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RESEARCH MEMORANDUM

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RESEARCH MEMORANDUM

SCORING METHODS, MULTIPLE CRITERIA, AND UTILITY ANALYSIS.

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October 1978

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SCORING METHODS, MULTIPLE CRITERIA, AND UTILITY ANALYSIS

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ABSTRACT

Scoring methods are popular in computer selection, and try to combine different attributes into an overall performance measure. Related is the multi-criteria evaluation of computerized information systems. The scoring method is criticized in the context of more general utility models, popular in economics. Scoring provides simplistic choice models, and should not be used as predictive, causal models. Relationships with mathematical programming in the management sciences are indicated. Many references for further study are included.

1. INTRODUCTION

Technical performance measures like throughput and response times were of major interest in the early years of computerization. (Besides, scientific evaluation methods such as simulation, queuing analysis and benchmarking tend to concentrate on a single performance measure.) Gradually, however, the computer buyer came to realize that many aspects of a computer are relevant. These aspects comprise hardware and software characteristics determining technical performance, but also such aspects as conversion effort, availability of additional hardware and software from the vendor in the future, flexibility of capacity increase, training facilities, delivery date, costs, and so on. Miller (1969) gives a checklist with 82 characteristics (see Table 1 below), and many such lists can be found in the literature.[1)] So there is certainly no unique performance characteristic.

Scoring methods were introduced to quantify the selection process of computer systems. In section 2 we shall discuss these computer scoring methods. In section 3 we show that scoring is a special case of the more general problem of utility analysis, addressed in economics, especially in the theory on consumer behavior. Section 4 shows how the issue of multiple criteria is approached in management science, especially in mathematical programming. Note that multiple criteria are faced nog only in computer selection, but also in information system's evaluation, where we may be interested in various financial benefits (such as profit and market share), in job satisfaction, and so on.[2)] So utility tradeoffs among various criteria is a topic addressed by various disciplines, especially economics, management science, and - as we shall see - psychometry.

2. SCORING METHODS IN COMPUTER SELECTION

Scoring methods as presented in the computer selection literature can be described as follows. We first prepare a list of computer characteristics (attributes, aspects) that we think to be relevant in the selection of a computer. In the introduction we have already mentioned some of these attributed. Let s_{ij} denote how well a particular computer, say j, scores relative to characteristic i; see also below. The relative importance or weight that we assign to characteristic i is denoted by w_i (observe that no index j is needed for the weight w). Then the performance of computer j may be measured as

$$P_j = w_1 . s_{1j} + w_2 . s_{2j} + \dots + w_n . s_{nj} \qquad (1)$$

where weights satisfy the obvious condititons

$$\sum_{i=1}^{n} w_i = 1 \text{ and } w_i \geq 0 \qquad (2)$$

Which characteristics may be relevant? As an illustration Table 1 shows a selection from the 82 attributes, grouped into 5 classes, as listed by Miller (1969). The terminology in this table is taken ad verbatim from Miller (1969). In eq. (4.1) s_{ij} quantifies how well

1. Cost data:
   - Total cost
   - Maintenance cost
   - Etc.
2. Performance data:
   - Compilation time, by compiler, on benchmark tasks
   - Sort timings (from sequential and random access files)
   - Readibility of printed output
   - Etc.
3. Hardware characteristics:
   - Average machine instruction time
   - Channel speed (total and per channel)
   - Total storage - random access
   - Average access speed - random access storage for data
   - Floating point and decimal arithmetic hardware
   - Character coding (6 or 8 bit bytes)
   - Expandability of memory
   - Virtual memory capability
   - Total number of channels available to high speed devices
   - Total number of remote terminals capable of support with a response delay of less than three seconds
   - Compatability to smaller or larger machine models
   - Total floor space (square feet) required
   - Memory protect features
   - Etc.

Tabel 1: Computer characteristics

4. Software support:

    Application programs available
    Conversion assistance
    Utility programs available and their features
    Memory utilized by operating system
    Debugging facilities of each language
    Automatic restart (recovery) procedures available
    Etc.

5. Miscellaneous data:

    Delay before system may be delivered
    Proximity to other similar systems available for backup support
    Reputation of the vendor for technical and maintenance support
    Training programs offered by the vendor
    Availability of software developed by independent software houses for the bid system
    Expandability of the total system and potential for use in systems with faster processors
    Main time between failure for each system component
    Purchase options, long term lease arrangements, guaranteed pricing for anticipated life and other benefits
    Etc.

Table 1: Computer characteristics (continued).

a particular computer j scores relative to characteristic i. These scores may be based on either objective measurements or subjective estimates. For instance, in Table 1 compilation time may be objectively measured using benchmark programs; total storage can be taken from the vendor's documentation; response delays may be estimated through queuing and simulation models. Subjective estimates may be collected for characteristics like readability of printed output, reputation of the vendor, etc. Reliance on such subjective judgments is certainly not ideal. Observe that we are criticizing the subjective character of judgments on scores like vendor reputation, not the subjectiveness of the weights attributed to these scores; we shall return to these weights later on.

Besides problems in the quantification of the scores, we see a basic fault in the scoring approach, as presented in the computer literature. The great many characteristics in Table 1 can impossibly all be considered as criteria! Some characteristics should be taken as input variables which determine the value (score) of the final criteria. For instance, maintenance costs contribute to total cost; average machine instruction time and total storage determine the response delay at the terminals; etc. It is not always clear whether a particular characteristic is an input or an output variable in the computer selection process. For example, are training facilities a criterion or should such facilities be converted into costs, i.e., another criterion? We also refer to the discussion on "overlapping criteria" in Moore & Baker (1969, p. 93). In many publications, not necessarily on computer selection, it is indeed recommended to restrict the number of criteria in practical studies to, say, 5.[3)]

A related issue is the organization of attributes into a hierarchy. In Table 1 the 82 attributes were grouped into 5 classes. More generally, the large number of attributes may be organized into a hierarchy where several subcriteria contribute to a single higher criterion that in turn contributes (together with other criteria) to a higher-level criterion, etc.[4)] We would comment that as we go down the hierarchy of objectives, we get to attributes that are no "ends" but which are "means" to an end. This takes us back to the issue of determining causal relationships between output variables.

Our general modeling philosophy is that we need to decide which output or response variables should be considered as criteria. Next we need to determine - through causal models - how these output variables depend on input variables. These input variables may be either under our control (decision variables such as memory size), or not (environmental variables such as future vendor support). The sensitivity of our choice to changes in the uncontrollable environmental variables should be investigated. The control variables should be selected such that the criterion variables are favorably affected. The input and output variables may further be subjected to certain restrictions, generated by user requirements (say, maximum response delays), corporate policy (diversified suppliers, no leasing), government regulations (privacy protection), labor unions, and so on.

As a benefit of the scoring method we see the elicitation of experts' opinions, and their communication. A list of possible important factors - not only technical factors - is generated. A further advantage of the scoring method is its inherent simplicity.

Note that after the selection of a particular computer system, we have to keep "tuning" the system, i.e., parameters of the operating system have to be adapted as the environment changes, additional disc drives can be connected, and so on. An approach that we consider to be related to scoring models, is based on Kiviat-graphs.[5)] Our discussion of scoring models and utility theory will provide the reader with enough knowledge to evaluate a simplistic approach like the Kiviat-graph.

3. UTILITY ANALYSIS IN ECONOMICS

In this section we shall present the economist's view of the utility (value, worth) of goods and services. We shall discuss this topic in three steps:

(i) The utility of different amounts of a single good.
(ii) The tradeoffs among two or more goods.
(iii) The empirical measurement of utilities
(iv) Utility under uncertainty (risk).

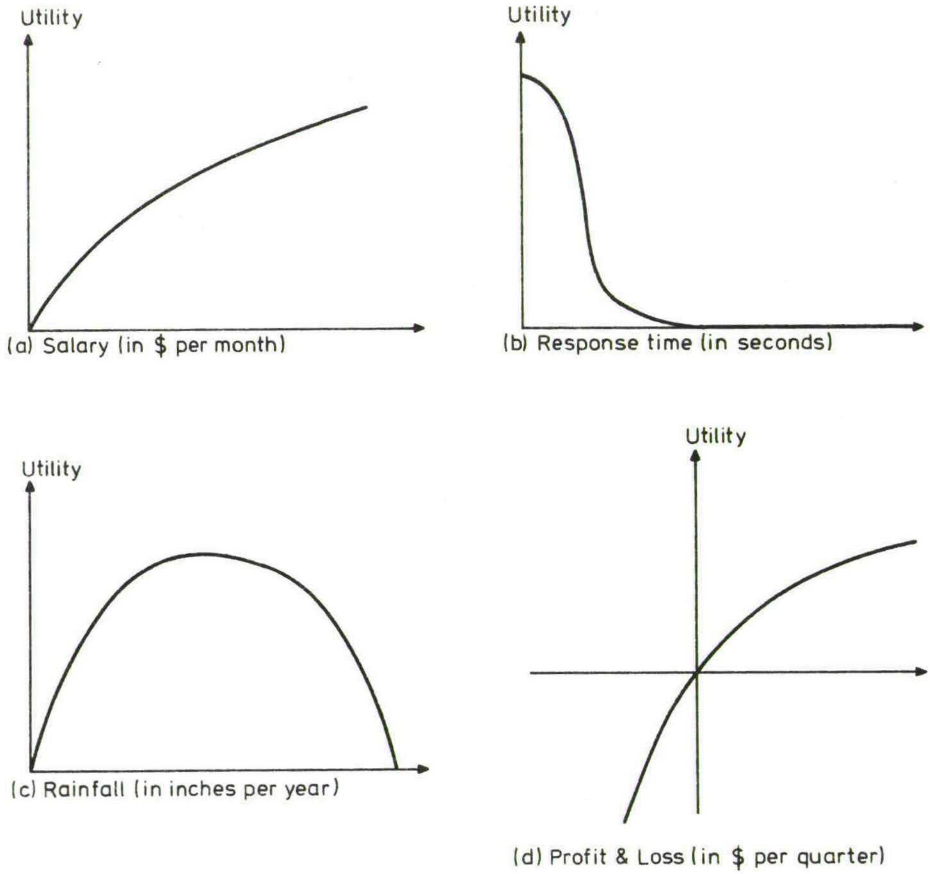

FIG. 1. Examples of utility functions

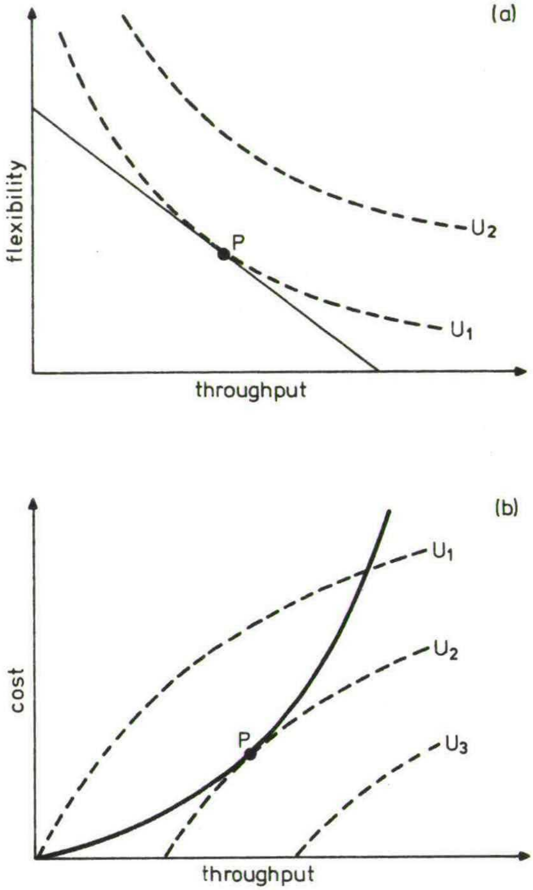

FIG. 2. Indifference curves

3.1. Utility of a single good

Let us first consider a single good. In economics the term "goods" may include services. Possible relationships between quantity of a particular item and its utility are pictured in FIG. 1. In case (a) we wish to demonstrate "Gossen's first law of decreasing marginal utility", i.e., as one acquires more of a particular good (salary, water), the increase in utility diminishes. Note that FIG. 1 does not show the units in which utility is measured. Case (b) illustrates the idea that in real-time applications response delays above a criterical level lead to a sharp drop in value. Case (c) shows that there may be an optimal quantity of a good. Case (d) demonstrates that utility may become negative, i.e., losses lead to bankruptcy: disutility.

3.2. Tradeoffs among several goods

As we mentioned before we may have to choose among 2 or more information systems, each system scoring differently on such criteria ("goods") as financial benefits, job satisfaction, privacy, etc. These scores were denoted by s_{ij}. A system may be immediately eliminated from consideration, if it is dominated by some other system.
System 1 dominates system 2 if $s_{i1} \geq s_{i2}$ for all criteria i, and $s_{i1} > s_{i2}$ for at least one criterion. For the non-dominated systems our choice problem may be modeled through indifference curves.

An indifference curve is a set of values of characteristics (quantities of goods) that yield the same utility. For illustrative purposes we distinguish only 2 "goods" in FIG. 2: throughput and flexibility in part (a); througput and cost (negative utility) in part (b). Indifference curves are denoted by broken lines, and utility U of increasing order is denoted by a higher index of U. If such indifference curves can be specified by the decision maker, then the optimal choice is determined by the point where an indifference curve is touched (in point P) by the "budget line", i.e., the solid line in FIG. 2(a) showing which combinations of throughput and flexibility can be purchased for a fixed budget. In FIG. 2(b) this line becomes the cost-throughput curve, i.e., the curve showing the minimum cost for each throughput level. Let us have a closer look at the specification of indifference curves.

An extremely simple example of an indifference curve is actually provided by eq. (1): keeping the performance index (utility) P fixed, means that various linear combinations of the scores s_{ij} can yield that same, indifferent utility. A <u>linear</u> utility function, however, conflicts with an assumption usually made in economics, namely, substitution between 2 attributes does not remain constant. More specifically, if we let s_{ij} denote the score of a characteristic like software, then eq. (1) implies that complete absence of software resulting in a zero score, can be perfectly compensated by other factors. Actually such a computer could not function! Therefore we look at a number of functions more complicated than purely linear functions.[6)]

(1) A simple, mathematically inspired, transformation can ensure that a system with a zero score for a particular attribute, becomes unattractive. Therefore we replace s_{ij} in eq. (1) by its logarithm:

$$P_j = w_1 . \ell n\ s_{1j} + w_2 . \ell n\ s_{2j} + \ldots + w_n . \ell n\ s_{nj} \tag{3}$$

which is equivalent to the <u>multiplicative</u> model

$$P'_j = s_{1j}^{w_1} . s_{2j}^{w_2} \ldots s_{nj}^{w_n} \tag{4}$$

where P' is a monotonic transformation of P, namely, P' = exp(P). Similar scoring models can be found in the literature.[7)]

(2) A more sophisticated mathematical apparatus - called <u>extended continuous logic</u> - has been derived by Dujmovic (1975). His mathematical tools permit us to specify that, say, at least one of the elementary criteria should be fulfilled to a sufficient degree, or in the author's own words "... the resulting global effectiveness ... is realized by taking into account the logic relationships among the elementary effectivenesses". In his approach the scores satisfy the technical condition

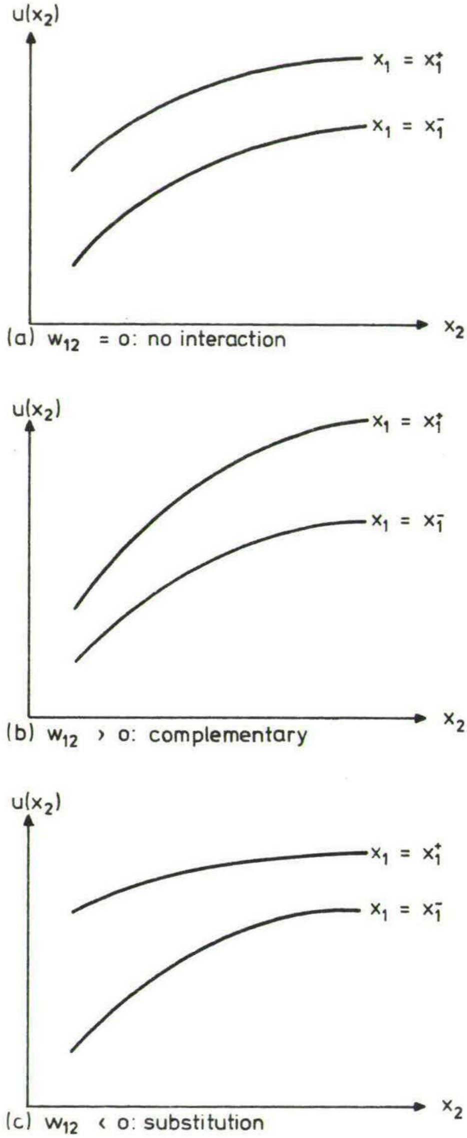

FIG. 3. Interactions

$$0 \leq s_{ij} \leq 1 \tag{5}$$

since they "represent the degree of truth in the statement: the value of the component for evaluation x_i completely fulfils the requirements of the i^{th} elementary criterion". Note that Dujmovic assumes that "complex criteria decompose into a sequence of independent elementary criteria". We shall return to this independence assumption. He applied his technique to the evaluation of a hybrid computer system, characterized by 84 attributes grouped into 4 classes. The reader interested in the, rather complicated, mathematical details of Dujmovic's approach, is advised to first read a related approach by White et al. (1963). Other approaches that try to take cause-effect relationships into account, are surveyed by Bemelmans (1976, pp. 112-125), for instance, QUEST or Quantitative Utility Estimates for Science and Technology. Our general comment is again that scoring models are useful if we wish to quantify the trade-offs we must make among criteria when selecting a system. However, scoring models should not be used to determine cause-effect relationships between criteria (output) and decision (input) variables.

(3) In economics there is a large body of literature on utility theory based on rigid mathematical principles. A recent excellent survey is provided by Keeney & Raiffa (1976), which inspired the following discussion. For the practical evaluation of utility functions some assumptions about their shapes must be made. A fundamental issue is whether multi-attribute utility functions can be separated into independent parts. An independence model with an additive structure is:

$$U(x_1,\dots,x_n) = \sum_{i=1}^{n} w_i . u_i(x_i) \tag{6}$$

with some technical conditions analogous to eqs. (2) and (5). Eq. (6) means that u_i - the utility of attribute i - does not depend on the value of the other attributes. Moreover, this equation specifies that elementary utilities $u_i(x_i)$ can be simply added, after scaling by means of w_i. A graphical example of additive utilities is given in part (a) of FIG. 3, which shows the utility effects of changes in x_2 given that we fix x_1 at a particular value, a "low" value being denoted by x_1^- and a "high" value by x_1^+. The additive independence implies that in part (a) the curves are parallel.

(4) Eq. (6) is actually a special case of a slightly more complicated function, namely the multilinear function. As an illustration we specify this function for just 2 attributes:

$$U(x_1,x_2) = w_1.u_1(x_1) + w_2.u_2(x_2) + w_{12}.u_1(x_1).u_2(x_2) \tag{7}$$

For $w_{12} = 0$ eq. (7) indeed reduces to eq. (6). For $w_{12} \neq 0$ eq. (7) reflects interaction between the two components x_1 and x_2. If $w_{12} > 0$ then both attributes are "complimentary"; if $w_{12} < 0$ then they are "substitutes". FIG. 3 demonstrates the role of interaction. Part (b) shows that as x_2 increases the increase of $u(x_2)$ is stimulated when the increase of x_2 is accompanied by an increase in x_1. In part (c) the marginal utility of x_2 is much smaller when more of x_1 is available which can be substituted for x_2. An example of complementarity in a computer system is provided by response time and availability, whereas the response time of a real-time subsystem and the throughput of a batch subsystem may be substitutes. More applications of the multilinear utility function can be found in Huber (1974).

Keeney & Raiffa (1976) prove that the multilinear function (7) can also be represented as the product of utility functions per attribute, i.e.,

$$U'(x_1,x_2) = u_1'(x_1).(u_2'(x_2) \tag{8}$$

provided $w_{12} \neq 0$ in eq. (7); otherwise the additive eq. (6) holds. An example is provided by eq. (4) where $u_1'(x_1) = s_1^{w_1}$ and $u_2'(x_2) = s_2^{w_2}$.

Even when 2 criteria interact as in eqs. (7) and (8), the overall utility can still be measured by establishing unidimensional utility curves $u_i(x_1)$ and $u_i'(x_i)$, so-called utility independence. This simplifies the practical measurement of the overall utility function, though it is no sinecure. When x_1 is utility independent of x_2, this independence does not imply the converse, i.e., x_2 is not necessarily utility independent of x_1. For instance, Grochow (1972) studied a time-sharing system and found that the utility of response time was independent of availability. However, the utility of availability was not of response time, for if response time is bad, then availability is not critical.

3.3. Empirical utility measurements

Empirical measurement is facilitated if we make certain assumptions about the shape of the utility function. The more general the form of this function is, the more observations are needed. There are several approaches to the quantification of the tradeoffs among criteria:
(1) Assign specific values s_{ij} to the criteria (attributes) i of system j, and ask the decision-maker to rank the resulting systems j. This ranking implicitly determines the weights w_i which can be estimated through statistical procedures, analogous to multiple regression analysis. An example of such a regression model is:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 . x_1 + \hat{\beta}_2 . x_2 + \dots + \hat{\beta}_n . x_n \qquad (9)$$

which is obviously analogous to eq. (1) if we replace $\hat{\beta}$ by the estimated weights $\hat{w}$ and x by the specified scores s.
(2) Alternatively, no specific systems are compared, but the decision-maker is asked to consider n attributes sec. The decision-maker may be asked to make all n(n-1)/2 pairwise comparisons separately, or he may be invited to assign weights to all n attributes in a single shot. It is important to check for consistency in the answers.
If several persons are asked for their utility functions, we may try to reconcile significant differences. Weights may further be specified apriori, but it is also possible to elicite them by interactive, man-computer systems. Excellent discussions on the empirical evaluation of utility functions, including case-studies, can be found in the textbook Keeney & Raiffa (1976) and the review article Huber (1974).[8] The measurement of weights is also discussed in the computer literature.[9]

We emphasize that the tradeoffs among criteria is a personal, subjective matter. Nevertheless empirical, statistical work can be done to measure such personal preferences. Because of the personal character of utility, the scientific (i.e. reproducible) determination of utility functions will remain difficult.

3.4. Uncertain goods

An example of an uncertain attribute is response time as this attribute shows stochastic variation. The axiomatic approach to the uncertainty issue is based on the utility theory of von Neumann and Morgernstern, and is virtually ignored in the computer and information systems literature. To explain this axiomatic approach consider the following simplistic example. A person may either receive \$ 150 or flip a coin, receiving \$ 200 if heads show up, receiving \$ 100 if tails show up. This example raises questions like: are these 2 options indifferent to the decision-maker; does he prefer the certain option of \$ 150 if he desparately needs money; do his preferences remain unchanged when we replace \$ 100 and \$ 200 by \$ 1,000,000 and \$ 2,000,000; and so on. The von Neumann-Morgenstern theory assumes that the utilities are so scaled that selection of an alternative can be based on maximalization of expected utility. (Alternative approaches are the maximin strategy, etc.) A fundamental issue in utility theory is the introduction of the following lottery. We confront the decision-maker with a "certainty" option, i.e., he can choose to receive with 100% certainty (say) \$ 150. Next we confront him with 2 extremes (say) receiving \$ 500 with a change p, or receiving \$ 10 with a change 1-p. We ask him to specify the value of the probability p which would make him indifferent as to the choice between the certainty option (receiving \$ 150) and the lottery. We may expect that a "rational" decision-maker from whom the stakes of this lottery are not extremely high, will select p such that it solves the following equation:

$$150 = p.500 + (1-p).10 \qquad (10)$$

or p = 14/49. A risk-averse person, however, will trade in the certainty option only if the chance of a good outcome ($ 500) increases above 14/49. A risk-prone person prefers the lottery even if $p < 14/49$. So the decison-maker's risk attitude is measured by the value of p in the lottery that is substituted for the certainty option. There are many checks to determine whether the decision-maker remains consistent in his preference statements.[10)]

Preferences between present and future attributes can be analyzed from a strictly utility-theoretic viewpoint, but in practice the time dimension is handled by practical techniques like the Net Present Value. A number of practical studies using utility theory are summarized by Keeney & Raiffa (1976): air pollution control in New York City, choice of educational programs, fire department options, selecting business objectives in a consulting company, nuclear power site selection, airport development in Mexico City, etc.[11)]

4. MULTIPLE CRITERIA IN MANAGEMENT SCIENCE

In FIG. 2 we examined the optimal combination (tradeoff) of several attributes or criteria. However, the behavioral school of management suggests that each criterion should just satisfy specific aspiration levels. Hence, a "satisficing" solution is sough rather than "the" optimal solution; see Cyert & March (1963). This approach has been formalized by goal programming. Interactive assessment of utility is usually based on mathematical programming algorithms. So the literature on multiple criteria is rapidly growing in the mathematical programming area.[12)] Recently the multiple-criteria problem has been approached using fuzzy set theory pioneered by Zadeh.[13)] In computer selection a set of applications may be given, and we may wish to select the computer configuration that can execute these applications at minimal cost while satisfying certain restrictions on, say, response time. A few authors present linear programming solutions, but these solutions remain very theoretical.[14)]

5. CONCLUSION

Though multi-attribute utility theory remains quite theoretic, this theory provides a sound theoretical background for the more practical, simplistic approaches followed in computer selection and information system evaluation. In the computer literature lists with, say, 80 criteria are used. However, many attributes are input variables, and predictive causal models are needed to determine the resulting, limited set of true criteria. A normative choice model is provided by the computer scoring approach. However, its extremely simple (linear) model might be replaced by, e.g., multilinear models accounting for interactions. Nevertheless some authors favor simple linear models.[15)] As major benefits of scoring we see the elicitation of experts' and users' opinions and criteria, and the method's simplicity (cost-benefit of the method itself).

Note that in computer selection the information requirements (the applications) are considered to be given so that no attention is paid to gross benefit evaluation. For instance, in Table 1 none of the characteristics is an economic benefit. If we are interested in the <u>ultimate</u> criteria for the effectiveness of a computer system, then we cannot anly longer concentrate on the computer system itself, as scoring models do. Instead we must then focus on the benefits generated by the computer as part of the information system. So computer selection is a problem to be solved <u>after</u> the economic benefits of computerized information systems have been determined. This latter type of problem is the central issue in Kleijnen (1979).

NOTES

1. See the bibliography with 138 references in Dujmovic (1977) and the many references in Kleijnen (1979).

2. Bottler et al. (1972), Hawgood (1975).

3. Keeney & Raiffa (1976, pp. 29, 52), Miller (1956), Turban & Metersky (1971, p. 827).

4. Dujmovic (1977), Keeney & Raiffa (1976, pp. 41-49, 115-116, 123-125, 332-343), White et al. (1963). The hierarchy concept itself is discussed in detail by Saaty (1977).

5. See, for instance, Borovits & Ein-Dor (1977, p. 186).

6. The relationships between scoring methods and utility theory are discussed by Bemelmans (1976, pp. 148-151) and Sharpe (1969, pp. 287-292); see also Keeney & Raiffa (1976, p. 81-84).

7. For instance, White et al. (1963, p. 180).

8. See also Bell et al. (1977), Dujmovic (1977), Saaty (1977), Turban & Metersky (1971), and the references in Kleijnen (1979).

9. Bottler et al. (1972), Sharpe (1969), Zangemeister (1975); see also Kleijnen (1979).

10. Keeney & Raiffa (1976, pp. 198-200), Rowe (1977).

11. See also Bell et al. (1977) and Huber (1974).

12. Bell et al. (1977), Keeney & Raiffa (1976), Starr & Zeleny (1977).

13. See the bibliography Dyjmovic (1977).

14. Sharpe (1969, pp. 279-284).

15. Huber (1974), Keeney & Raiffa (1976, pp. 295-297).

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