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MULTIATTRIBUTE PREFERENCES: APPLICATION TO RESOURCE ALLOCATION

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ABSTRACT

The efficient allocation of scarce resources represents a complex value problem. Historical approaches to this problem include the labor theory of value, cost: benefit analysis and energy analysis. The limitations of these methods as applied to resource utilization are discussed, and the use of multiattribute utility theory is suggested. The primary objective of increasing the efficiency of resource use is used to generate an objectives hierarchy, and list of relevant attributes.

The objectives of using resources efficiently, economically, and with a minimum of environmental damage often conflict with each other. Dwindling energy resources are a current source of great concern. Mineral resources, particularly metals, are also becoming scarcer and more expensive, not only in terms of money, but also in terms of the energy needed to extract them. In addition, increasing attention is being given to the environmental effects of resource

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utilization. A formalized approach is required to adequately weigh the tradeoffs involved in resource allocation. This paper explores how multi-attribute utility theory may be applied to these types of problems.

Previous approaches to this problem have involved converting all the variables into one common unit and adding them directly. In the nineteenth century, the unit of measurement employed was labor. Adam Smith, in his treatise on the wealth of nations, described labor as the real measure of the exchangeable value of all commodities [1]. Karl Marx took this idea even further in asserting that the value of a product has a physical basis in the labor consumed to produce it. The labor theory of value does not adequately weigh energy and natural resources, describing them as free gifts of nature, an increasingly untenable assumption. In addition, the labor theory of value has no mechanism for valuing environmental impacts.

The labor theory gave way to cost: benefit analysis. The benefits, b_1, $b_2, \ldots, b_n$, are condensed into a single composite measure B, often by the use of a set of conversion factors:

$$B = f_1 b_1 + f_2 b_2 + \ldots + f_n b_n$$

B is then compared with the total cost, C, and the alternative course of action showing the highest B:C ratio is chosen. Obvious problems are encountered in specifying conversion factors that price out benefits in terms of dollars, especially in the realm of environmental impacts. Many schemes have been detailed for pricing out environmental impacts in terms of the cost of pollution control. Peterson and Voss have recently described a method for arriving at optimal effluent standards or charges by equating the value of the lost environmental assimilative capacity with the surplus generated by avoiding costly treatment [2]. While this assumption is correct with respect to economic theory, it fails to take into account other, more serious environmental impacts; humans depend on the natural environment for continued biological survival, not just for its capacity to assimilate wastes. This approach also ignores the uncertainty associated with environmental impacts.

The uniqueness of energy as a resource has only been recognized in recent years. Slesser has termed energy as the ultimate resource [3]. A growing awareness of the importance of energy as the determinant of progress is evidenced by the development of an accounting procedure called energy analysis. The unit of accounting is the energy content of goods and services. Energy analysis is described by three different approaches, which have been reviewed by Urban and Ramsey [4]. The first is based on the first law of thermodynamics and includes four levels of analysis. Level 1 requires a determination of all direct energy inputs to the process except labor, level 2 assesses the energy required to obtain the material inputs to the process, level 3 assesses the energy used to obtain raw materials and level 4 describes the energy inputs needed to produce the capital used. Summing up the energy use in the various levels gives the energy requirement for the provision of the product or service. To obtain a value for the gross energy requirement, the energy supplied to the process at the various levels must be corrected for the primary energy use which went into the provision of the fuel itself. The procedure has been described in detail by Slesser [3]. The results of this analysis, whether in the form of total fuel use or in the form of primary energy use, consider only the concentrated fuel inputs in the production of the product or service. No energies in the form of labor or environmental energy are considered.

Another method of energy analysis is based on the second law of thermodynamics. The analysis procedure calls for the calculation of the ratio of the theoretical energy required to perform the function to the energy actually required to perform the function by each postulated performance pathway. Selection of the most favorable pathway can be made then by comparison of the resulting ratios. The primary use of this technique has been to evaluate the direct fuel consumption of different technologies rather than to evaluate the fuel used to produce a product or service [5]. This approach possesses greatest potential for evaluating the ways in which energy can be supplied to meet a specific need.

The energy analysis technique that has been advanced by Howard Odum [6] incorporates into an energy unit of value an evaluation of all forms of energy: concentrated fuels, labor, and the environmental energies from the sun, water and biological systems that enter into the production of a product or service. Problems quickly develop in attempting to force the diverse forms of energy common to each sector into a single universal energy unit. Odum's theory is that energy analysis is a better basis for establishing the value of a natural system or a man-created system than economic analysis since in his concept energy controls the economy.

Hyman has written a criticism of the energy theory of value which points out that the approach leads to maximization of net energy, rather than social welfare [7]. Net energy has no necessary connection to social welfare. He further states that the theory fails to account for the fact that energy comes in different qualities that limit the ability to harness it, and that energy pricing leads to absurd results. He cites the example of Virginia hayland, which is assigned a perpetual value of $6960/acre by energy pricing. Virginia farmland commands a market value of $556/acre including buildings, and hay is a low value crop [8].

All three of the methods described above attempt to make the problem of efficient resource allocation more tractable by forcing all variables into a single common unit of measurement. This type of approach is inadequate as a sole basis for decisions relating to complex value problems not only because of the inherent measurement difficulties but also because uncertainty is not considered. Most complex problems involve many objectives, and in many cases, none of the alternative actions are clearly dominant with respect to all of the objectives. "In essence, the decision maker is faced with a problem of trading off the achievement of one objective against another objective . . . If there is uncertainty in the problem, the tradeoff issue remains, but difficulties are compounded because it is not clear what the consequences of each alternative will be . . . . There are two possibilities for resolving the issue: (1) the decision maker can informally weigh the tradeoffs in his mind; or (2) he can formalize explicitly his value structure and use this to evaluate the contending alternatives." [9]

Utility theory, a branch of decision analysis that aids in quantifying multiattribute preferences under uncertainty, can be fruitfully applied to the complex problem of resource utilization. Even when a numerical solution is not forthcoming, these procedures greatly help the decision maker to resolve the question of the relative importance of the variables that must be considered.

Decision analysis starts with an objectives hierarchy that specifies in ever greater levels of detail the variables upon which the decision rests. Given the primary objective of increasing the efficiency of resource use, the decision between alternative courses of action could be approached by considering the secondary and tertiary objectives specified in Table 1. The tertiary objectives are sufficiently detailed that they can be associated with attributes, which measure the degree to which the objective has been achieved.

Table 1 could also be written in the form of a decision tree. The attributes listed should be ascertained for all phases of each alternative action: production/construction, operation, maintenance, and the disposal of wastes. The set E describes all of the energy inputs necessary, set M describes each material input, and L includes the various types of labor that will be necessary. It will be assumed in the following discussion that the original problem that has generated alternative courses of action is solved equally well by all actions, and that the sole basis of decision rests on which alternative shows the greatest efficiency of resource use. If this were not the case, additional branches could be added to the decision tree.

The scarcity index is a subjective scale, $0 < \mathrm{SI} \leqslant 1$, normalized with respect to all of the energy resources to be used by any of the alternative courses of action. Renewable resources are given a score of 1, and other sources are scored less than one. The absolute SI given the nonrenewable energy resources could depend on some convenient unit of comparison such as world reserves. The relationship between the renewable and non-renewable sources (i.e., at how much less than 1 to start the non-renewable scale, 0.98?, 0.5?, 0.01?) depends on how much weight the decision maker thinks should be given the use of renewable resources. Techniques for getting at such value functions are well documented in the literature [9, 10].

Estimated world reserves can be gotten from a variety of publications. The Commodity Data Summaries, published as an appendix to *Mining + Minerals Policy*, by the U.S. Bureau of Mines, contains information about domestic and world production as well as world reserves for energy and mineral resources [11].

Dividing the quantity used by the scarcity index results in a pseudovariable

Table 1. Hierarchy of Objectives

Primary Objective: Increase efficiency of resource use

Secondary Objectives	*Tertiary Objectives*	*Attributes*
decrease use of scarce energy resources	decrease quantity	$\sum_{i=1}^{n}$ (BTU/SI)
	decrease scarcity	
	decrease cost	$
$E = E_1, \ldots, E_n$	decrease environmental degradation	?
	increase security of supply and substitutability	subjective indices
decrease use of scarce material resources $M = M_1, \ldots, M_n$	decrease quantity	
	decrease scarcity	$\sum_{i=1}^{n}$ [(tons)/(RP(SI)]
	increase recyclability	RP
	decrease cost	$
	decrease environmental degradation	?
	increase substitutability and security	subjective indices
increase efficiency of labor usage $L = L_1, \ldots, L_n$	decrease quantity	hours
	decrease costs	$

that can be thought of as BTUs of scarcity, and summed across the set E. In this way, using many BTUs of a plentiful or renewable resource will be equivalent to using a few BTUs of a very scarce resource. Whether or not to lump these attributes is the prerogative of the decision maker. Since these attributes are not mutually preferentially independent, considering them separately complicates the resulting utility function.

The recycle potential, RP, of a material resource is also a subjective scale, $0 < \mathrm{RP} \leqslant 1$, which specifies the fraction of the quantity used that will be or can be recovered and reused. If none of the materials to be used can be recycled, the RP can be left out of the analysis altogether. Again, the absolute scale used is a reflection of the values of the decision maker. Dividing the quantity of material used by the RP and SI also gives rise to a pseudovariable that can be thought of as tons of scarcity, and summed over the set M.

The attribute security of supply recognizes that concentrations of many, if not most, energy and material resources are unevenly distributed on a global scale. This attribute should only be assessed for those materials and energy resources needed on an ongoing basis over the life of the project, and not those that must be procured on a one-time basis. This attribute is also described by a subjective index, $0 < \mathrm{SC} \leqslant 1$, with a wholly US- or NATO-owned supply being assigned a value of 1, and those owned by politically or economically unstable countries being assigned progressively smaller values based on the perceptions of the decision maker.

The substitutability of a material is also measured on a subjective scale, $0 < Sb \leqslant 1$. Goeller and Weinberg conclude that with two exceptions—phosphorous and fossil fuels—society can exist on infinite and near-infinite minerals [12]. They acknowledge that due to institutional difficulties, the human race can arrive at this age of substitutability only at severe cost in terms of standard of living. For the purposes of this type of analysis, Sb should take into account the availability and acceptability of currently recognized substitutes for the material or energy resource.

The environmental degradation attribute is actually a number of factors that together describe the impact on the environment of the proposed action. These consequences are usually of uncertain magnitude and must be described in terms of a probability distribution. Regulatory constraints should be used to set minimum aspiration levels for the attributes.

Once the environmental impacts have been specified in terms of probability distributions, the full power of utility theory can be brought to bear. Keeney and Raiffa have identified five steps to follow in assessing a utility function [9]:

1. preparing for assessment.
2. identifying the relevant independence assumptions.
3. assessing conditional utility functions or isopreference curves.
4. assessing scaling constants.
5. checking for consistency and reiterating.

The discussion so far has completed step 1; the objectives hierarchy has been specified and the attributes defined. The rest of the analysis is completely problem-specific; the results depend entirely on the values of each particular decision maker.

If the decision maker feels that subsets E, M and L are preferentially independent, i.e., that his preferences depend only on the marginal probability distribution of their respective attributes, the utility function is additive and can be expressed by:

$$u(X) = k_e U_e(E) + k_m U_m(M) + k_L U_L(L)$$

where $u_x(X)$ describes nested multiattribute utility functions that specify preferences over the x attributes in each subset, subject to these conditions:

1. U is normalized by $U(X_1^0 . X_2^0, \ldots, X_n^0) = 0$ and

$$U(X_1^*, X_2^*, \ldots, X_n^*) = 1$$

where X^* is a most preferred alternative
X^0 is a least preferred alternative

2. U_i is a conditional utility function of X_i,

   normalized by $U_i(X_i^0) = 0$

   $U_i(X_i^*) = 1, i = 1, 2, \ldots, n.$

3. $k_i = u(X_i^*, X_i^0), i = 1, 2, \ldots, n.$

However, if the decision maker's preferences depend on the joint probability distribution of the attributes as well as their marginal probability distributions, a muntiplicative utility function of the following form will be needed:

$$\begin{aligned} u(X) &= k_E U_E(E) + k_M U_M(M) + k_L U_L(L) \\ &+ k[(k_E k_M U_E(E) U_M(M) + k_M k_L U_M(M) U_L(L)] \\ &+ k^2 [k_E k_M k_L U_E(E) U_M(M) U_L(L)] \end{aligned}$$

where the 3 conditions applicable to an additive function apply as well as:

4. k is a scaling constant that is a solution to

$$1 + k = \pi_{i=1}^{n} (1 + kk_i)$$

By using one of these two functions, the assessment of n one-attribute utility function has been reduced to the assessment of n one-attribute utility functions, greatly simplifying the original problem. Each of the utility functions can be assessed independently, since the k scaling constants insure consistent scaling among the n utility functions. Obviously, choosing the correct k values is of utmost importance. Several techniques for setting up a system of consistent, independent equations that can be solved for the k values are presented in Keeney and Raiffa [9].

This approach to the problem of efficient resource allocation is not without disadvantages. First, it is totally problem-specific, and the results cannot be generalized to other problems. Second, the preferences of one person are quantified, so that the applicability of the results rests on how well that person understands both the relevant facts and the values of the group(s) he represents. Finally, it is a time-consuming and expensive process that requires the services of a decision analyst and provides no guarantee of a clear, numerical solution at the end. In spite of this, this kind of analysis is clearly superior to approaches that involve artificially valuing all considerations in terms of one variable. It encourages the decision maker to think comprehensively and systematically about all the aspects of his problem.

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