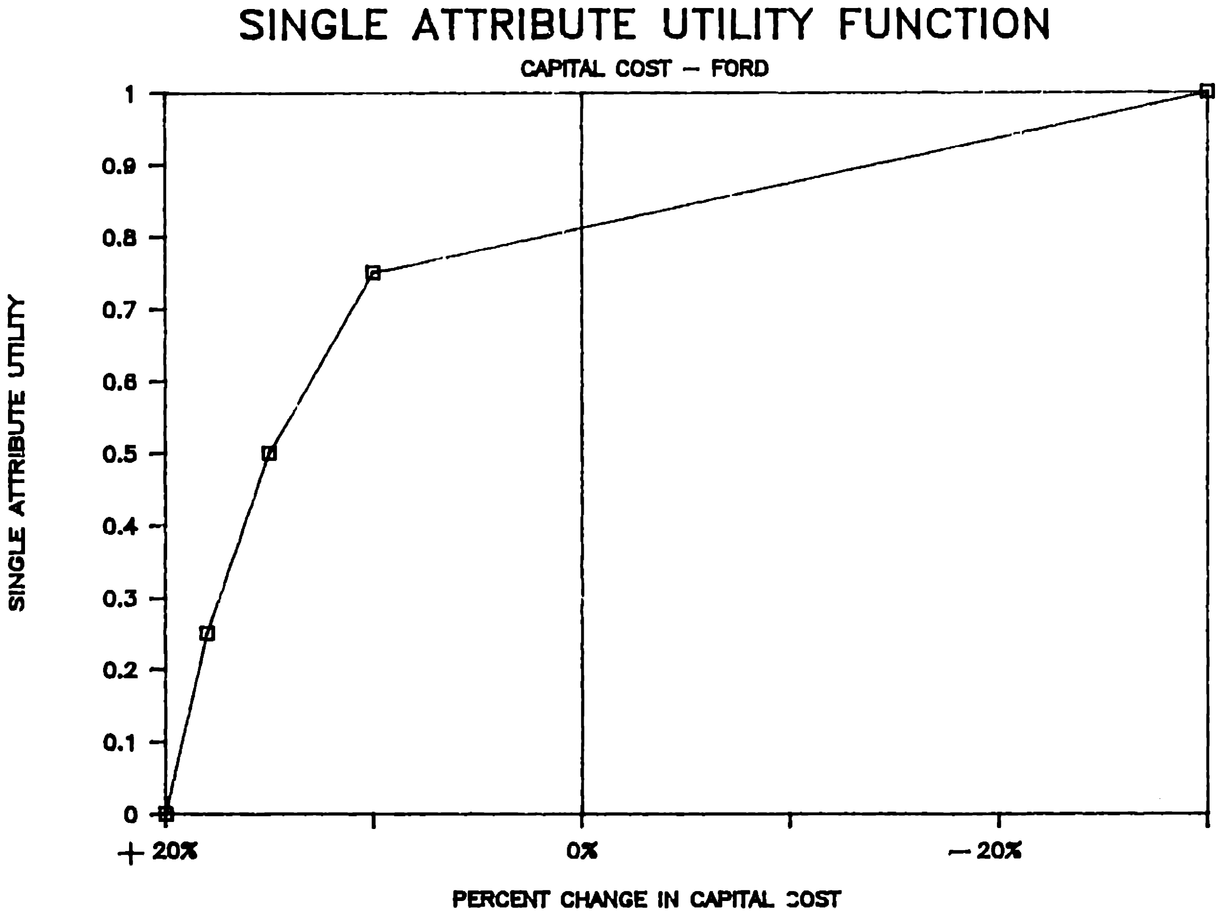


SINGLE ATTRIBUTE UTILITY FUNCTION

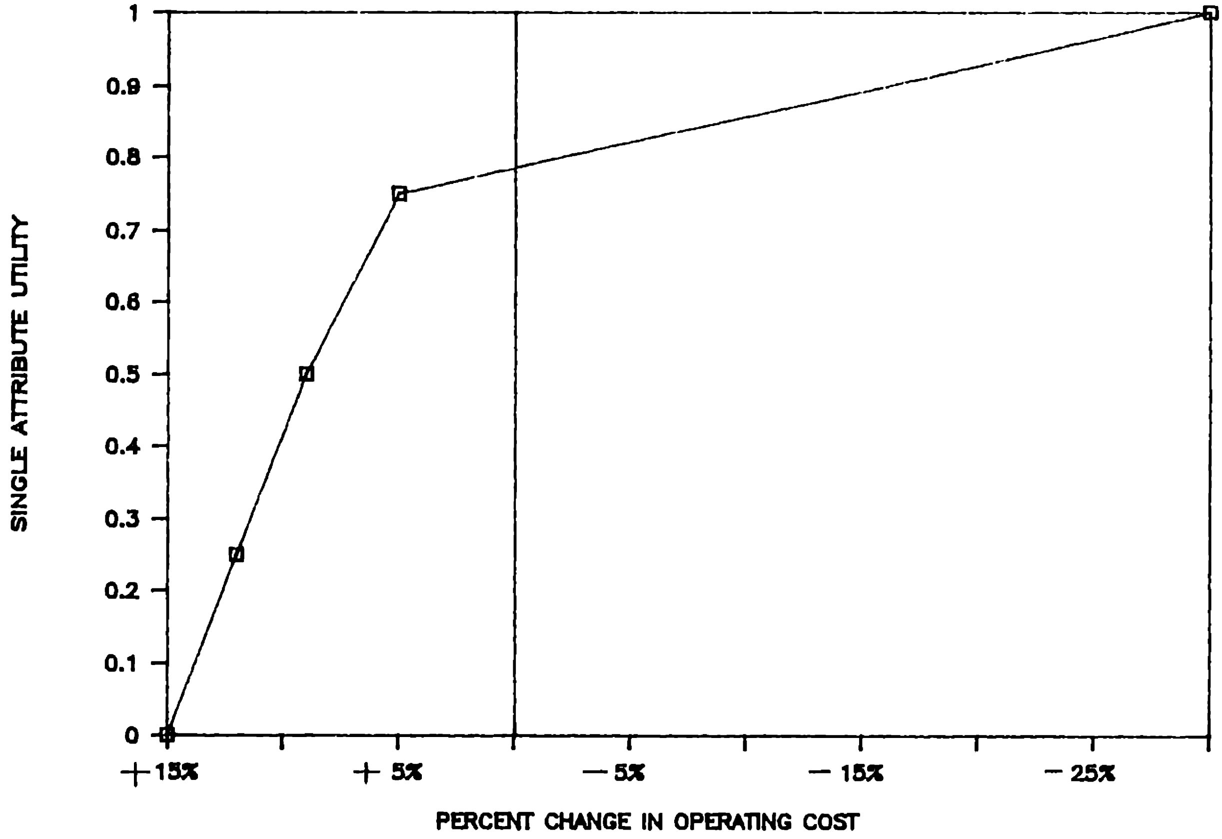
DESIGN FLEXIBILITY — CHRYSLER


SINGLE ATTRIBUTE UTILITY FUNCTION

CORROSION RESISTANCE – CHRYSLER

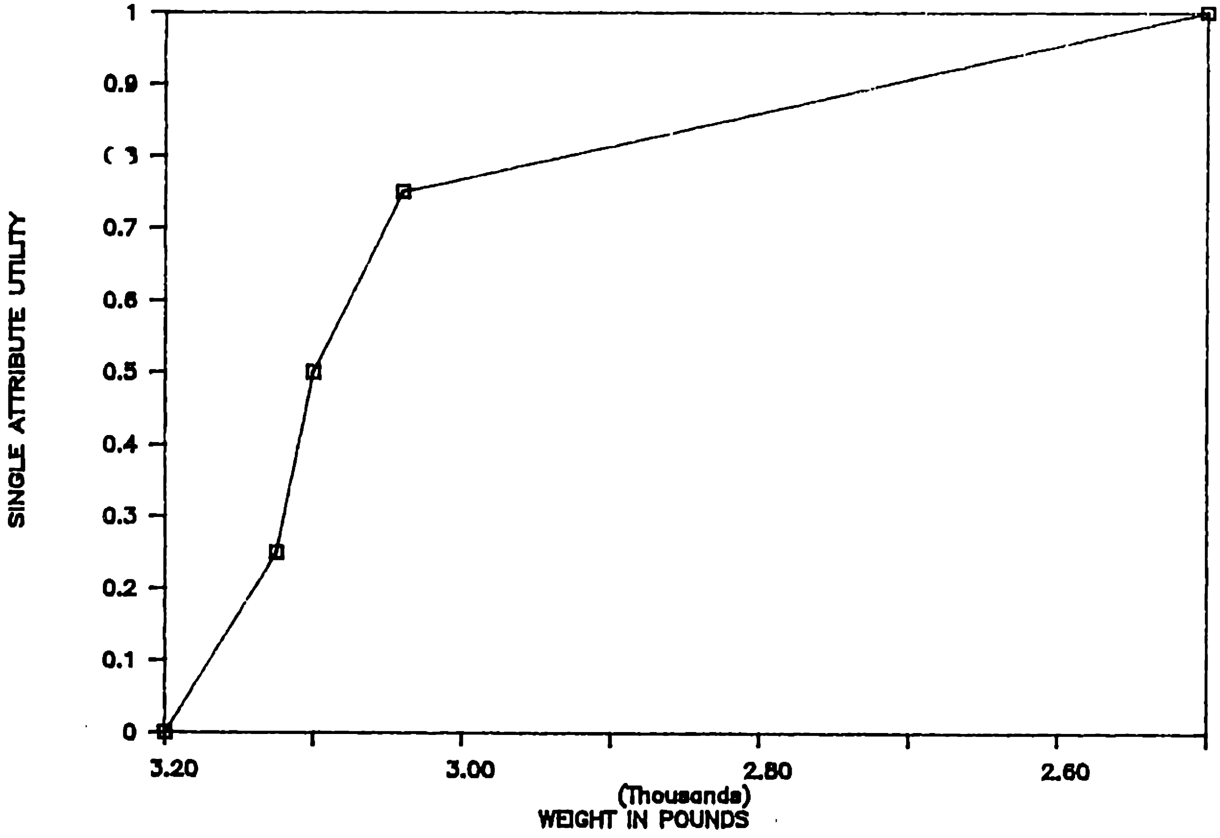

SINGLE ATTRIBUTE UTILITY FUNCTION

CAPITAL COST – FORD



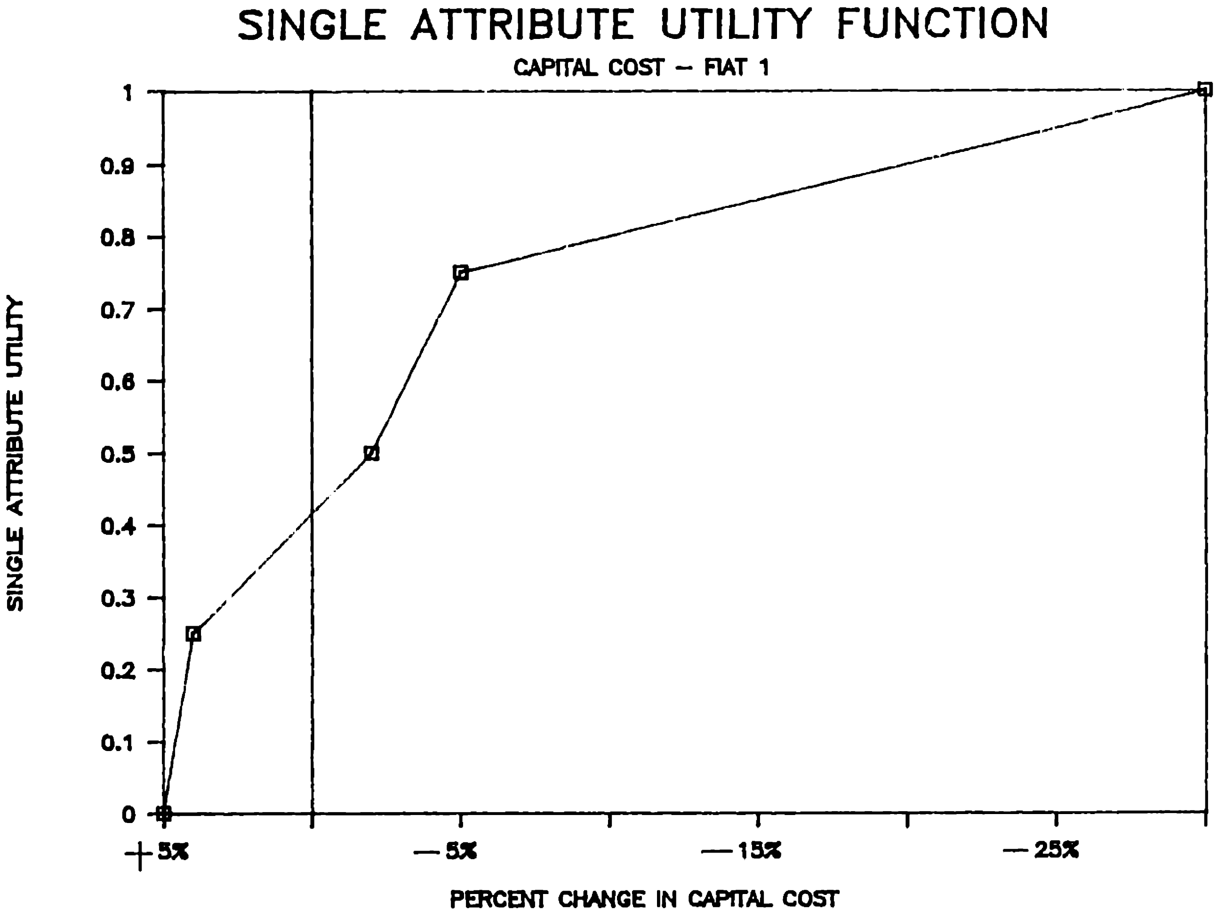
SINGLE ATTRIBUTE UTILITY FUNCTION

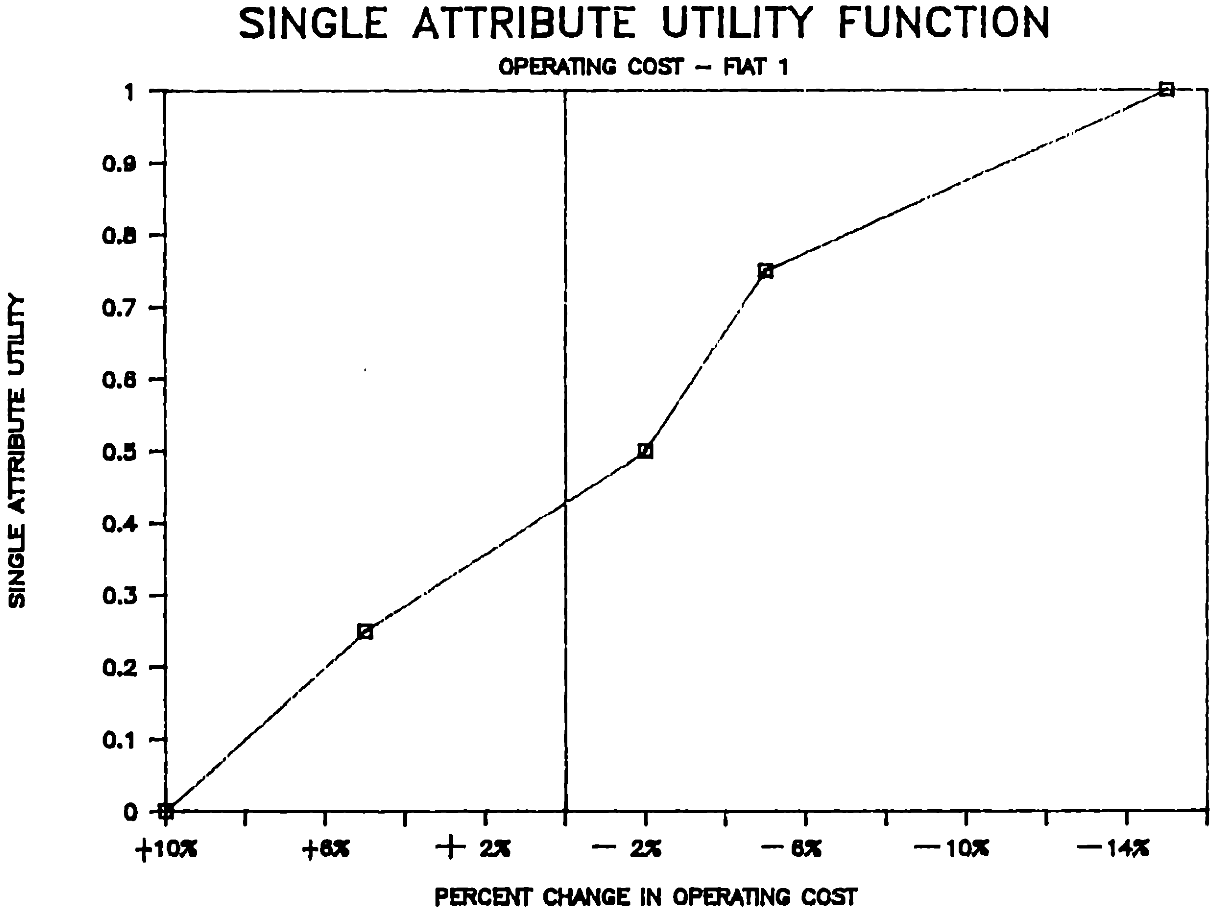
OPERATING COST — FORD

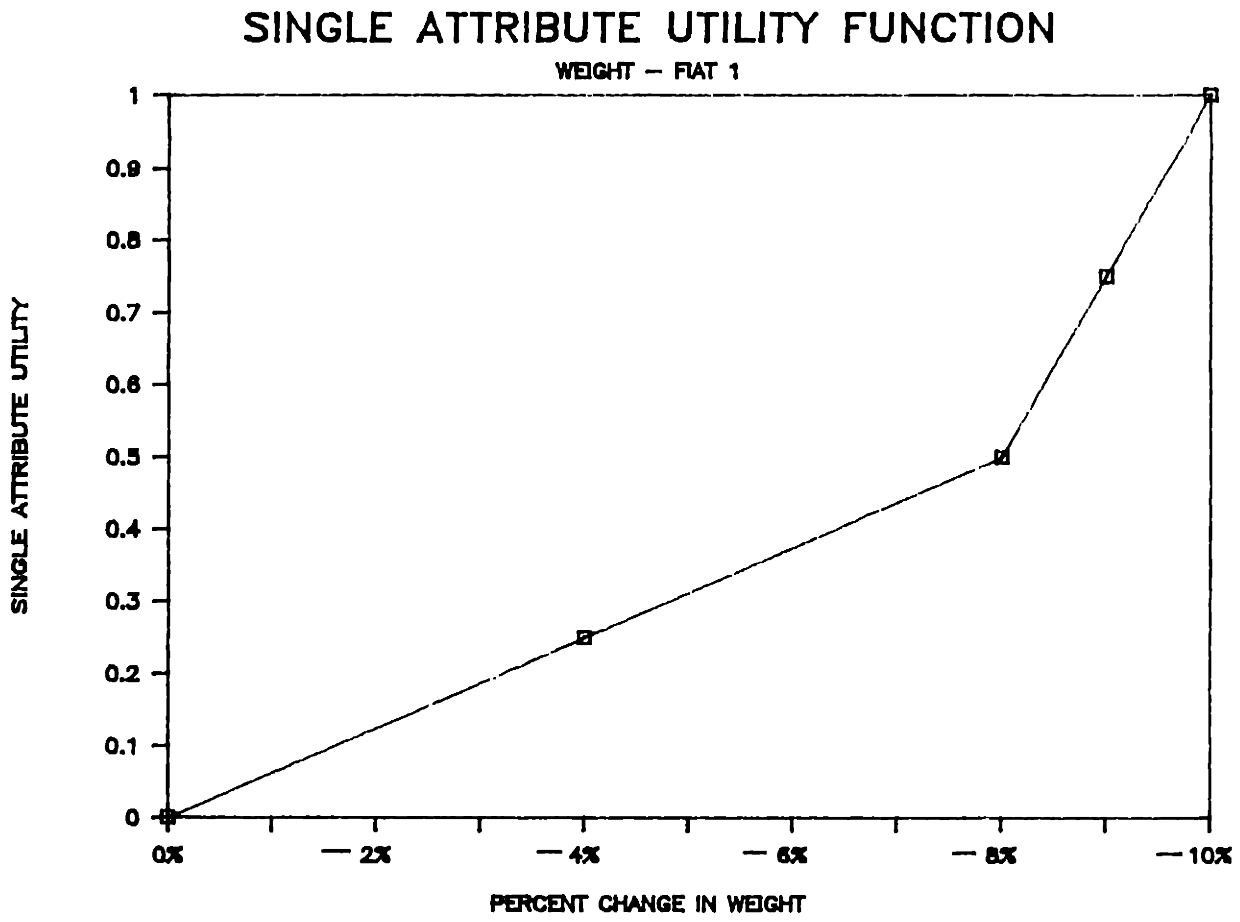


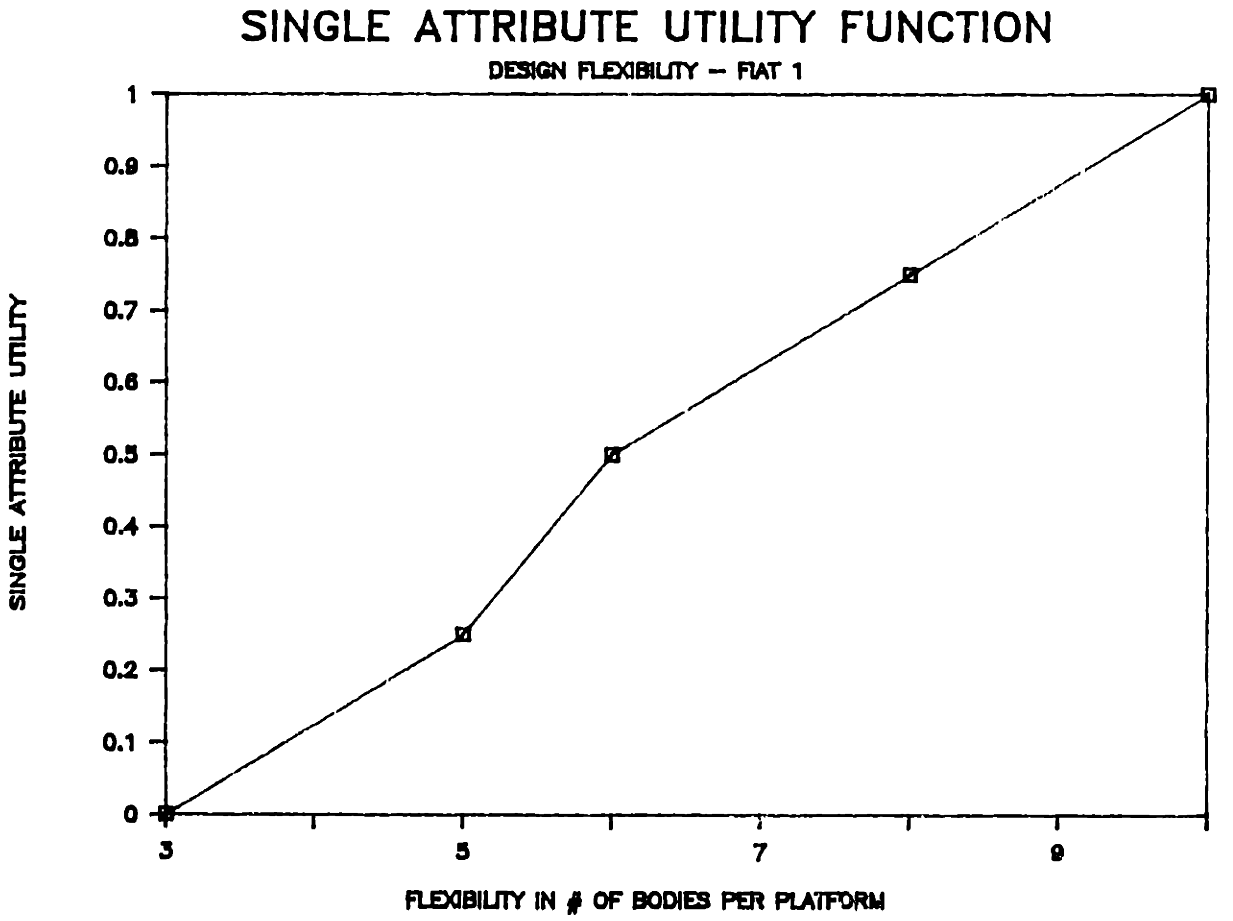
SINGLE ATTRIBUTE UTILITY FUNCTION

WEIGHT — FORD


SINGLE ATTRIBUTE UTILITY FUNCTION
CAPITAL COST – FIAT 1
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
+5%
−5%
−15%
−25%
PERCENT CHANGE IN CAPITAL COST

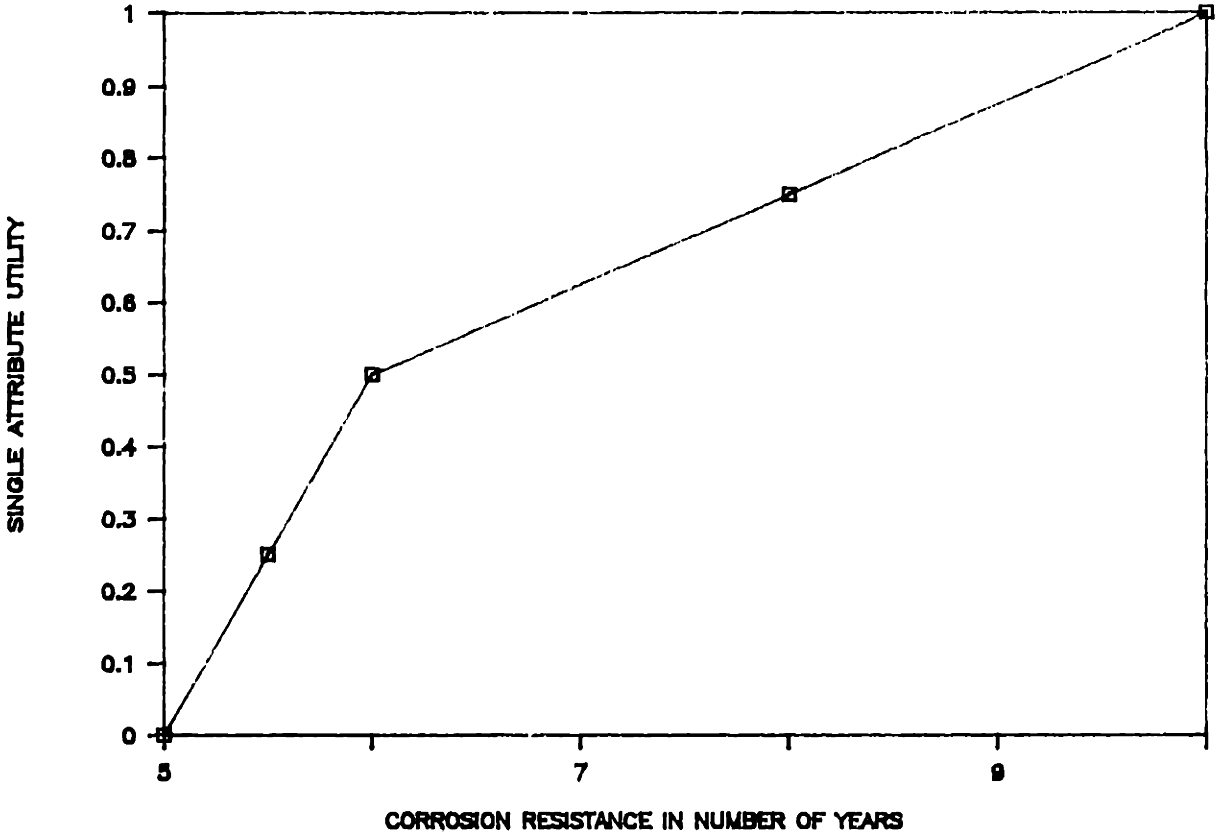

SINGLE ATTRIBUTE UTILITY FUNCTION
OPERATING COST – FIAT 1
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
+10%
+6%
+ 2%
− 2%
− 6%
−10%
−14%
PERCENT CHANGE IN OPERATING COST

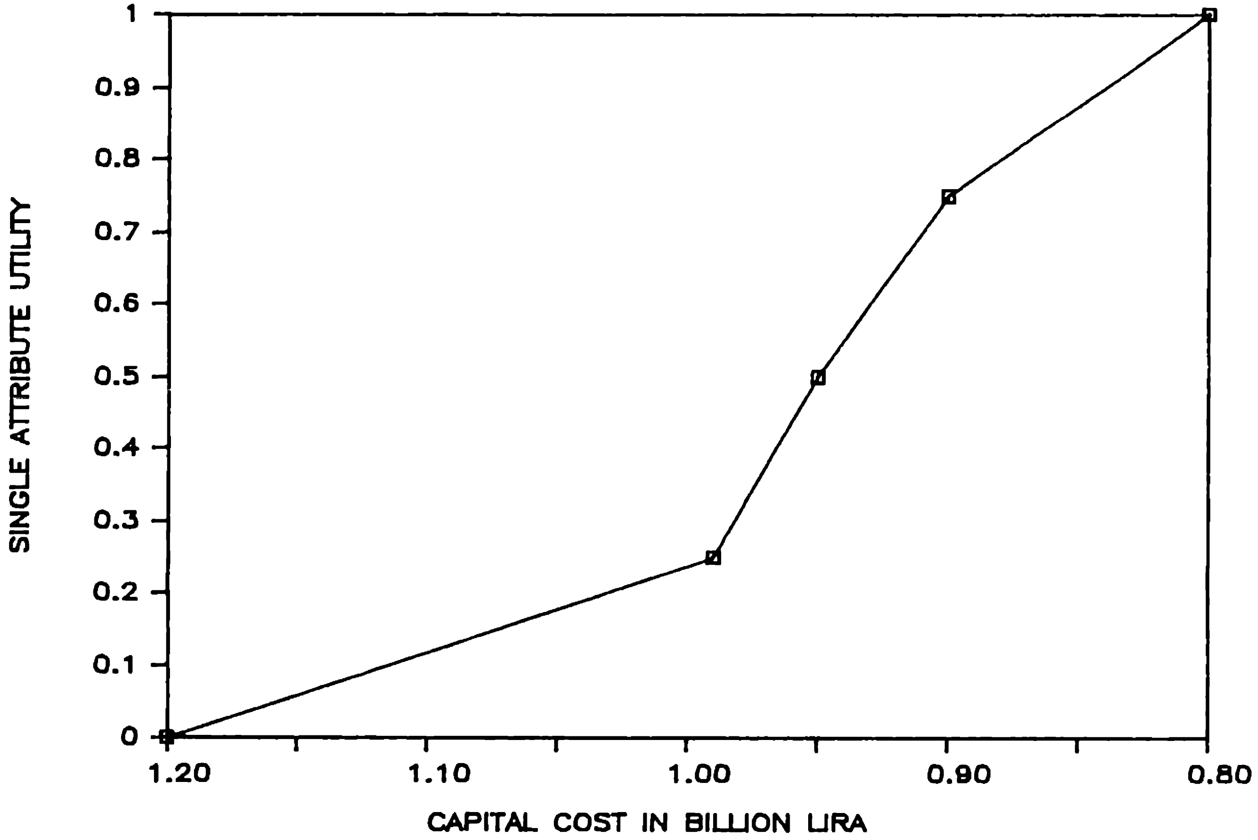

SINGLE ATTRIBUTE UTILITY FUNCTION
WEIGHT — FIAT 1
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0%
— 2%
— 4%
— 6%
— 8%
— 10%
PERCENT CHANGE IN WEIGHT


SINGLE ATTRIBUTE UTILITY FUNCTION
DESIGN FLEXIBILITY — FIAT 1
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
5
7
9
FLEXIBILITY IN # OF BODIES PER PLATFORM

SINGLE ATTRIBUTE UTILITY FUNCTION

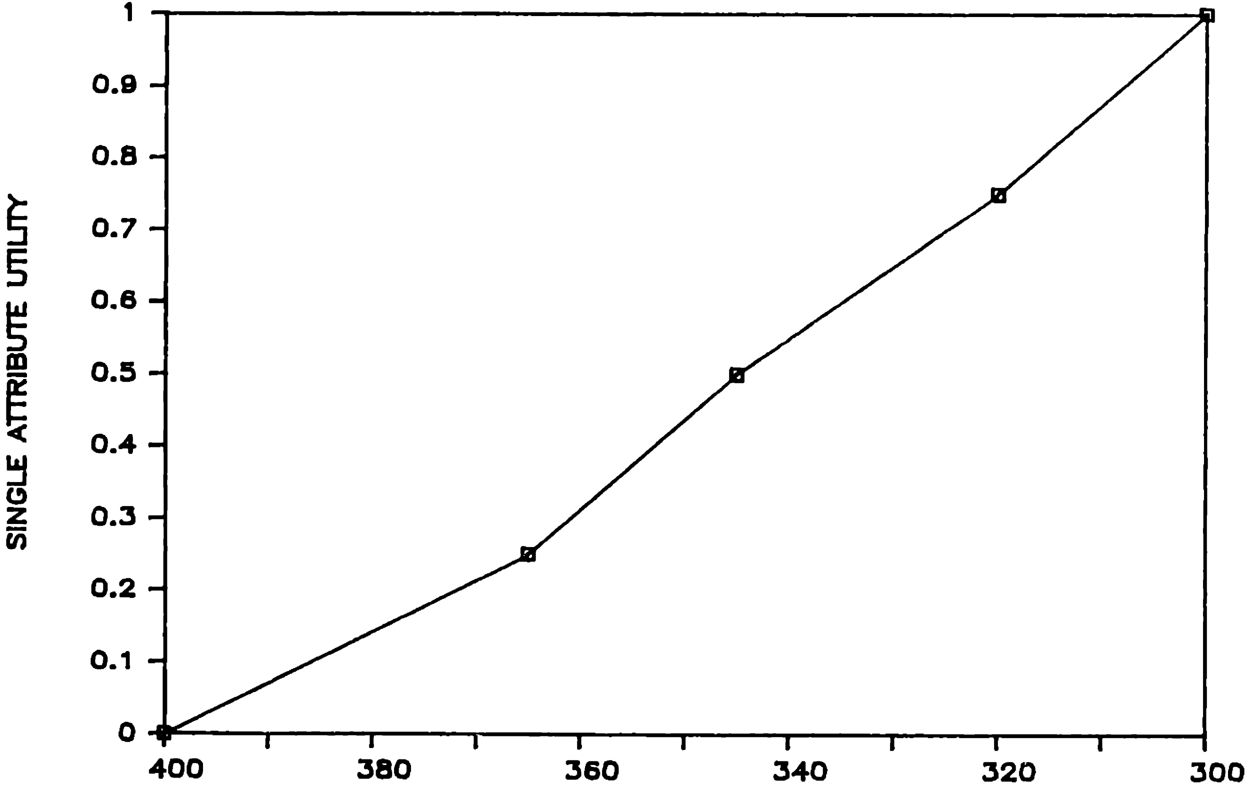
CORROSION RESISTANCE – FIAT 1





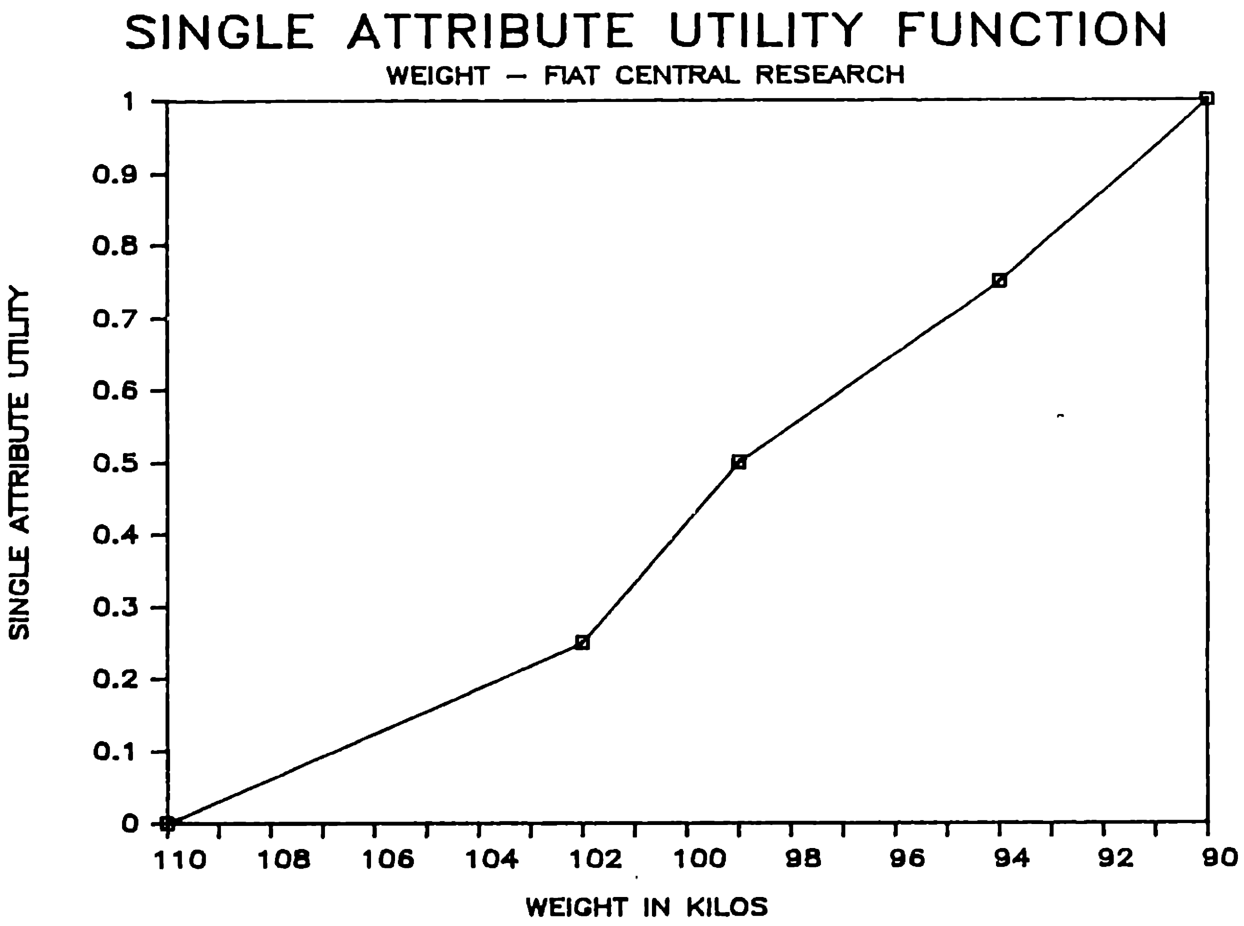
SINGLE ATTRIBUTE UTILITY FUNCTION

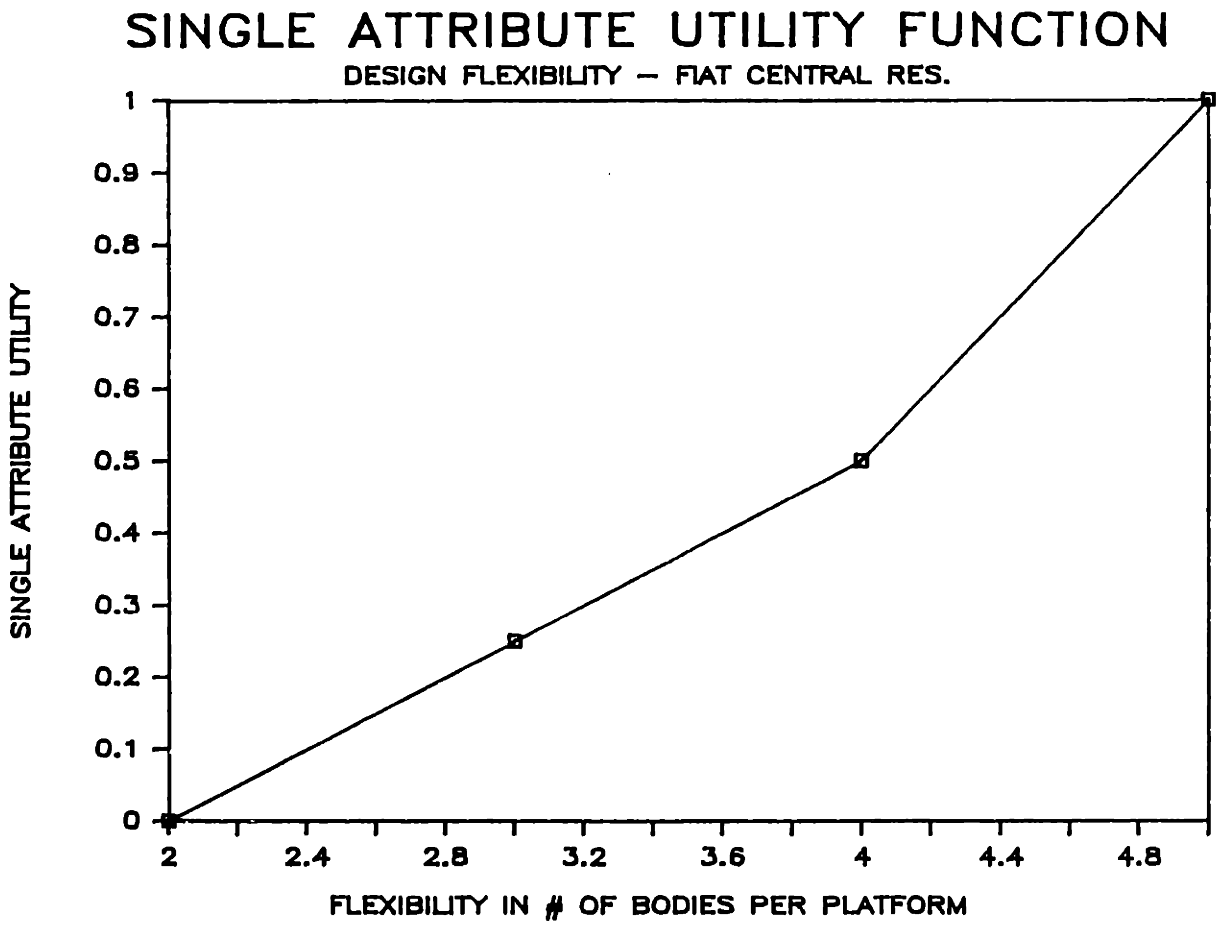
CAPITAL COST – FIAT CENTRAL RESEARCH

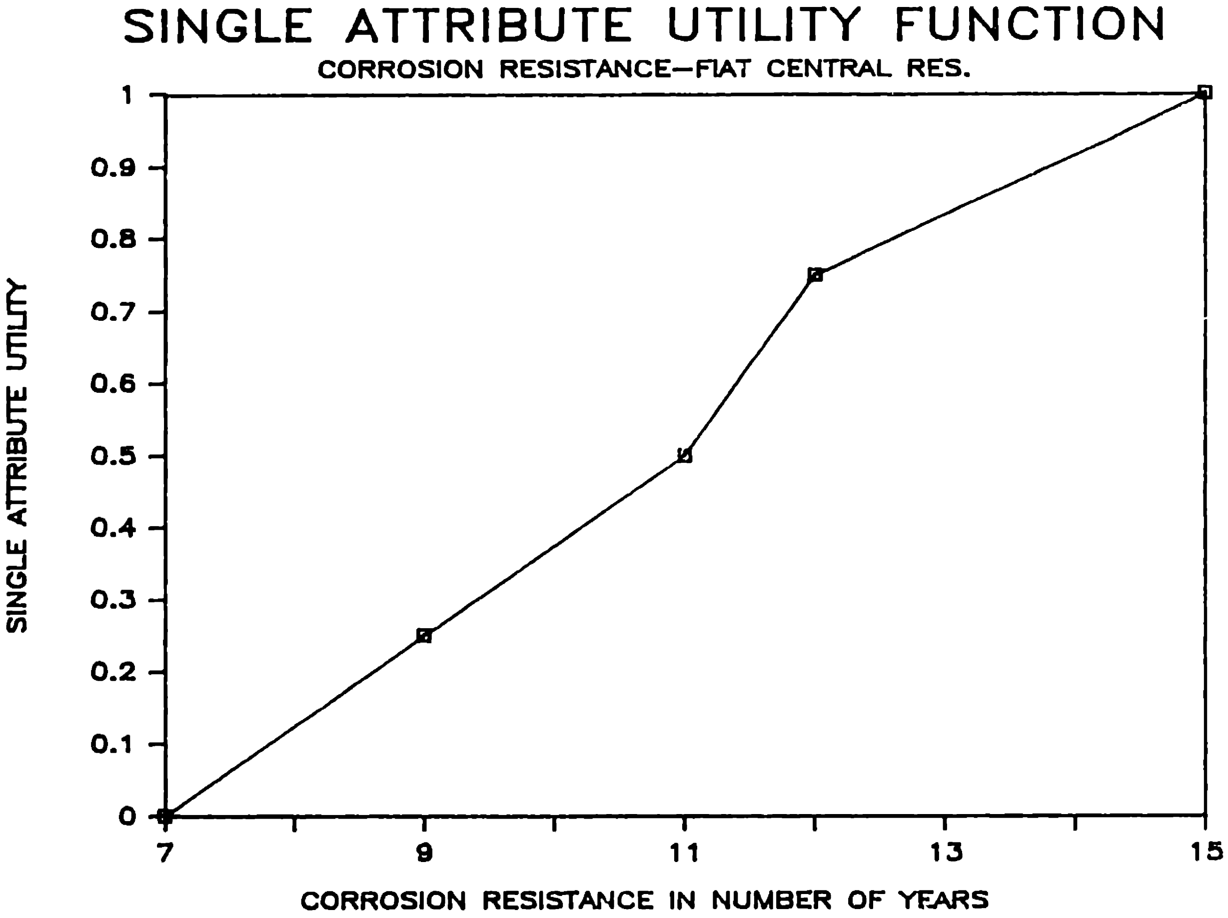


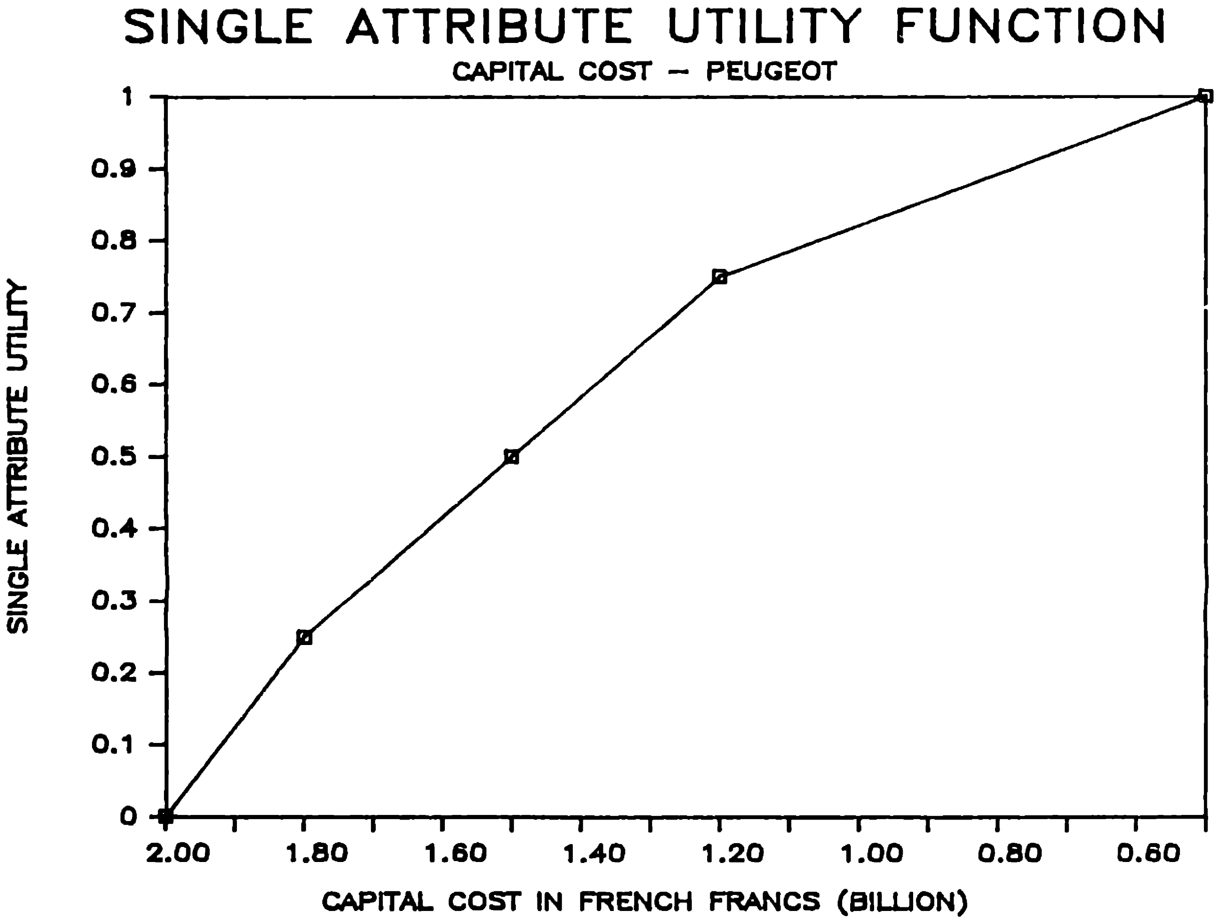
SINGLE ATTRIBUTE UTILITY FUNCTION

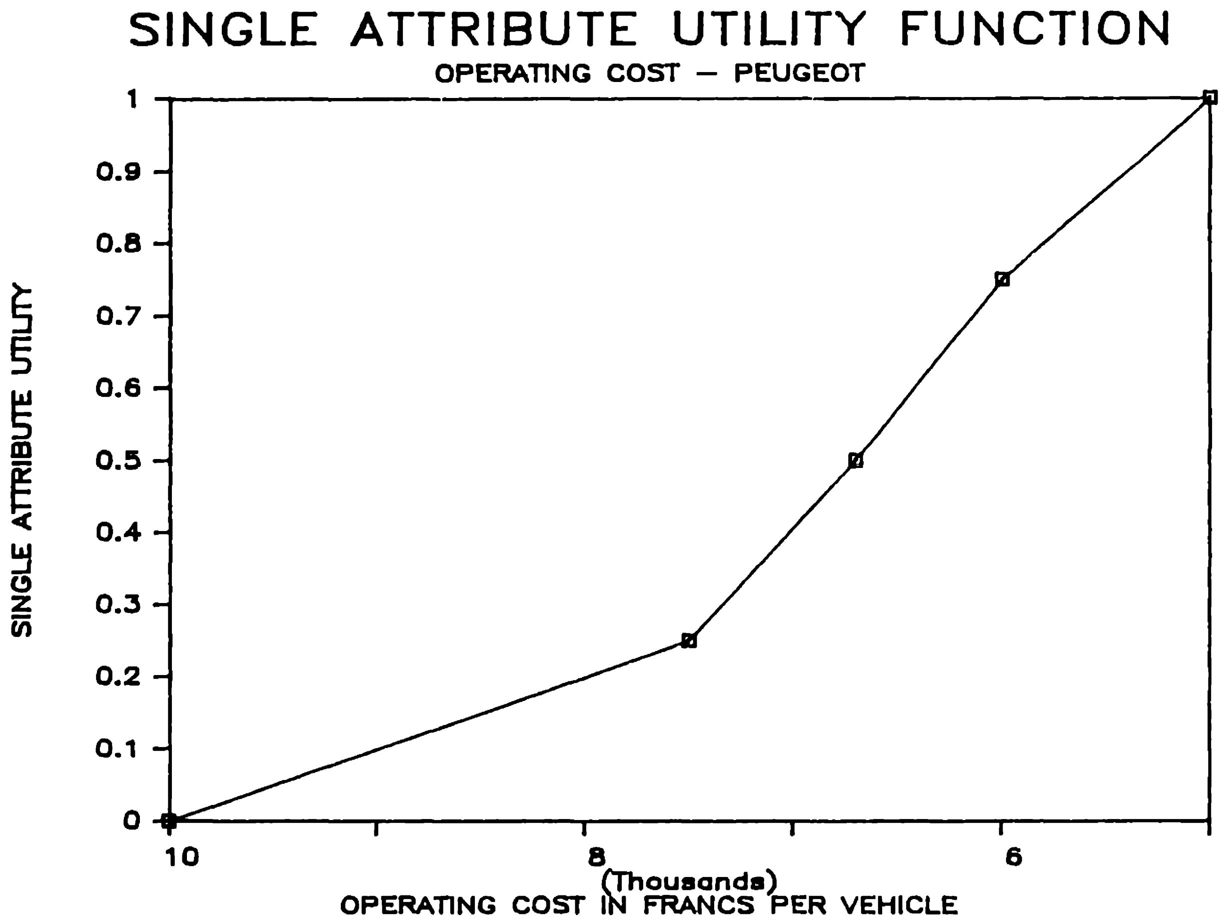
OPERATING COST – FIAT CENTRAL RESEARCH

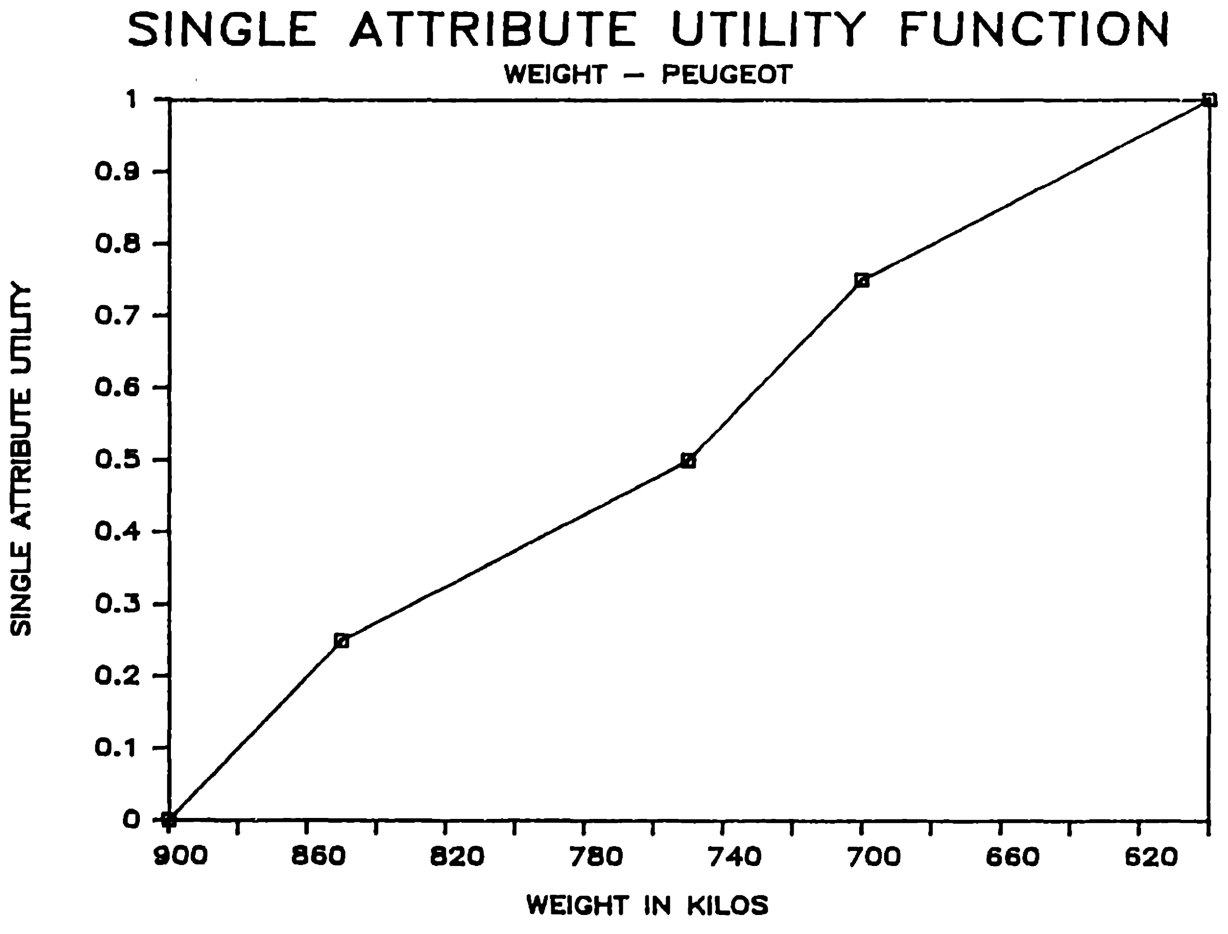

SINGLE ATTRIBUTE UTILITY FUNCTION
WEIGHT – FIAT CENTRAL RESEARCH
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
110
108
106
104
102
100
98
96
94
92
90
WEIGHT IN KILOS

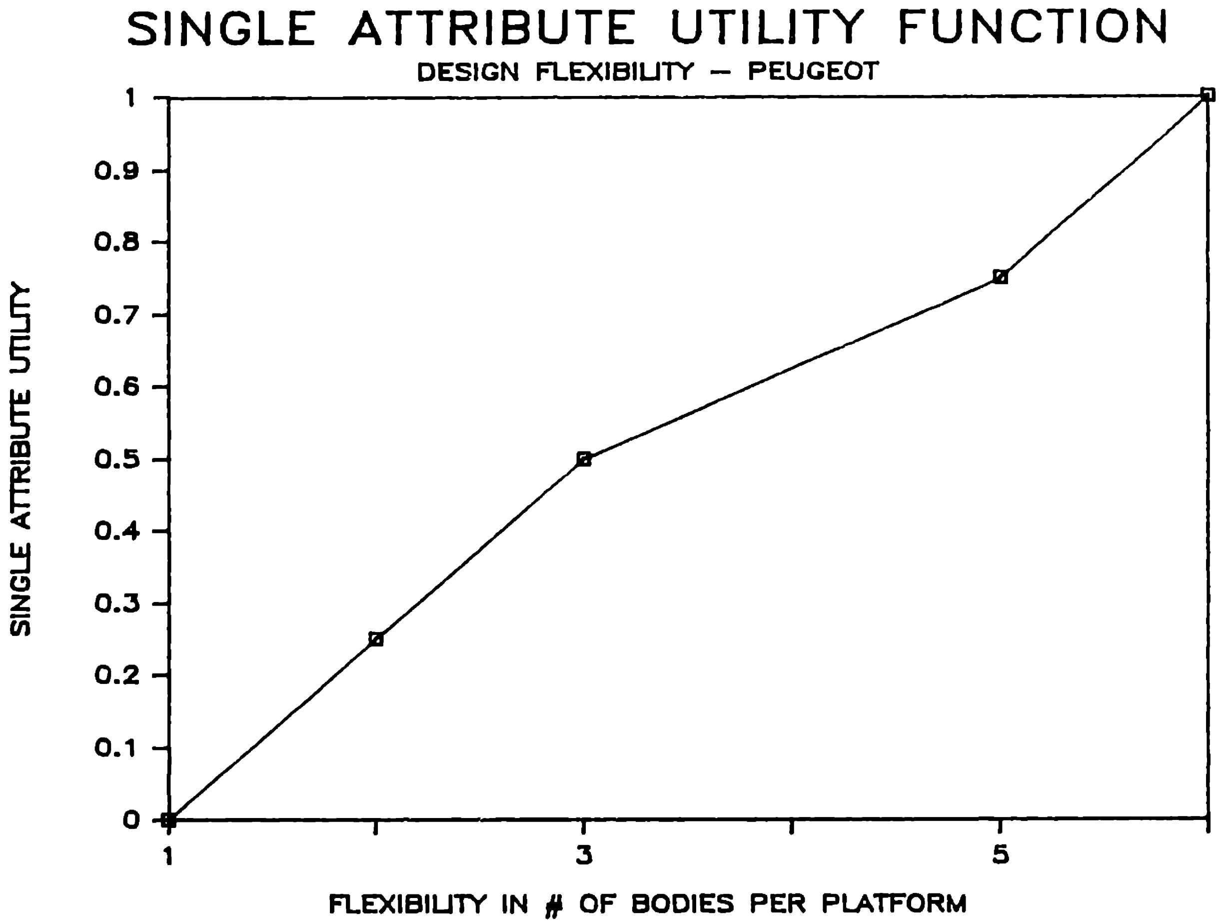

SINGLE ATTRIBUTE UTILITY FUNCTION
DESIGN FLEXIBILITY – FIAT CENTRAL RES.
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
2.4
2.8
3.2
3.6
4
4.4
4.8
FLEXIBILITY IN # OF BODIES PER PLATFORM


SINGLE ATTRIBUTE UTILITY FUNCTION
CORROSION RESISTANCE–FIAT CENTRAL RES.
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
7
9
11
13
15
CORROSION RESISTANCE IN NUMBER OF YEARS

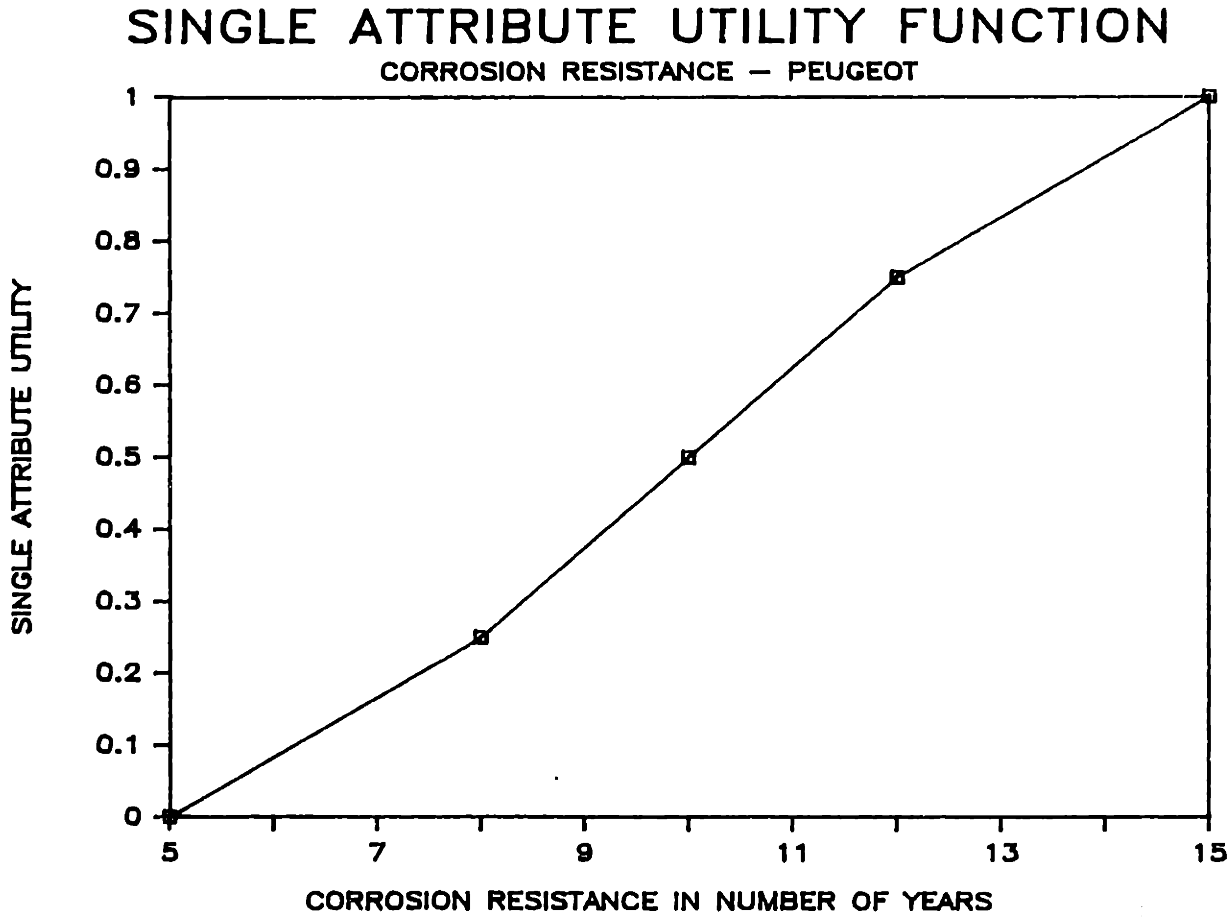

SINGLE ATTRIBUTE UTILITY FUNCTION
CAPITAL COST – PEUGEOT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
CAPITAL COST IN FRENCH FRANCS (BILLION)


SINGLE ATTRIBUTE UTILITY FUNCTION
OPERATING COST – PEUGEOT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
8
6
(Thousands)
OPERATING COST IN FRANCS PER VEHICLE

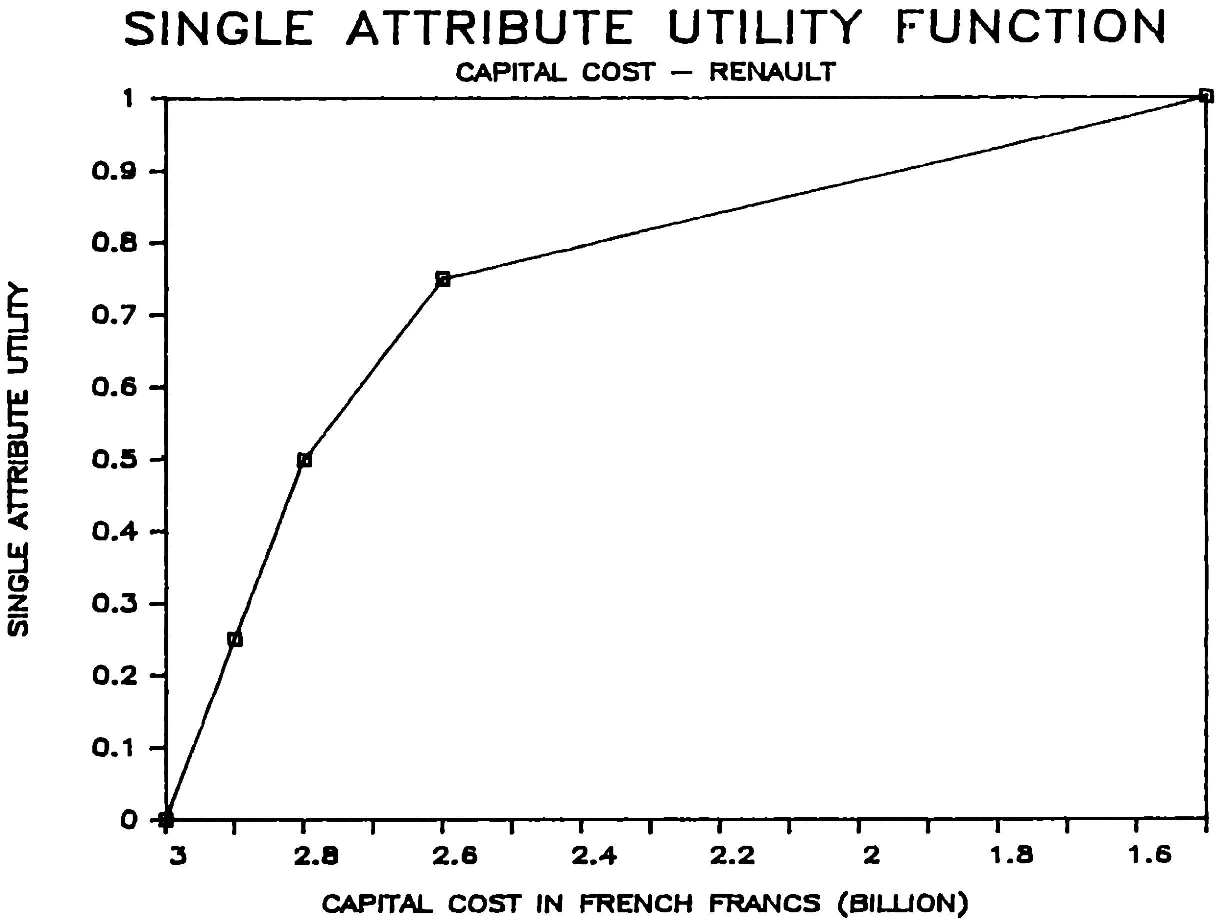

SINGLE ATTRIBUTE UTILITY FUNCTION
WEIGHT – PEUGEOT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
900
860
820
780
740
700
660
620
WEIGHT IN KILOS

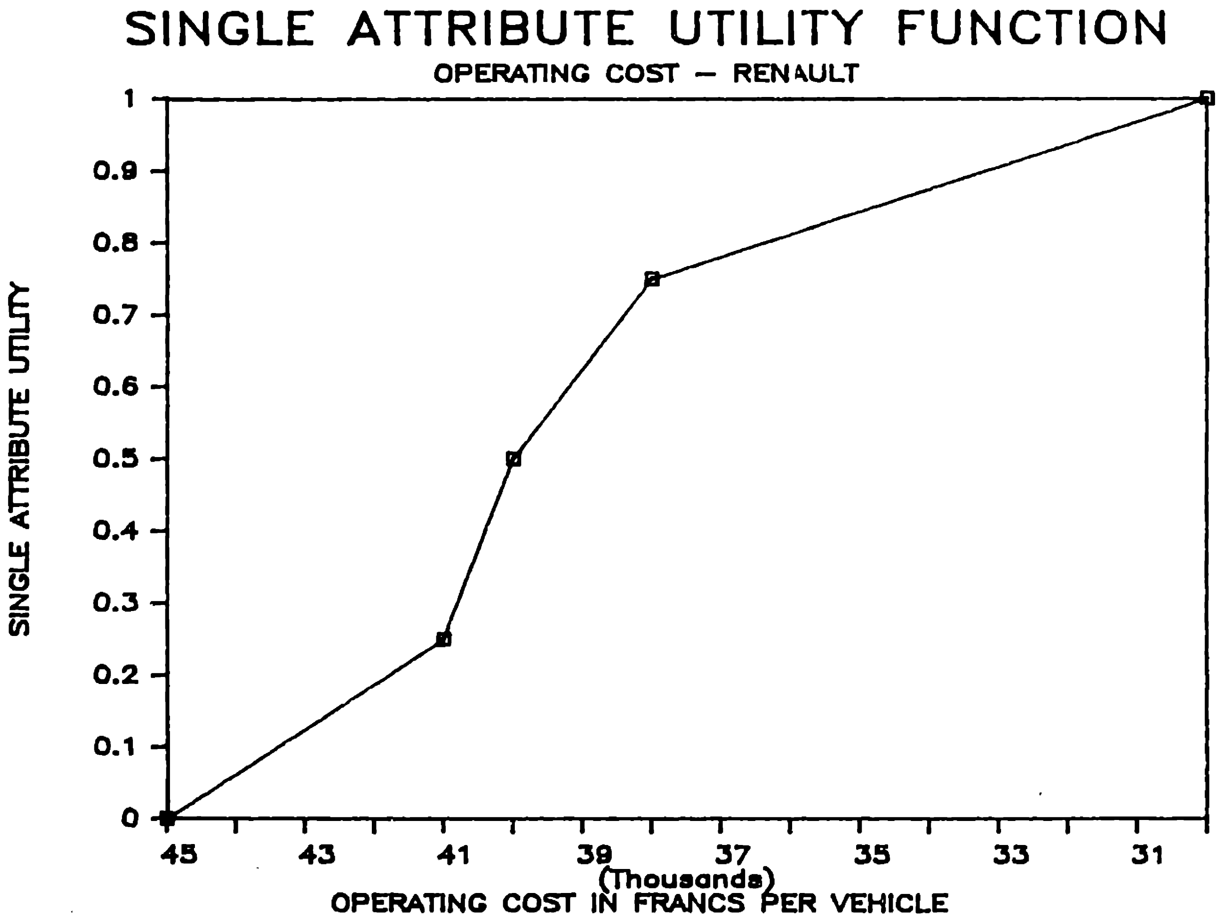


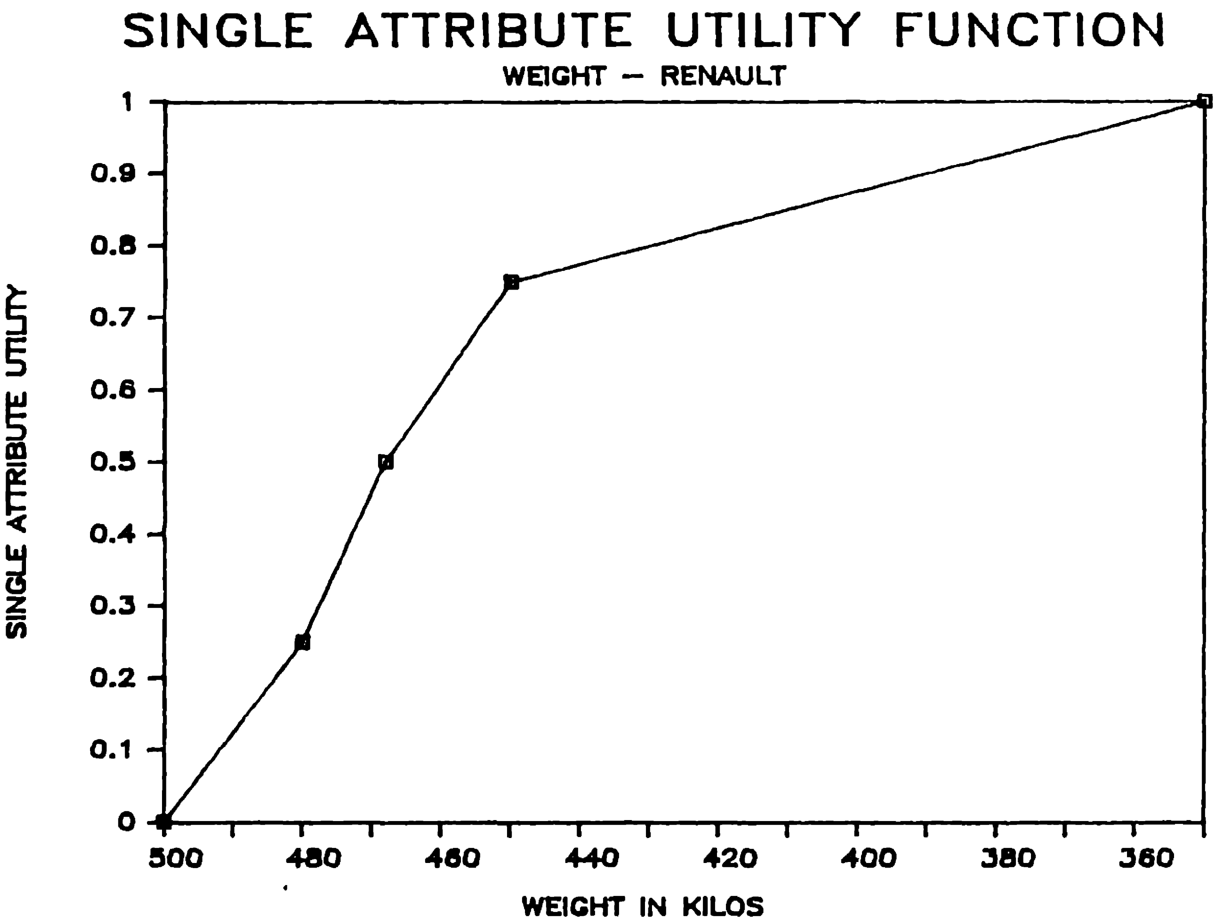
SINGLE ATTRIBUTE UTILITY FUNCTION
DESIGN FLEXIBILITY – PEUGEOT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
3
5
FLEXIBILITY IN # OF BODIES PER PLATFORM



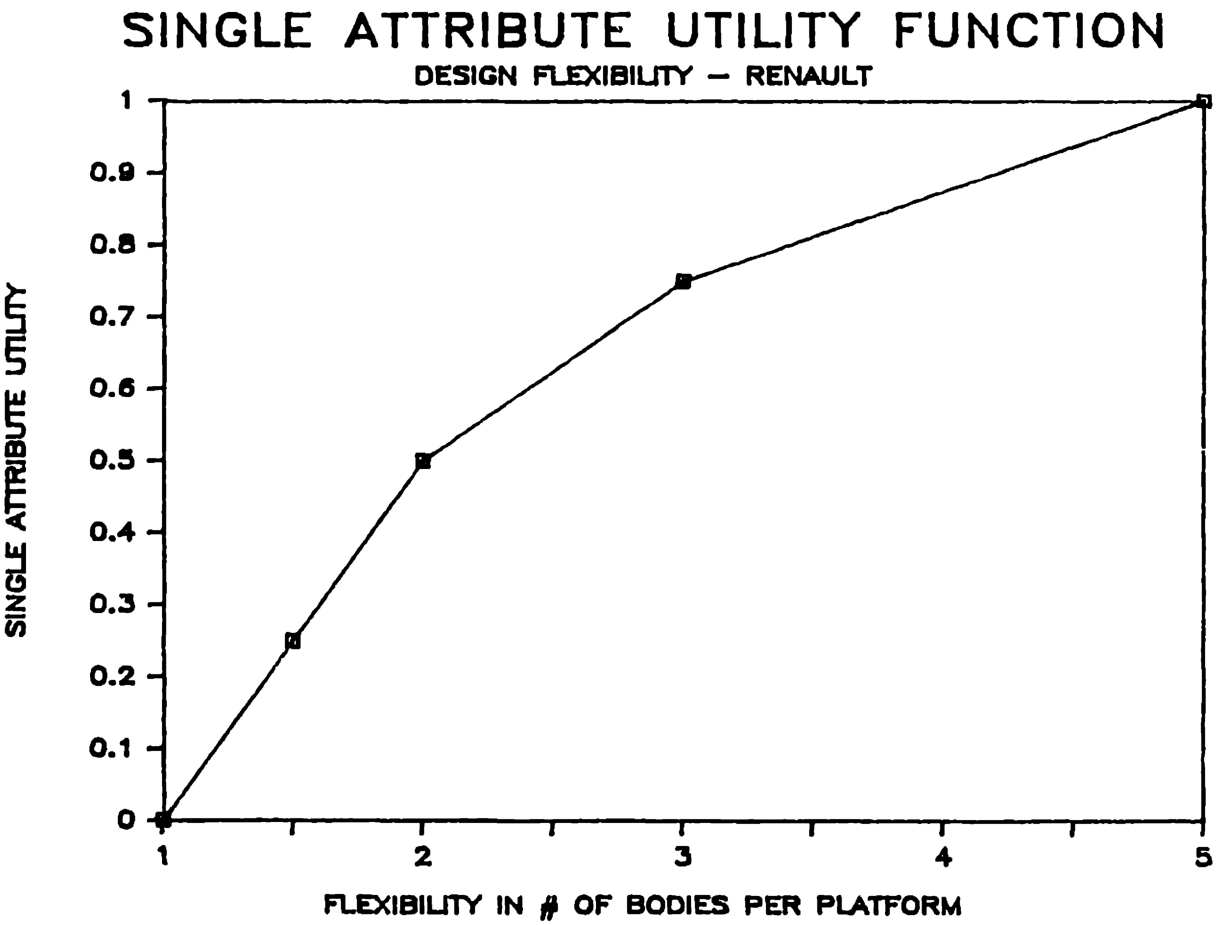
SINGLE ATTRIBUTE UTILITY FUNCTION
CORROSION RESISTANCE – PEUGEOT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7
9
11
13
15
CORROSION RESISTANCE IN NUMBER OF YEARS


SINGLE ATTRIBUTE UTILITY FUNCTION
CAPITAL COST — RENAULT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
2.8
2.6
2.4
2.2
2
1.8
1.6
CAPITAL COST IN FRENCH FRANCS (BILLION)

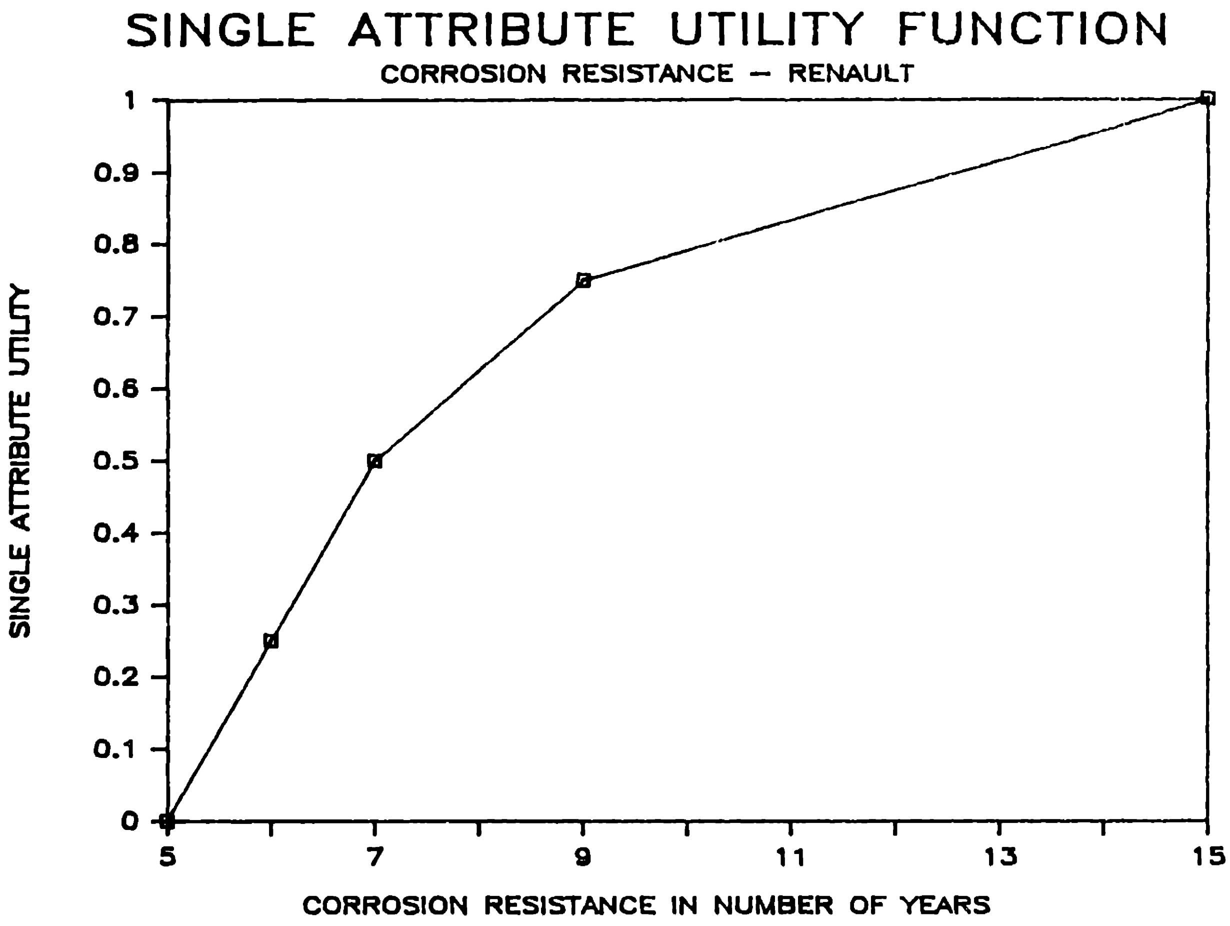

SINGLE ATTRIBUTE UTILITY FUNCTION
OPERATING COST — RENAULT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
45
43
41
39
37
35
33
31
(Thousands)
OPERATING COST IN FRANCS PER VEHICLE


SINGLE ATTRIBUTE UTILITY FUNCTION

WEIGHT – RENAULT


SINGLE ATTRIBUTE UTILITY FUNCTION

DESIGN FLEXIBILITY – RENAULT


SINGLE ATTRIBUTE UTILITY FUNCTION
CORROSION RESISTANCE – RENAULT
SINGLE ATTRIBUTE UTILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
7
9
11
13
15
CORROSION RESISTANCE IN NUMBER OF YEARS

APPENDIX D - COMPUTER SURVEY OUTPUT

FIAT "ASSESS" SURVEY OUTPUT

```
UTILITY FOR ATTRIBUTE 1 [investimento]


- investimento - utility

- 800 -- 1.00
- 900 -- 0.75
- 950 -- 0.50
- 990 -- 0.25
- 1200 -- 0.00


UTILITY FOR ATTRIBUTE 2 [variable]


- variable - utility

- 300 -- 1.00
- 320 -- 0.75
- 345 -- 0.50
- 365 -- 0.25
- 400 -- 0.00


UTILITY FOR ATTRIBUTE 3 [peso]


- peso - utility

- 90 -- 1.00
- 94 -- 0.75
- 99 -- 0.50
- 102 -- 0.25
- 110 -- 0.00
```

```
UTILITY FOR ATTRIBUTE 4 [flessibilita]


- flessibilita - utility

- 2 -- 0.00
- 3 -- 0.25
- 4 -- 0.50
- 5 -- 1.00

UTILITY FOR ATTRIBUTE 5 [corrosione]


- corrosione - utility

- 7 -- 0.00
- 9 -- 0.25
- 11 -- 0.50
- 12 -- 0.75
- 15 -- 1.00


SCALING COEFFICIENTS:


attribute [investimento]: k(1) = 0.15

attribute [variable]: k(2) = 0.15

attribute [peso]: k(3) = 0.05

attribute [flessibilita]: k(4) = 0.90

attribute [corrosione]: k(5) = 0.90

Utility scaling factor (K) = -0.992100
```

PEUGEOT "ASSESS" SURVEY OUTPUT

```
UTILITY FOR ATTRIBUTE 1 [investissement]


- investissement - utility

- 500 -- 1.00
- 1200 -- 0.75
- 1500 -- 0.50
- 1800 -- 0.25
- 2000 -- 0.00


UTILITY FOR ATTRIBUTE 2 [fabrication]


- fabrication - utility

- 5000 -- 1.00
- 6000 -- 0.75
- 6700 -- 0.50
- 7500 -- 0.25
- 10000 -- 0.00


UTILITY FOR ATTRIBUTE 3 [poids]


- poids - utility

- 600 -- 1.00
- 700 -- 0.75
- 750 -- 0.50
- 850 -- 0.25
- 900 -- 0.00
```

```
UTILITY FOR ATTRIBUTE 4 [flexibilite]


- flexibilite - utility

- 1 -- 0.00
- 2 -- 0.25
- 3 -- 0.50
- 5 -- 0.75
- 6 -- 1.00

UTILITY FOR ATTRIBUTE 5 [corrosion]


- corrosion - utility

- 5 -- 0.00
- 8 -- 0.25
- 10 -- 0.50
- 12 -- 0.75
- 15 -- 1.00


SCALING COEFFICIENTS:


attribute [investissement]: k(1) = 0.30

attribute [fabrication]: k(2) = 0.35

attribute [poids]: k(3) = 0.40

attribute [flexibilite]: k(4) = 0.05

attribute [corrosion]: k(5) = 0.45

Utility scaling factor (K) = -0.738428
```

APPENDIX E - SPREADSHEET RESULTS

CHRYSLER

The following tables are sections of the spreadsheet developed and used to analyze the results. In the first column, the name of the design alternative is entered. The next five (or three in the case of Ford) column headings are the names of the attributes relevant to the decision maker. In the first row of each attribute column are entered the estimated attribute levels for each alternative design. For example, Capital Cost of 525 for the steel uni-body design for Chrysler in the first table. Directly below each attribute level entry, the single attribute utility for that attribute level is indicated (0.15 in the same column), derived by the model. In the final column is the overall utility value calculated by the spreadsheet model based on the input attribute levels for each alternative.

	INPUT ATTRIBUTE LEVELS & RESULTING SINGLE ATTRIBUTE UTILITY LEVELS					OVERALL UTILITY FOR
DESIGN	CAPITAL COST	PIECE COST	WEIGHT	FLEX.	CORR. RESIST.	CHRYSLER
STEEL UNI-BODY	525	625	550	3	7	
	0.15	0.75	0.34	0.25	0.25	0.6234
ALUMINUM INTENSIVE VEHICLE	364	580	385	5	12	
	0.36	1.00	1.00	0.42	0.50	0.9115
STEEL FRAME; PC SKIN	404	446	475	5	10	
	0.25	1.00	0.58	0.42	0.40	0.8120
STEEL & PC FRAME; PC SKIN	318	398	350	8	15	
	0.51	1.00	1.00	0.60	0.63	0.9429

FORD

Design	Input Attribute Levels & Resulting Single Attribute Utility Levels			
	Capital Cost	Variable Cost	Weight	Utility for Ford
Steel Uni-Body	0	0	3000	
	0.87	0.83	0.80	0.9857
Steel Frame; PC Skin	-0.05	0.011	2957	
	0.91	0.82	0.82	0.9882
PC Frame; PC Skin	-0.01	0.15	2834	
	0.88	0.00	0.87	0.9559

FIAT 1

Design	Input Attribute Levels & Resulting Single Attribute Utility Levels					Overall Utility for
	Capital Cost	Oper. Cost	Weight	Flex.	Corr. Resist.	Fiat; Odone
Steel Uni-Body	0	0	0	3	5	
	0.50	0.50	0.00	0.00	0.00	0.4824
Steel Frame; PC Skin	-0.3	-0.15	-0.05	10	10	
	1.00	1.00	0.29	1.00	1.00	0.9897
Steel Frame; Steel & PC Skin	-0.1	0.05	-0.025	10	8	
	0.79	0.21	0.14	1.00	0.78	0.8556

FIAT 2

	INPUT ATTRIBUTE LEVELS & RESULTING SINGLE ATTRIBUTE UTILITY LEVELS					OVERALL UTILITY FOR
DESIGN	CAPITAL COST	PIECE COST	WEIGHT	FLEX.	CORR. RESIST.	FIAT; DI CARLO
STEEL UNI-BODY	0	0	0	2	4.5	
	0.88	0.93	0.38	0.25	0.00	0.9802
STEEL FRAME; PC SKIN	-0.1	0.6	-0.3	8	8	
	1.00	0.00	1.00	0.89	0.50	0.9704
STEEL FRAME; STEEL & PC SKIN	-0.1	0.5	-0.2	7	7	
	1.00	0.25	0.88	0.83	0.25	0.9757

PEUGEOT

	INPUT ATTRIBUTE LEVELS & RESULTING SINGLE ATTRIBUTE UTILITY LEVELS					OVERALL UTILITY FOR
DESIGN	CAPITAL COST	OPER. COST	WEIGHT	FLEX.	CORR. RESIST.	PEUGEOT
STEEL UNI-BODY	2000	5000	900	1	5	
	0.00	1.00	0.00	0.00	0.00	0.3500
STEEL FRAME, PC SKIN	1600	10000	600	6	15	
	0.42	0.00	1.00	1.00	1.00	0.7973
STEEL FRAME, STEEL & PC SKIN	2000	7000	800	3	5	
	0.00	0.41	0.38	0.50	0.00	0.2963

RENAULT

	INPUT ATTRIBUTE LEVELS & RESULTING SINGLE ATTRIBUTE UTILITY LEVELS					OVERALL UTILITY FOR
DESIGN	CAPITAL COST	OPER. COST	WEIGHT	FLEX.	CORR. RESIST.	RENAULT; COSTES
STEEL UNI-BODY	3	30	500	1	5	
	0.00	1.00	0.00	0.00	0.00	0.9000
STEEL FRAME; PC SKIN	2	40	425	5	15	
	0.89	0.50	0.81	1.00	1.00	0.9082
STEEL & PC FRAME; PC SKIN	1.5	45	350	5	15	
	1.00	0.00	1.00	1.00	1.00	0.8694

APPENDIX F - SPREADSHEET IN ENTIRETY

```
Fiatl;   Odone
S.A.Util.Cap.Cost Oper.CostWeight   Flexib.  Corr.Res.
       0     0.05     0.10     0.00        3        5
    0.25     0.03     0.04    -0.05     4.75      5.5
     0.5     0.00     0.00    -0.08     6.25     6.25
    0.75    -0.06    -0.06    -0.09        8     7.75
       1    -0.30    -0.15    -0.10       10       10

                                                 Kc =          0.4
         Single Attribute Levels as a Function   Ko =          0.7
Input    of Single Attribute Utility             Kw =          0.3
S.A. U   Cap.Cost Oper.CostWeight   Flexib.  Corr.Res.Kf =     0.5
                                                 Kr =         0.55
     0.5        0        0   -0.075     6.25     6.25
                                                 K =       -0.9658
         Single Attribute Utility Levels as a Function
         of Single Attribute Levels
         Cap.Cost Oper.CostWeight   Flexib.  Corr.Res.
Input        -0.2     0.05    -0.09        8        9
Calc.U   0.895833 0.208333     0.75     0.75 0.888888
```

	Input Attribute Levels & Resulting Single Attribute Utility Levels					Overall Utility for
Design	Capital Cost	Oper. Cost	Weight	Flex.	Corr. Resist.	Fiat; Odone
Steel	0	0	0	3	5	
Uni-Body	0.50	0.50	0.00	0.00	0.00	0.48
% of rang	0.14	0.40	0.00	0.00	0.00	
Steel						
Frame;	-0.3	-0.15	-0.05	10	10	
PC Skin	1.00	1.00	0.29	1.00	1.00	0.99
% of rang	1.00	1.00	0.50	1.00	1.00	
Steel						
Frame;	-0.1	0.05	-0.025	10	8	
Steel &	0.79	0.21	0.14	1.00	0.78	0.86
PC Skin	0.43	0.20	0.25	1.00	0.60	
% of range						
4	320	740	385	6	12	
	0.00	0.00	0.00	0.46	1.00	0.66
	-914.14	-2959.60	-3850.00	0.43	1.40	

```
Determine Cap. Cost       Determine Oper. Cost      Determine Weight
Input U =     0.75        Input U =     0.69        Input U =      0.8

Cap. Cost    -0.30        Cap. Cost     0.00        Cap. Cost  525.00
U (Cc)        1.88        U (Cc)        0.50        U (Cc)       0.00

Oper.Cost   769.53        Oper.Cost     0.05        Oper.Cost  600.00
U (Oc)        0.00        U (Oc)        0.20        U (Oc)       0.00

Weight      550.00        Weight       -0.08        Weight      -0.10
U (W)         0.00        U (W)         0.50        U (Oc)       2.67

Flexiblty     3.00        Flexiblty     6.25        Flexiblty    3.00
U (F)         0.00        U (F)         0.50        U (F)        0.00

Corr.Res.     5.00        Corr.Res.     6.25        Corr.Res.    5.00
U (R)         0.00        U (R)         0.50        U (R)        0.00
```

Table of calculated values for Oper. Cost given Cap. Cost in (I28..I46)
and Overall Utility in (J27..O27)
Weight, Design Flexibility and Corrosion Resistance Constant
as indicated in cells M12, M15 and M18

Cap.Cost	Total Utility					
0.053114	0.9	0.89	0.88	0.87	0.86	0.85
0.05	-0.150	-0.150	-0.150	-0.144	-0.133	-0.122
0.03	-0.150	-0.149	-0.137	-0.125	-0.113	-0.101
0.01	-0.148	-0.135	-0.123	-0.110	-0.097	-0.084
-0.01	-0.138	-0.124	-0.110	-0.097	-0.083	-0.069
-0.03	-0.130	-0.116	-0.101	-0.087	-0.073	-0.059
-0.05	-0.121	-0.106	-0.092	-0.077	-0.062	-0.051
-0.07	-0.116	-0.100	-0.085	-0.070	-0.056	-0.046
-0.09	-0.113	-0.098	-0.082	-0.067	-0.054	-0.044
-0.11	-0.111	-0.095	-0.079	-0.064	-0.052	-0.042
-0.13	-0.108	-0.092	-0.077	-0.061	-0.050	-0.039
-0.15	-0.106	-0.090	-0.074	-0.058	-0.048	-0.037
-0.17	-0.103	-0.087	-0.071	-0.056	-0.045	-0.035
-0.19	-0.100	-0.084	-0.067	-0.054	-0.043	-0.032
-0.21	-0.098	-0.081	-0.064	-0.052	-0.041	-0.030
-0.23	-0.095	-0.078	-0.061	-0.050	-0.038	-0.027
-0.25	-0.092	-0.075	-0.059	-0.047	-0.036	-0.024
-0.27	-0.089	-0.072	-0.056	-0.045	-0.033	-0.022
-0.29	-0.086	-0.068	-0.054	-0.042	-0.031	-0.019
-0.3	-0.084	-0.067	-0.053	-0.041	-0.029	-0.018

Table of calculated values for Oper. Cost given Weight in (I68..I83)
and Overall Utility in (J67..O67)
Capital Cost, Design Flexibility and Corrosion Resistance Constant
as indicated in cells M6, M15 and M18

Weight	Total Utility					
0.053114	0.95	0.9	0.8	0.75	0.7	0.65
0	-0.150	-0.150	-0.055	-0.017	0.014	0.039
-0.01	-0.150	-0.150	-0.052	-0.014	0.017	0.044
-0.02	-0.150	-0.150	-0.049	-0.010	0.020	0.049
-0.03	-0.150	-0.150	-0.046	-0.006	0.023	0.054
-0.04	-0.150	-0.150	-0.043	-0.002	0.026	0.059
-0.05	-0.150	-0.150	-0.039	0.002	0.030	0.066
-0.06	-0.150	-0.149	-0.034	0.006	0.035	0.075
-0.07	-0.150	-0.144	-0.028	0.011	0.040	0.084
-0.08	-0.150	-0.136	-0.019	0.018	0.053	0.099
-0.09	-0.150	-0.125	-0.006	0.029	0.072	ERR
-0.1	-0.150	-0.104	0.012	0.052	ERR	ERR

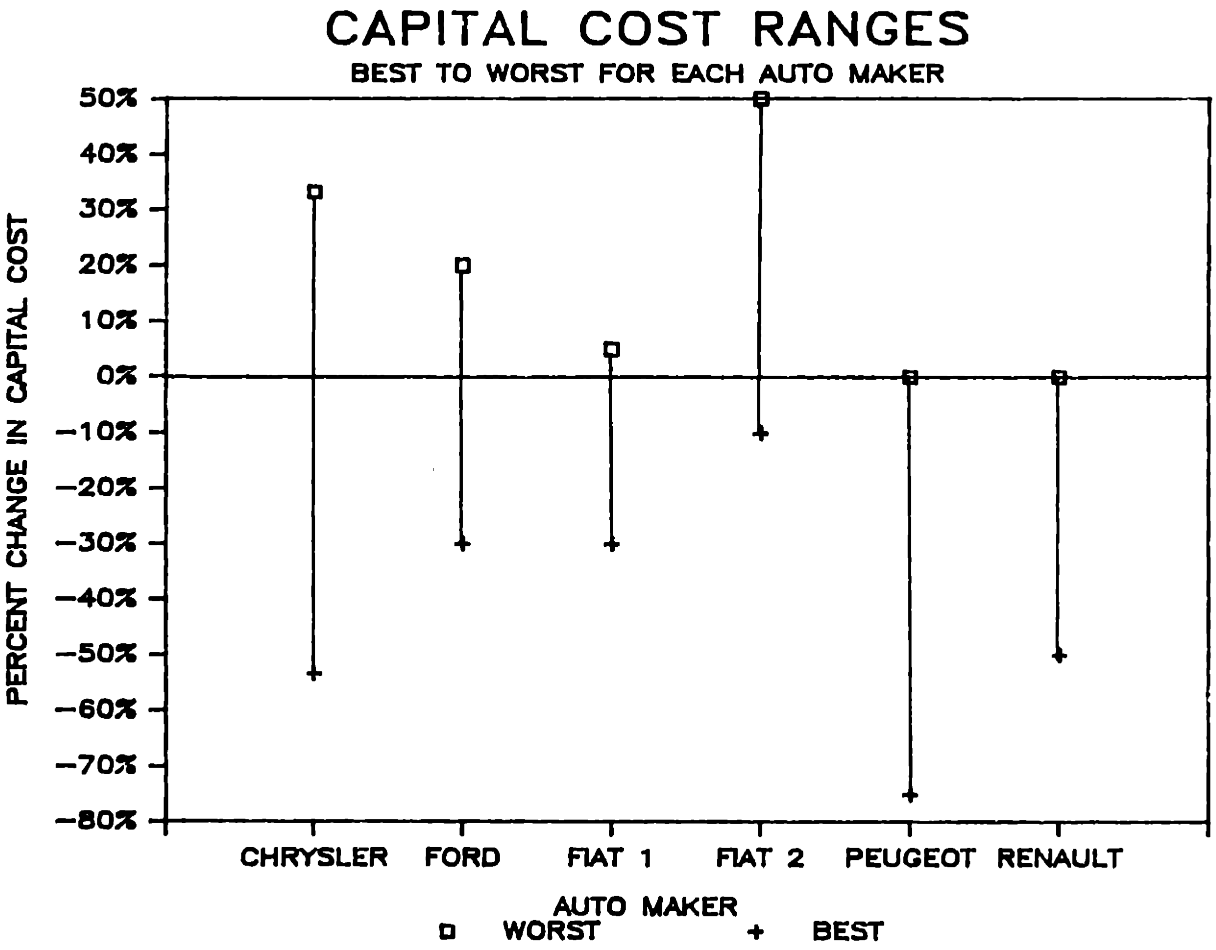
Table of calculated values for Oper. Cost given Des. Flex in (I108..I119
and Overall Utility in (J107..O107)
Cap. Cost, Weight, and Corrosion Resistance Constant

Des.Flex.	Total Utility					
0.053114	0.9	0.8	0.7	0.6	0.5	0.4
10	-5.78%	5.30%	ERR	ERR	ERR	ERR
9	-8.45%	2.72%	ERR	ERR	ERR	ERR
8	-10.70%	0.98%	ERR	ERR	ERR	ERR
7	-12.81%	-0.96%	6.61%	ERR	ERR	ERR
6	-14.60%	-3.04%	3.76%	ERR	ERR	ERR
5	-15.00%	-4.96%	1.94%	8.79%	ERR	ERR
4	-15.00%	-6.59%	0.58%	6.14%	ERR	ERR
3	-15.00%	-8.36%	-0.80%	3.97%	ERR	ERR

```
Determine Flexibility         Determine Corrosion Resistance
Input U =      0.80           Input U =      0.80
Cap. Cost    525.00           Cap. Cost    301.57
U (Cc)         0.00           U (Cc)         0.00

Oper.Cost    769.53           Oper.Cost    769.53
U (Oc)         0.00           U (Oc)         0.00

Weight       550.00           Weight       450.00
U (W)          0.00           U (W)          0.00

Flexiblty     10.00           Flexiblty      5.86
U (F)          1.60           U (F)          0.44

Corr.Res.      5.00           Corr.Res.     10.00
U (R)          0.00           U (R)          1.34
```

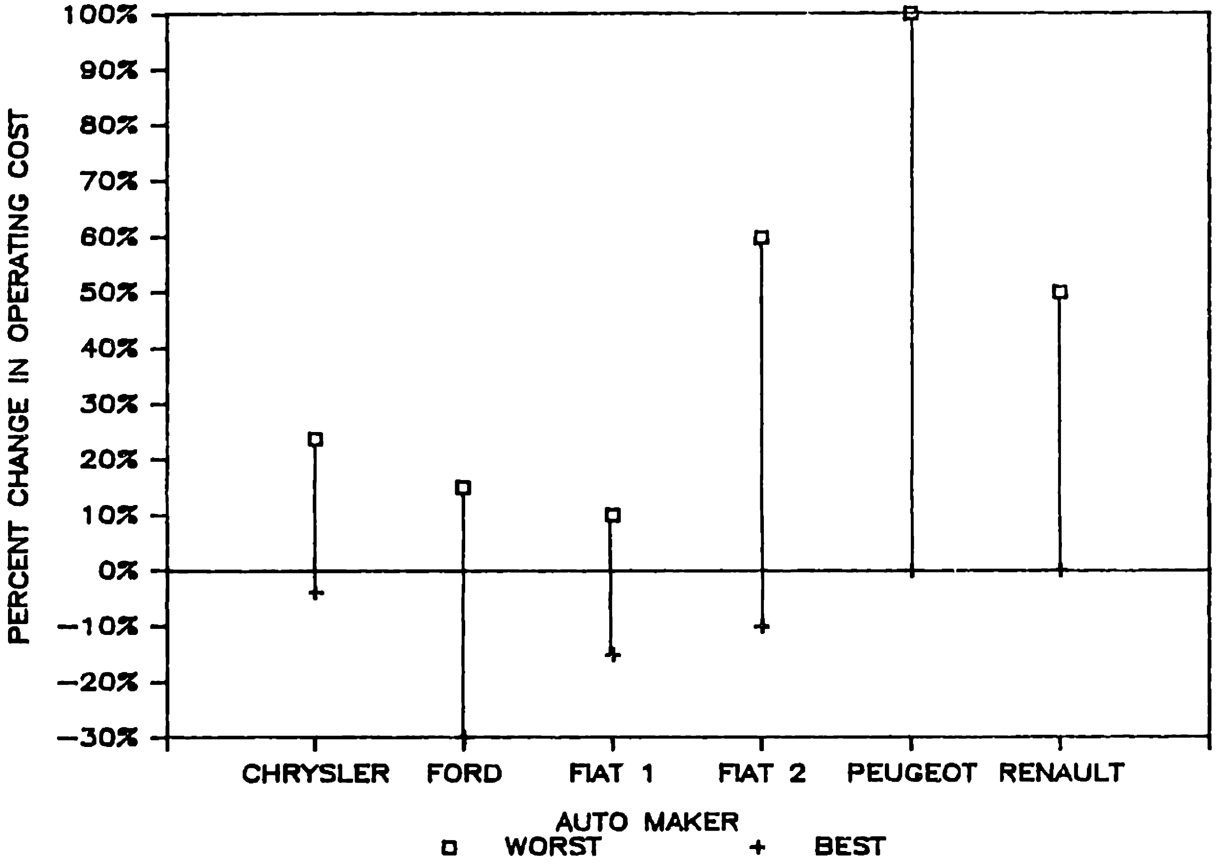
Table of calculated values for Oper. Cost given Corr.Res. in (I128..I146
and Overall Utility in (J127..O127)
Cap.Cost, Weight and Design Flexibility Constant

Corr.Res.	Total Utility					
0.053114	0.95	0.9	0.85	0.8	0.75	0.7
10	-0.14347	-0.04577	0.016060	0.073959	ERR	ERR
9.5	-0.15	-0.05698	0.005831	0.054478	ERR	ERR
9	-0.15	-0.07040	-0.00488	0.038117	0.099231	ERR
8.5	-0.15	-0.08375	-0.01706	0.027803	0.080475	ERR
8	-0.15	-0.09575	-0.02802	0.018527	0.063606	ERR
7.5	-0.15	-0.10916	-0.04026	0.008166	0.044763	0.097277
7	-0.15	-0.12330	-0.05316	-0.00413	0.029933	0.073934
6.5	-0.15	-0.13568	-0.06670	-0.01848	0.018336	0.053491
6	-0.15	-0.15	-0.08851	-0.03694	0.003413	0.031457
5.5	-0.15	-0.15	-0.11240	-0.05716	-0.01939	0.012252
5	-0.15	-0.15	-0.14030	-0.09116	-0.04802	-0.01526


CAPITAL COST RANGES
BEST TO WORST FOR EACH AUTO MAKER
PERCENT CHANGE IN CAPITAL COST
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
CHRYSLER
FORD
FIAT 1
FIAT 2
PEUGEOT
RENAULT
AUTO MAKER
□ WORST
+ BEST

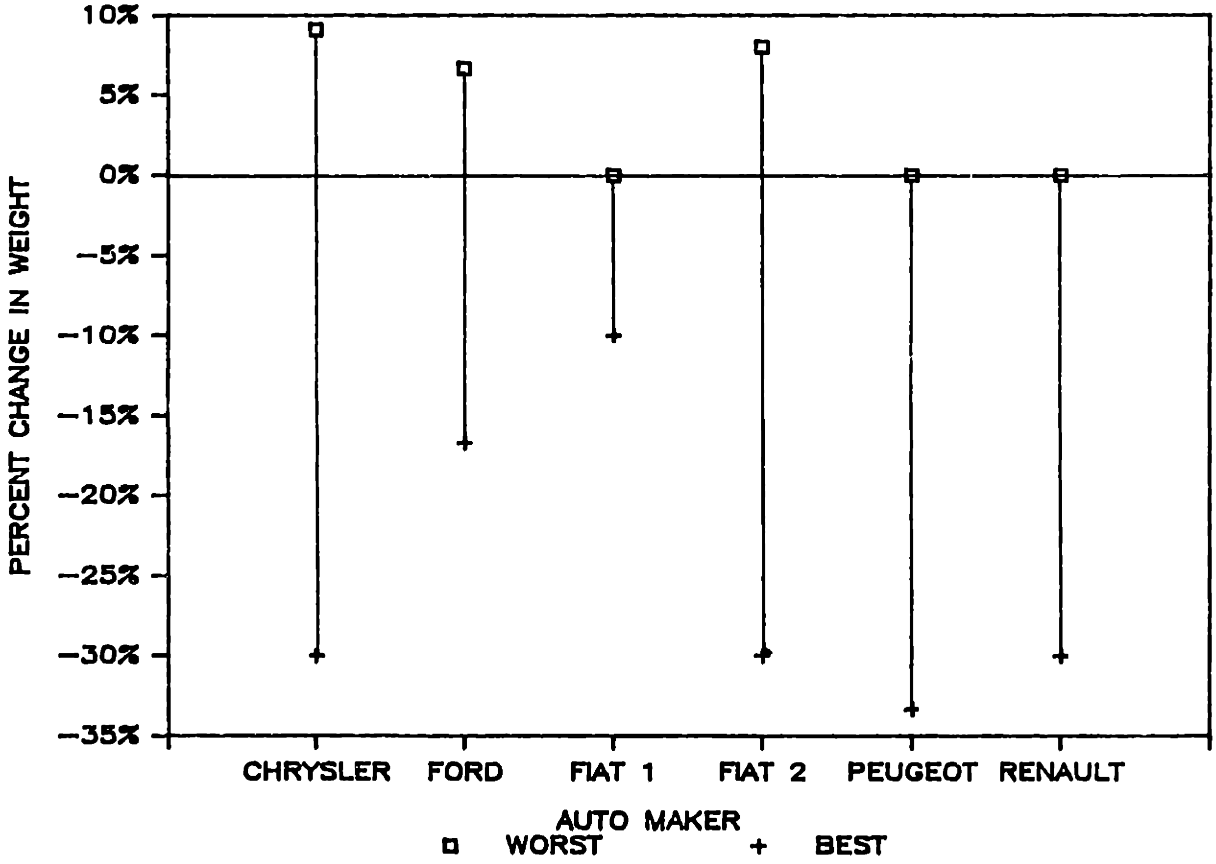
OPERATING COST RANGES

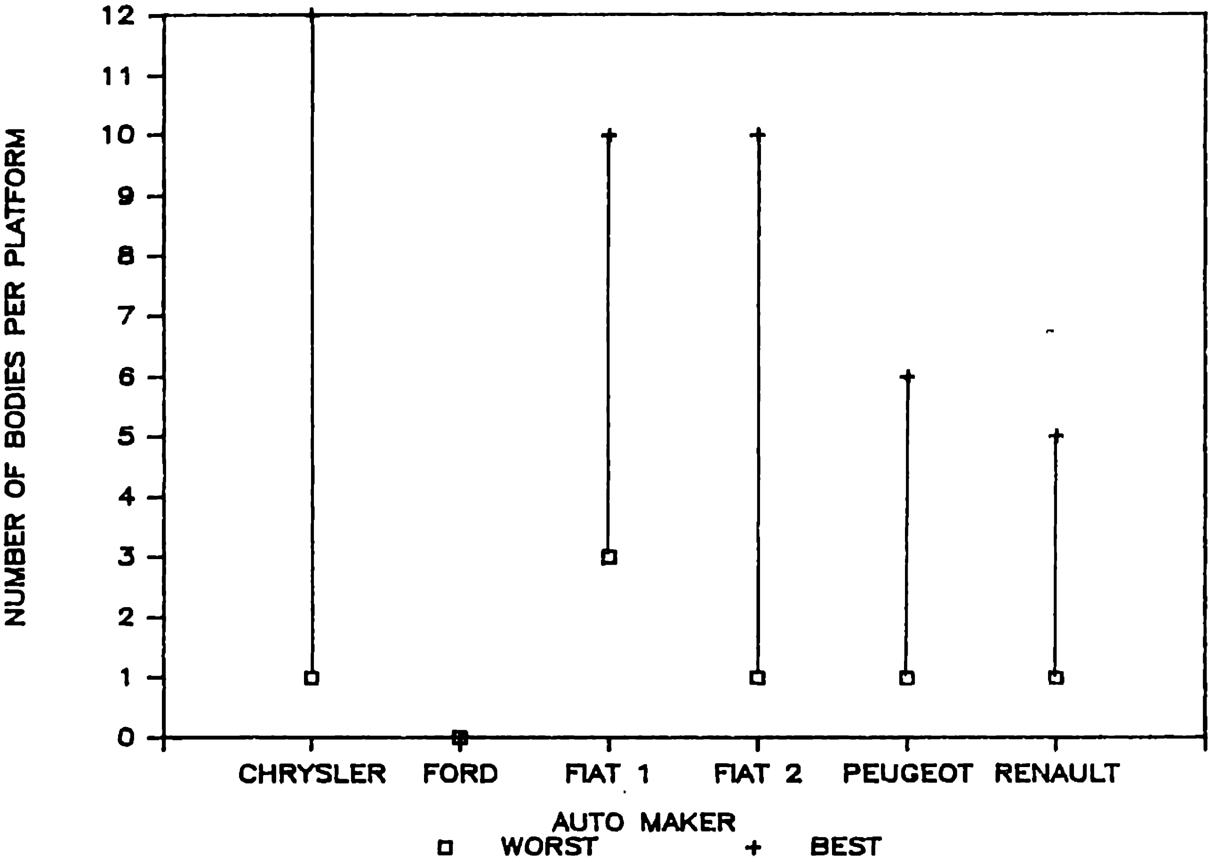
BEST TO WORST FOR EACH AUTO MAKER



WEIGHT RANGES

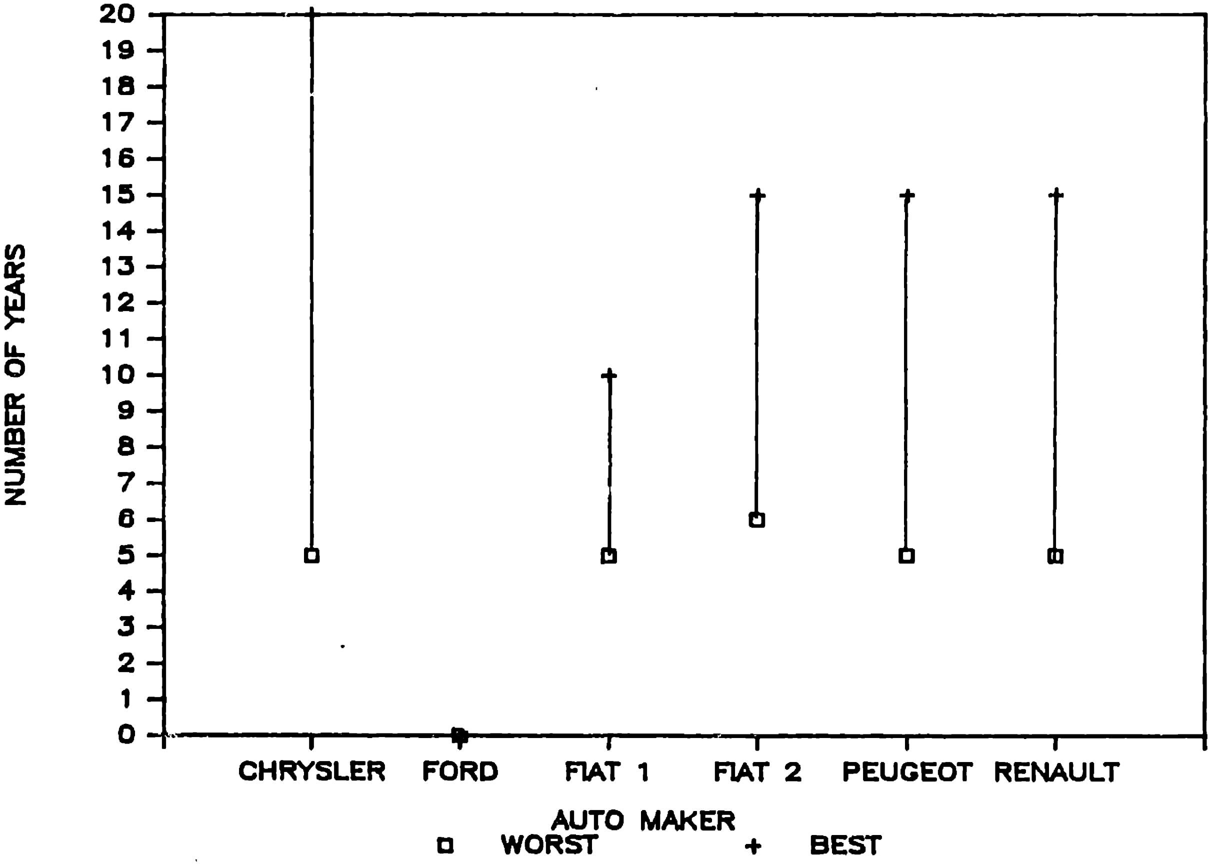
BEST TO WORST FOR EACH AUTO MAKER





DESIGN FLEXIBILITY RANGES

BEST TO WORST FOR EACH AUTO MAKER



CORROSION RESISTANCE RANGES

BEST TO WORST FOR EACH AUTO MAKER

APPENDIX H - REFERENCES

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