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BALANCING APPLES AND ORANGES:

METHODOLOGIES FOR FACILITY SITING DECISIONS

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Preface

A shared interest of the Energy and Urban & Regional Systems groups at IIASA, from its very inception, has been the thorny issue of siting large energy production facilities. In general the problems of embedding very large capital investments into regions which bear most of the external costs but capture few of the benefits are major ones for planning, and nowhere more so than in the complex and frequently emotional business of siting nuclear power and fuel reprocessing plants.

The present review of the analytic methods available as aids in siting decisions focuses on a single crucial stage in the process: after the decision that a specific kind of facility is needed somewhere, but before the detailed problems of implementation and administration have to be considered. Even in this restricted domain, the authors point out that substantial intractabilities remain in the choice of objectives, the determination of legitimacy, the treatment of uncertainty, and the handling of incommensurable values--particularly those involving risk to human life or to unique ecological communities, where the standard apparatus for discounting the future becomes nonsensical. Improvements in method, however, rest on a firm understanding of present techniques, which is the reason for this first paper in what will likely become a series on siting decisions and embedding strategies.

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Authors' Preface

The question of siting decisions for major facilities involves complex interrelationships of spatial and societal distributions of impacts and at the upper end gradates into larger decisions of social policy and public welfare. We have attempted to isolate one facet of this process, the methodological approach to site evaluation, and analyze the assumptions implicit in commonly used or recommended methodologies. Were we considering an individual siting decision, we would attempt to use a combination of the techniques reviewed here as each has recommending properties that the others lack. Nevertheless, a discussion of each methodology by itself is helpful as it illuminates characteristics that might remain hidden in normal application. We have emphasized two seemingly simple concepts, which nevertheless are often transgressed in practice: rigorous properties of scaling, and interdependencies in desirability.

Our hope in formulating these thoughts stems from a desire not so much to advance the state of theoretical evaluation methodologies, as to aggregate a body of work in a consistent way so that site evaluation might be done without flagrant disregard for internal consistency and the principles of measurement.

As with any joint work, the responsibility and blame for the content of our observations are not equally shared. The organization and writing of this review was primarily the work of G.B. Baecher; J.G. Gros contributed his ideas and experience with mathematical aspects of evaluation techniques and siting in general, and wrote some of the sections, and K.A. McCusker organized much of the literature, particularly that on matrix techniques.

We would particularly like to acknowledge the care which Harry Swain has taken in reviewing this paper and offering comments.

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Balancing Apples and Oranges: Methodologies for Facility Siting Decisions

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Abstract

Evaluating alternative sites for major constructed facilities requires comparing impacts of different levels and different types to establish desirable yet feasible balances. Currently employed and proposed methodologies for evaluating the desirability of sets of impacts generated by large facilities are compared, and the theoretical assumptions implicit in each are discussed. In aggregate, the three sets of methodologies considered are Cost-Benefit Analysis and its various modifications, matrix or tableau methods of several sorts, and preference theory (of which utility is a special case). Primary attention is given to the structure of objective functions defined over impacts.

I. Introduction

Major constructed facilities generate a spectrum of impacts in addition to their central function: power plants generate air and water pollution, transportation projects generate land-use changes, and large water resources projects generate ecological disruptions. These impacts have always been recognized, if not before construction, then certainly afterwards. Historically, however, the central function of the facility has always received paramount attention, whether

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out of commitment to general welfare (the Roman aqueducts) or to profit (the Suez Canal). Secondary effects were considered of sufficiently lesser importance to be ignorable.

Large-scale water resources development during the first half of the twentieth century spawned increased attention to techniques of evaluating the spectrum of impacts generated by large facilities, but it has been the more recent difficulty of siting nuclear power facilities which has brought this problem to the awareness of the public. Often this awareness has manifested itself in emotional and at times semi-rational argument and confrontation. It would be unfair to attribute this widespread concern to greater vision and more complex times. Rather, our present attention stems from the growing scarcity of resources, in particular suitable sites for large facilities, and a growing affluence that allows us to adopt more multi-attributed definitions of societal well-being.

Ultimately, siting decisions are political, both in principle and in fact. Within the democratic framework they have traditionally been settled by debate, compromise, and majority approval, constrained by notions of minority rights and long-term policy. However, the process of filtering large numbers of possible sites and making predictions about impacts is too large and burdensome for complete analyses in the political realm. This is where the analyst enters the siting decision process, and where the present review begins.

Analytical comparison of prospective sites requires balancing adverse and beneficial impacts against the multiple and often incompatible objectives of society: it involves trading off apples for oranges. The coordinating theme of this balancing is the "desirability" we as a society associate with specific impacts against objectives, and this is what allows us to compare qualitatively different impacts of large facilities. Because it is the desirability of impacts and not their level that is important, decisions are ultimately based on subjective preference and not on "objective" criteria. One may elect, on subjective bases, to *use* a seemingly objective selection criterion--for example, monetary cost--but this does not make the selection objective; it rests upon the criterion, and the criterion upon judgement.

In approaching site selection, the analyst attempts to implement some consistent scheme for assigning desirabilities to individual impacts and for coalescing these into a decision. The result is a set of predicted impacts for each tentative site and each important objective, and two or three sites emerge which seem most favorable in the sense that the net desirability of associated impacts is the greatest. This short list of sites and the associated impact predictions (not the assigned desirabilities but the impacts themselves) is the departure point for political decision-making.

The nature of the results the analyst derives depends on the models (conceptual or mathematical) he uses to make impact predictions and the "consistent scheme" for evaluating and coalescing them. In this paper we compare these schemes in terms of the assumptions implicit in their structure and their applicability. We emphasize two points in this comparison:

1) Methodologies for comparing the desirabilities of impacts differ only in the specification of the objective function; this objective function makes implicit assumptions about the structure of desirability over impacts.
2) For scales of evaluation to be meaningful, one must know how numbers behave when combined by simple rules; any scaling and combination of impacts and their associated desirabilities must be firmly grounded in the theory of measurement.

Although this paper deals entirely with methodologies for evaluation, one should keep in mind that analytical evaluation is only one phase of the broad process of decision-making. By giving it preeminence here, we do not imply its actual preeminence in the entire siting process.

We carefully have drawn boundaries for our discussion so that primary attention could be focused upon methodological questions rather than political and social ones. One could easily argue that what has been eliminated is more important than what has been kept; we agree in spirit, but as always the normal constraints of time, expertise, and interest have dictated these boundaries. We assume that larger-scale policy decisions--for example, whether or not a facility is to be constructed at all--have already been taken; or alternatively, that larger-scale benefits and costs that are site-independent may be disassociated from siting itself. That is, the question whether a nuclear power plant or a highway should be built at all, while important and an issue of evaluation itself, is not considered here.

The paper is organized in four parts: siting decisions are discussed in general; then an overview of analytical evaluation schemes is presented along with their basis in measurement theory; three sets of methodologies are summarized and compared (cost-benefit analysis, matrix methods, and preference theory methods); and finally, application of the methodologies and general conclusions are discussed.

II. Siting and Public Decision-Making

1. The Siting Process

On a conceptual level the question of siting is straightforward: it is merely the comparison of favorable and unfavorable impacts of a facility according to consistent rules for evaluating desirability, and the selection of the site that is found to have the highest net desirability. In reality, of course, this process is complex, involving both the seemingly irreconcilable interests of coalitions and vague notions of what social policy principles ought to be used as measuring rods of desirability.

The initial criterion in reviewing sites is feasibility. For a site to be feasible, the predicted impacts of placing a facility there must be within bounds chosen *a priori*. These constraints may include: excessive cost, excessive environmental degradation, undesired land-use alterations, and inequity in the distribution of net benefits. This process of eliminating infeasible sites is sometimes referred to as *screening*. Sites which remain after screening are evaluated in depth (Figure 1).

In the evaluation stage careful predictions are made of the type and magnitude of impacts generated by placing the facility at each feasible site. Desirabilities of individual impacts are evaluated as a function of the importance of the social objective they bear on their magnitude, and their probability of occurrence. This procedure rests on identifying social objectives and specifying desirabilities of impacts against those objectives. Impact predictions, while often difficult to make with precision (Buehring, 1975), present technical rather than philosophical problems; whereas the central questions in evaluation, and those on which the entire analysis depends, are what social objectives are used for evaluation, and whose concept of desirability is adopted?

2. Social Welfare and Selectivity

Ideally, one would like to make decisions having a social impact in light of a general theory of social welfare using a comprehensive objective index, which is based on the ethical or normative precepts of the society. In reality, of course,

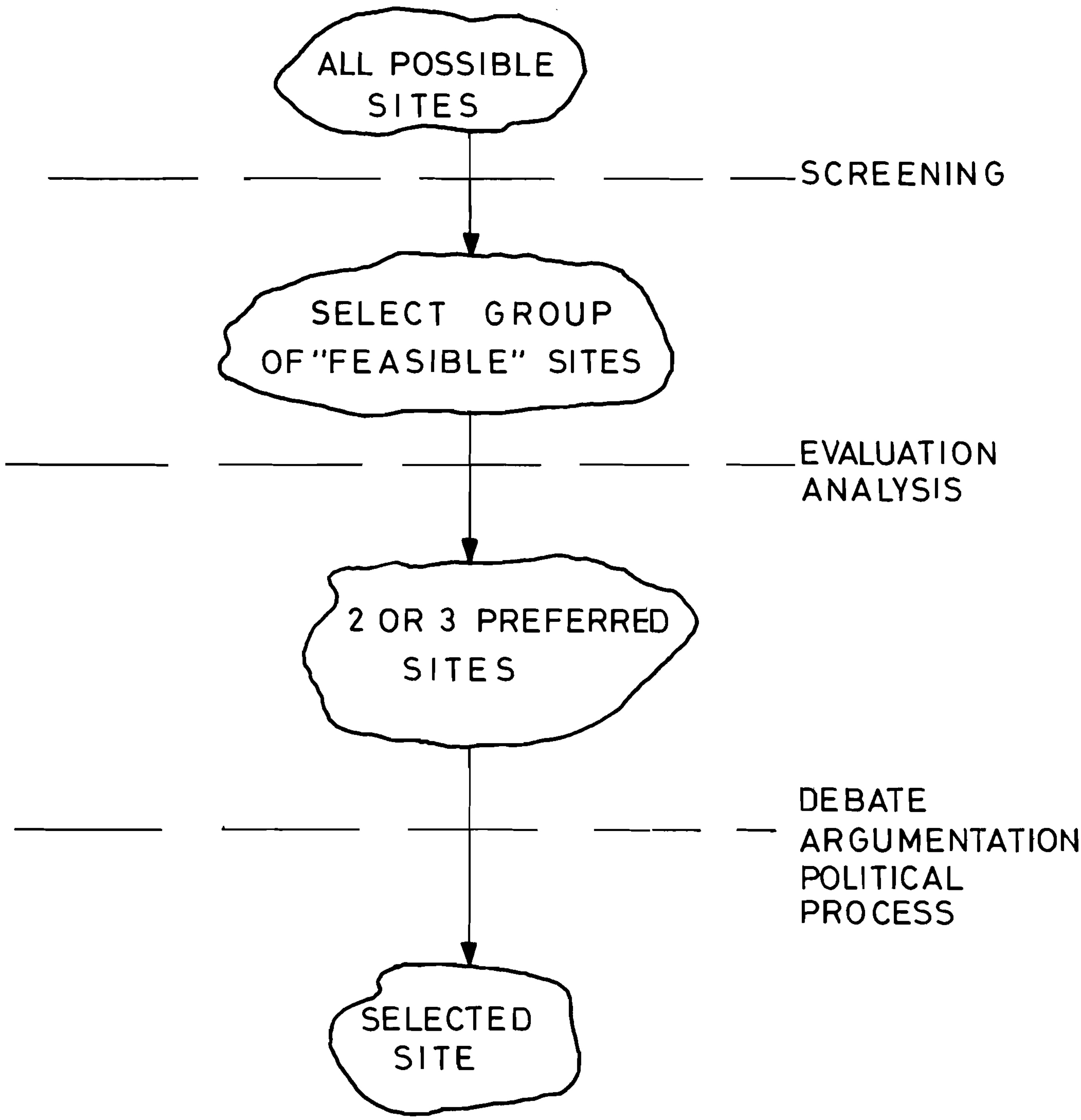
ALL POSSIBLE SITES
SCREENING
SELECT GROUP OF "FEASIBLE" SITES
EVALUATION ANALYSIS
2 OR 3 PREFERRED SITES
DEBATE ARGUMENTATION POLITICAL PROCESS
SELECTED SITE

FIGURE 1

attempts to develop a social welfare function have not been fruitful, so in practical decision-making a more pragmatic and less "objective" criterion must be reverted to.

Our ability to make comprehensive evaluations is limited not only by lack of a general welfare function, but also by our inability to predict the myriad of secondary, tertiary, and higher-order impacts which a decision generates. The 1960's thus saw the development of large simulation models, many of them for regional planning, whose purpose was to simulate interactions and dependencies via a logical chain too complicated to be analyzed intuitively. The hope was that this approach to analysis would enable us to predict indirect impacts and include them in decision-making. But this attempt, too, has not been entirely successful (Lee, 1973; Brewer, 1973).

This brings into clear perspective the problem of identifying and selecting important impacts for analysis. We must select a limited number of objectives against which we consider impacts to be important, and a limited set of indices for prediction. In assigning desirabilities to levels of those impacts, we must do so subjectively--if not in the way the final numbers are placed on impact levels, then in the way assumptions are made and data collected. The criteria and measurements represent value judgements by the analyst whether or not he readily admits it. There is a continuum between the analyst and the political decision-maker. In both cases decisions are made the same way: the analyst tends to use a larger criteria set, and explicitly combines his evaluations according to logical rules. But the philosophy of decision and the form of evaluation are the same at their philosophical foundations.

What is the overall criterion of evaluation? Given benevolence in government or a democratic ethic, the criterion of evaluation is the well-being of the population. In positive economics and democratic theory this is held to be the preferences of individuals within society. How these preferences are assessed and interpreted is integrally related to the technique used for comparing desirabilities of impacts against objectives. Assessment methods may be indirect as in using market structure and prices, or direct as in opinion surveys. Once again, the analyst's role in this process is to interpret those preferences from data and logically combine them so as to yield recommendations for the political decision-makers (who ultimately interpret desirabilities judgementally).

3. Siting vs. Planning Decisions

National and regional planning goes on at many levels, and it is in the analyst's interest not to confuse the proper distribution of authority and decision responsibility within that hierarchy. Not every decision made in society must involve a reassessment of the basic ethical and economic policies of society. In other words, the decision to site a nuclear power plant is not the most appropriate point for reassessing national energy policy. In actuality, the siting decision may be the only (or most accessible) point at which a citizen may exert pressure against what is perceived as an unresponsive political process; but from the point of view of governmental planning this is clearly not the case. On the other hand, though, gradations of planning responsibility are fuzzy, and the resources for analyzing major siting decisions may be much greater than those available for planning overall regional development; perhaps this is an inverted situation, but it is nevertheless the case. So, another facet of the selection question is, how broad does one make the impacts and societal objectives considered, and where in the analysis does one adopt the results of higher-level decisions as either constraints or scales of desirability? In a hierarchy of decision which is not rigid, this question assumes considerable importance.

Ostensibly, we have planning authorities whose business it is to evaluate proposals for regional development and to arrive at preferred scenarios. To the degree that such bodies do have sufficient expertise and financial resources to accomplish their mandate, impacts generated by siting a facility should be evaluated for their compatibility with these preferred plans. If the preferred plan calls for slow development and primarily agricultural patterns of land use, then a facility causing inharmonious land uses (e.g., large transportation facilities) generates undesired development impacts. In the reverse situation, a facility inducing larger local employment, and thus accelerated development, would be deemed more desirable than one that does not. In this ideal world the siting analyst's life would be simpler.

When no local planning authority exists, the ethical question arises, is it appropriate that the analyst treat questions of regional development policy. If such questions have not been dealt with, they *de facto* become his responsibility, and he must grapple with them. Conceptually, the task is clear, but practically it is difficult; the project's long-term indirect impacts on population, migration, settlement, and regional land use must be considered in the same way as are impacts against other objectives. Typically, this can only be accomplished by judgemental or conceptual models, or by rather large computer models which include complex interactions of employment, infrastructure development, and changes in environmental quality. The latter models suffer the disadvantages of all large models as discussed by Lee (1973).

If longer-term predictions of land-use and development impacts can be made, the analyst is still faced with the problem of evaluating the desirability of such changes. The time is past when simple economic indices of regional development (e.g., increases in tax base, increases in real income flow) can be used as positively correlated measures of desirability. At present even the desirability of regional development is in question. Local residents do not always favor increased development; or they may do so, while far distant urbanites prefer to maintain unspoiled rural landscapes--even if they are unlikely ever to visit the region.

In short, unless a well-conceived plan for regional development exists, the analyst, by default, must develop a surrogate plan. We would hold that this is not really his mandate, but a burden which is dealt him.

4. Coalitions and Equity

There are two distinct concepts with respect to the disaggregation of society into groups. The first is that individuals place different weights on the desirabilities of impacts and on marginal rates of preferential substitution among impacts; here, the question naturally arises whose definition of desirability ought to be used in siting decisions. The second concept is that of the distribution of benefits and costs over society. Large facilities have uneven spatial and social distributions of impacts, and one may value a level of equity in these distributions. We will address legitimacy of interest first, and then return to equity.

Welfare economics has attempted to structure a theory to account for differences in individual preference, and has succeeded mostly in proving the great difficulty or the impossibility of doing so. Pragmatically, therefore, in siting decisions one normally views differences in preference or definition of desirability as being represented by groups of opinion. While the term is misused in this context, we often call these assumedly homogeneous clusters of preferences interest groups, and we assume that the interests of individuals within groups can be approximated by a single structure of desirability for impacts. (In fact, this is not the case; interest groups either are not organized groups at all (e.g., see Olson, 1965), or are coalitions formed for attaining some common goal, but one sought by each individual within the coalition for perhaps very different reasons.) Such simplifications are undertaken to make the problem of analysis tractable, just as one makes simplifications in analyses, whether they be mathematical or purely judgemental constructs.

The ultimate burden in combining different concepts of desirability rests with political decision-makers, this being a fundamental function of the political system. The analyst's role is to indicate to the political decision-maker the implications of weighting different groups' interests in different ways on the "optimal" decision. In the more purely economic approaches to siting decisions, such as cost-benefit analysis, an assumption is made that differing preferences are naturally and properly aggregated in the market-place; yet even here, the desirabilities of non-market impacts (or impacts with which there is little experience) still require an artificial weighting and coalescence. If one uses the market-aggregated willingness-to-pay of urban and rural residents as a measure of the desirability of aesthetically pleasing landscapes, a value assumption is still made about the relative weights given each group, though the weights are not explicitly stated as they would be with other methods. No matter how a siting decision is evaluated, the preferences of different groups must be weighted. Methods that do not do so explicitly must do so implicitly; usually this means weighting all groups equally.

Conceptually, one can think of the question of weighting interest group preferences as movement along the so-called Pareto frontier. This surface is the locus of all decision alternatives (sites) for which no other alternative exists that would be equally preferred by all groups and more preferred by at least one. In Figure 2 no sites are available which, for the several impacts they generate, are more preferable to *both* groups A and B than, say, site #1. Here, we would hold that it is the analyst's role to determine those sites which are on the frontier, and the sensitivity of each group's level of desirability to movement along the frontier. The decision among sites on the frontier is innately political, although this task might be aided by sensitivity analysis which would indicate "optimal" sites for ranges of weights applied to each group's interests.[1]

The dynamics of the political process makes the view just presented myopic. At any one time many projects are being considered by political bodies, and often equity is achieved not within a single project over several projects. A project that favors one interest group over another might be offset by one which favors in reverse. In the democratic framework this is related to keeping constituencies satisfied (or placated) and is a natural offshoot of the legislators' self-interest in remaining in office. Thus, the question of whose measures of desirability we use is closely related to the concept of equity of impact distribution.

A fundamental tenet of contemporary political philosophy is that fruits and labors of society should be equitably shared by members of society. However, equity is one of those nebulous policy concepts mentioned in the introduction. No one is quite sure, in operational terms, what equity ought

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[1]The concept of Pareto optimality and the frontier are used here for illustration only. There are theoretical questions relevant to using Paretian analysis in actual decisions, one of which is taken up in Appendix II.

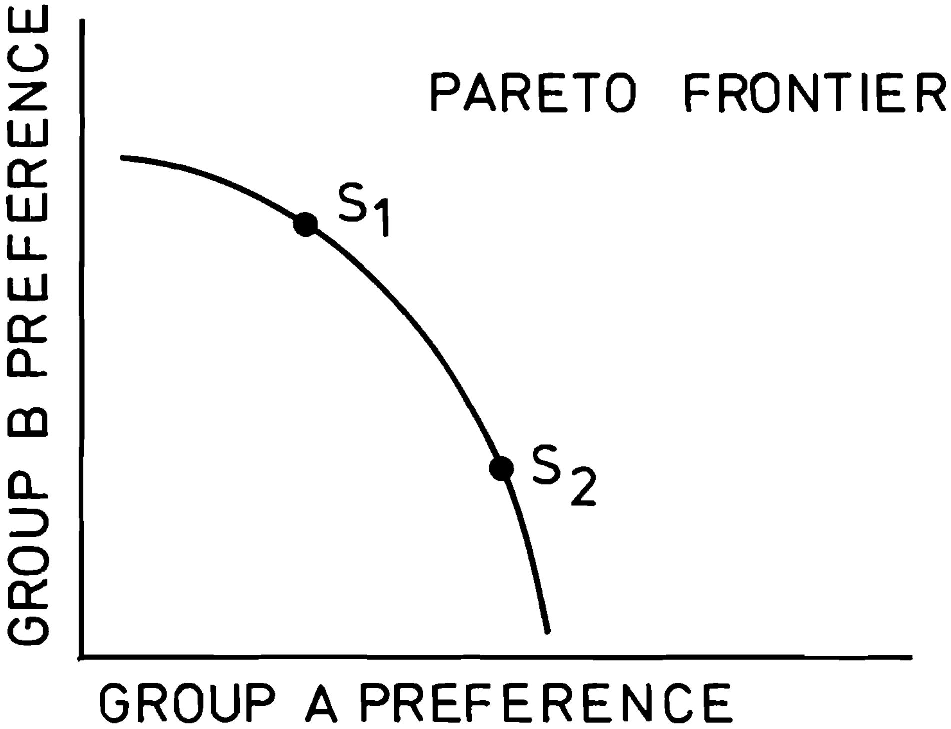
PARETO FRONTIER
S_1
S_2
GROUP B PREFERENCE
GROUP A PREFERENCE

FIGURE 2

to mean, but we all know that it's important. In traditional project decision-making, equity has been treated either as a prior constraint that a proposal must satisfy or as an "external" weighted in conjunction with economic efficiency. A project that is otherwise efficient in the sense of producing a net increase in benefit to society, irrespective of to whom it accrues (i.e., potential Pareto improvement), might be discarded if it produces what is politically viewed as a severely adverse distribution of those costs and benefits. More recently introduced methodologies, as discussed in Sections IV - VII, attempt to measure equity explicitly as one impact of the decision and subjectively assign desirabilities to it which can then be combined with other impacts. We are, however, far from a workable definition of equity or attribute scale that could be included in an analysis; even equity of income distribution generated by projects, a seemingly simple problem, is difficult to grapple with normatively (Mishan, 1971). The further complication, in siting studies, of the geographic distribution of effects (Figure 3) makes the problem exceedingly difficult unless purely judgemental approaches using political opinion are introduced.

Once again, though, to maintain our perspective merely at the single project level is naive. Political decision-makers almost invariably favor projects generating impact distributions as shown schematically by curve A in Figure 4 over those generating curve B, even though an analytic index of equity might rate A and B at about the same quantitative level of "inequity."[2] There is a quality difference in the inequity caused by A and B because, if need be, a purely redistributional project can be formulated, aimed directly at the groups adversely affected by project A. In a conflict

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[2]This example is due to H. Swain (personal communication, 1975).

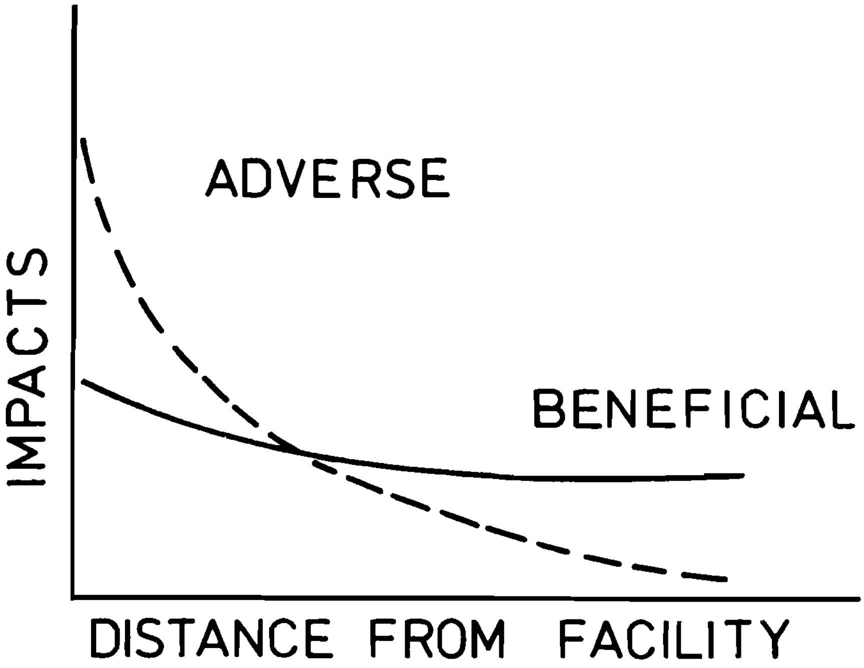

FIGURE 3

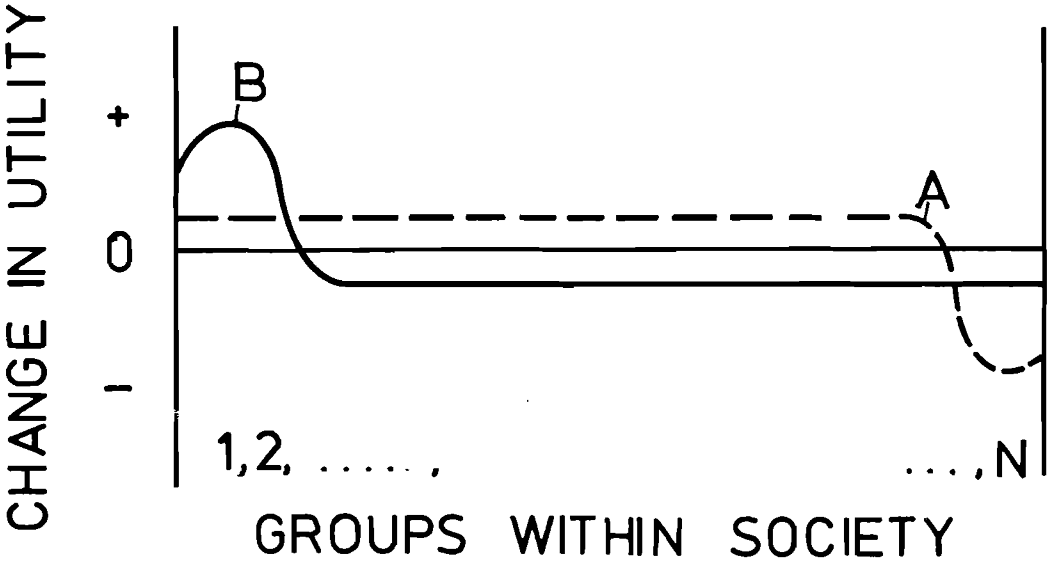

FIGURE 4

resolution sense, this would be the same as a side payment to adversely affected groups to "get them to go along" with the project--something which is not at all rare in siting major facilities. Techniques used to include equity in specific evaluation methodologies are discussed further in Sections IV - VI.

5. Temporal Distribution of Impacts and Irreversibilities

Benefits and costs accrue from a project non-uniformly in time. Capital outlays for facility construction are necessarily made at the very beginning, while financial returns on investment, social disruptions, and environmental impacts come at varying times, from almost immediately to the distant future. Some irreversible impacts, such as major ecological changes, continue in perpetuity. Ideally one would like some analytical way of treating these streams of benefits and costs.

Analytically, this evaluation might be simply represented by a series of the following type, in which NB_t is the net benefit of the project accruing at time t:

$$NB_{total} = NB_0 + v_1 NB_1 + \cdots + v_n NB_n \quad . \tag{1}$$

The question is how to evaluate the constants $v_1, \ldots, v_n$; and whether or not the aggregation ought to have a more complicated form than a simple sum (Meyer, 1969; Koopmans, 1960). This is a problem that has received extensive attention, yet remains unanswered.

The traditional way of handling intertemporal streams of costs and benefits has been to assume an additive form as shown in Equation 1 and adopt a discounting factor relating the value v_t to its predecessor by a constant ratio, r,

$$\frac{v_{t-1} - v_t}{v_t} = r = \text{discount rate} \quad . \tag{2}$$

Koopmans (1960) gives the necessary conditions for this form of discounting, called the "discounted sum," to be theoretically correct. The discounted sum has been generally applied in cost-benefit analysis, and considerable work has gone into techniques of establishing appropriate discount factors (e.g., Layard, 1972; Roskill, 1970; Mishan, 1971, UNIDO, 1972). Some of these are the market interest rate on capital, the marginal rate of productivity of capital in the economy, or simply a value judgement of political decision-makers. The time-aggregated net benefit (NB_{total}) of a project may fluctuate substantially on the basis of changes in the discount rate, and varying of this rate has often been used to justify bureaucratically favored projects that would not be justified by more impartial analysis (Berkman and Viscusi, 1973). Further, the normal procedures for establishing the discount rate are not entirely satisfactory because for societal projects, the discount rate reflects social policy on how much one is willing to forego now for future benefit. In a traditional sense, the best procedure, as with equity, is to do a sensitivity analysis using discount rate as a variable, and then see how high or low the rate would need to be to change the "best" decision.

Specifically with respect to siting decisions for large facilities, two points are important. First, many of these decisions are private ones involving private funding; this being the case, the discount rate for financial costs and returns can be chosen by the private agent and will probably reflect market costs of capital. Second, the siting decision as we have outlined it here is not a decision to construct or not to construct a facility, but is limited rather to where to construct it. Therefore, as a given type of facility constructed in different places generates approximately the same temporal distribution of impacts (although not in the same intensity), siting decisions are less sensitive to discounting than the overall project decision might be.

While discounted sum techniques may be appropriate for financial impacts even though the actual rate of discount is difficult to specify, the discounted sum is not so apparently appropriate for non-financial impacts (i.e., social and environmental ones), and the whole question of non-renewable resources is still in an embryonic state of analysis. An approach of the type used by Meyer (1969) may shed light on time streams of non-financial impacts as that work expands; similar comments can be made on work evaluating alternatives that exhaust non-renewable resources or generate irreversible impacts that is being undertaken by Krutilla and his associates at Resources for the Future (Fisher and Krutilla, 1974; Krutilla et al., 1972). At present, these remain unanswered questions.

An associated set of problems is that of option foreclosure, resilience, and incrementalism. One type of irreversibility, although not the type usually dealt with, is that of foreclosing options that might later have been open. Krutilla et al. (1972) discusses this, as does Walters (1975). Option foreclosure means that impacts generated by a decision will make future decision alternatives impossible. For example, siting a nuclear waste storage facility will mean that the site is forever unusable for other purposes. The degree of desirability of foreclosing future options depends on the probability that one would at some later time elect to use them, the time when that might occur, and the benefit that would have been derived from their use. In some cases, positive discounting factors (i.e., which give more weight to future benefits) might be appropriate to describe goods that will become increasingly scarse with time. Some of these might be open space, environmentally undisturbed wilderness, or non-renewable resources (Krutilla, 1972). Option foreclosure also deals with impacts that cannot be predicted, but that will change the environment of future decisions and thus change in unpredictable ways the options that would have become available (Walters, 1975). Perhaps the best way of treating such foreclosure practically is by instituting incremental decisions the results of which can be sequentially evaluated, and by designing alternatives which are resilient to unforeseen events. In siting, while incrementalism can be practiced only by building small facilities, resilience would mean selecting sites that are far enough removed from population, naturally undisturbed areas, etc., that unforeseen impacts would have little undesirability. Unfortunately, it is because of a lack of such sites that the issue has become so important.

A major issue growing out of resilience and option foreclosure is what Häfele has called "hypotheticality," that is, the problem of dealing with low-probability events with which we have no experience, (e.g., large-scale accidental releases of radiation from reactors) (Häfele, 1974). This problem increases in importance with rapid technological developments which exclude an incremental approach to decision-making. The question is not beyond the bounds of the siting decision since the major objection to urban sites is large-scale health and safety risks.

APPENDIX

Pareto Admissibility under Uncertainty

If equity is considered important by the decision-maker, an optimal alternative need not lie on the Pareto frontier defined by interest-group preference (Keeney, personal communication). In the case shown in Figure 5 the problem is to select site A or site B. These sites are associated with uncertain impacts along one attribute which lead to different levels of desirability (i.e., utility) for the two groups G_1 and G_2. Clearly, alternative A is a point on the Pareto frontier composed of the expected utilities of impacts, and has a higher expected utility for both G_1 and G_2 than alternative B, which must therefore be below the frontier. Yet, if the decision-maker considers equity to be an important attribute of any set of impacts, then he might favor alternative B to A, because no matter how impacts accrue, equity of impact will be maintained. Thus, under uncertainty an optimal decision alternative need not be on the Pareto frontier.

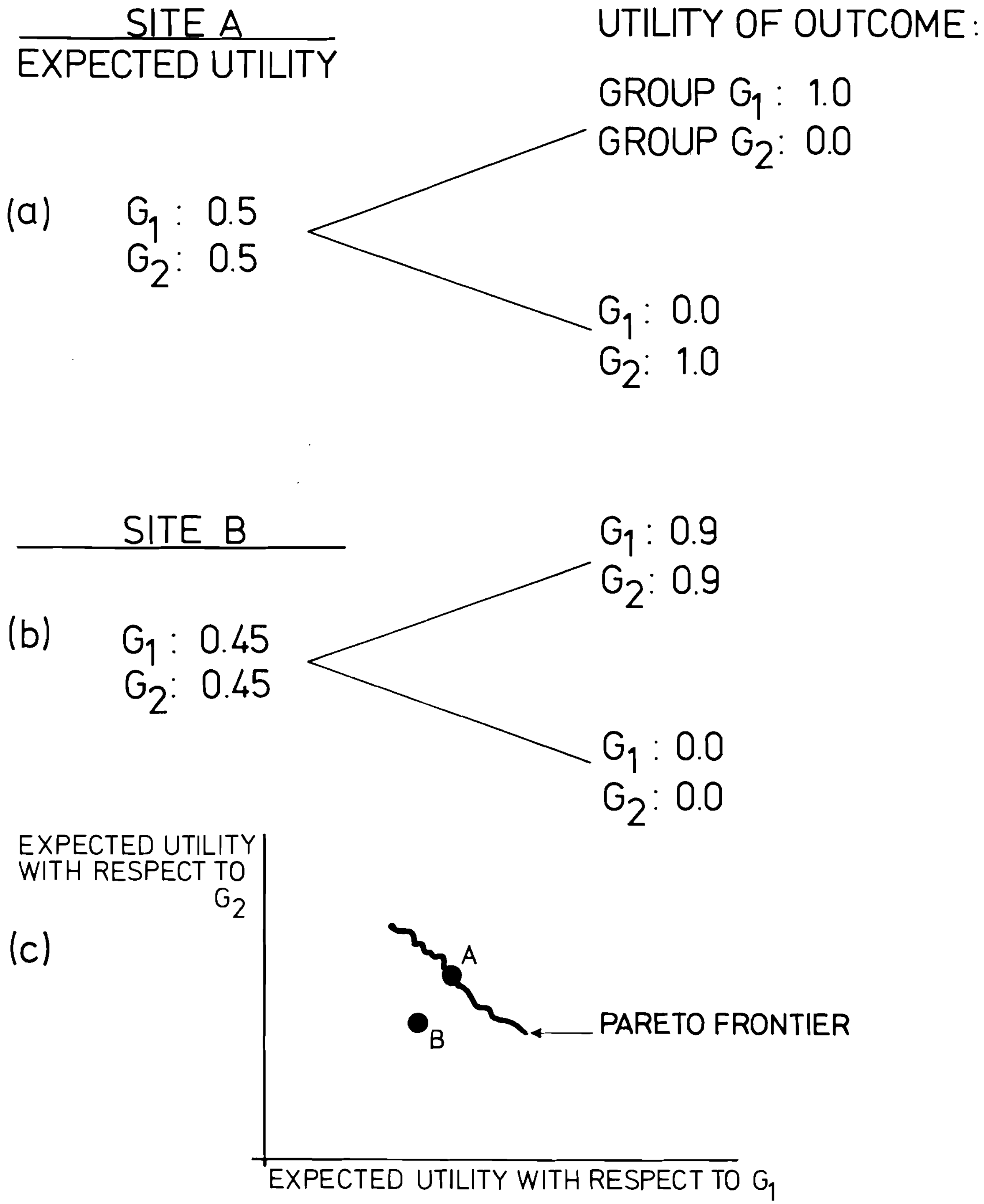
SITE A
EXPECTED UTILITY
UTILITY OF OUTCOME:
(a)
G1 : 0.5
G2: 0.5
GROUP G1 : 1.0
GROUP G2: 0.0
G1 : 0.0
G2: 1.0
SITE B
(b)
G1 : 0.45
G2: 0.45
G1 : 0.9
G2: 0.9
G1 : 0.0
G2: 0.0
(c)
EXPECTED UTILITY WITH RESPECT TO G2
A
B
PARETO FRONTIER
EXPECTED UTILITY WITH RESPECT TO G1

FIGURE 5

III. Structure of Evaluation Methodologies

Analytically, all evaluation methodologies have a similar structure. In this section we discuss that structure and introduce terms and notations to simplify our further comments.

Siting decisions are, in fact, decisions among variables in two sets: a set of possible sites, and a set of possible facility technologies. Jointly, these might be called the set of *feasible alternatives*. Symbolically, if the set of sites is $\underline{S} = [s_1,\ldots,s_v]$ and the set of facility technologies is $\underline{Q} = [q_1,\ldots,q_w]$, then the set of feasible alternatives is composed of all possible pairs (s_i,q_j) that remain after screening. As impacts depend on both the site and technology selected, "siting" decisions must involve both variables.

Feasible alternatives are judged by their impacts against a set of objectives society holds important--e.g., cost, environmental degradations, and social disruption. Since objectives are usually vague and qualitative concepts, a set of indices is chosen for measuring levels of impact against objectives. We will call these *attributes*. For example, to quantify the degree of impact a site-technology pair has on the objective "minimize water pollution," we might use the attribute "concentration of pollutant y in effluent waters." Associated with each objective is at least one scalar or vector attribute; let the set of attributes be denoted $\underline{X} = [x_1,\ldots,x_n]$.

Decisions are made on the basis of predicted impacts measured on the set of attributes associated with important objectives. These predictions are made judgementally by experts using mathematical and statistical models, basic concepts and relationships from the physical and social sciences, and the like. In general, these predictive relationships might be said to map site-technology pairs onto the attribute space. Since predictions are uncertain and depend on exogenous random variables, such as weather, accidents, and future population densities, they are actually probability distributions defined over the set of attributes. Collectively, we call these predictive distributions the set of *technological relations*, and denote them as the joint probability function

$$f(\underline{x},\underline{\theta}|s_i,q_j) \quad ,$$

in which $\underline{\theta}$ is the set of exogenous variables (Figure 6).

Implicit in the set of technological relations are not only impact predictions for a given site-technology pair, but also the *marginal rate of technical substitution* among impacts; that is, the rate at which it is technically possible to trade one impact for another (in an uncertain domain). For example, pollution emissions can be reduced if one is willing to increase project cost; or a natural wilderness area can be preserved if one is willing to site a power plant nearer to a densely populated area. The concept of marginal rate of technical substitution is an important one because it is, in some sense, half of the evaluation. The other half is the *marginal rate of preferential substitution*, the rate at which one impact can be traded for another without changing the aggregate level of desirability of the set of impacts. At the optimal decision (under certainty) these two marginal rates are equal (Figure 7).

The marginal rate of preferential substitution is implicit in whatever objective function is used to evaluate different sets of impacts. Objective functions are numerical representations of preferences for different attribute levels; the optimal decision is the one which has the largest objective function value. It is the nature of this objective function and of the assumptions implicit in its derivation which

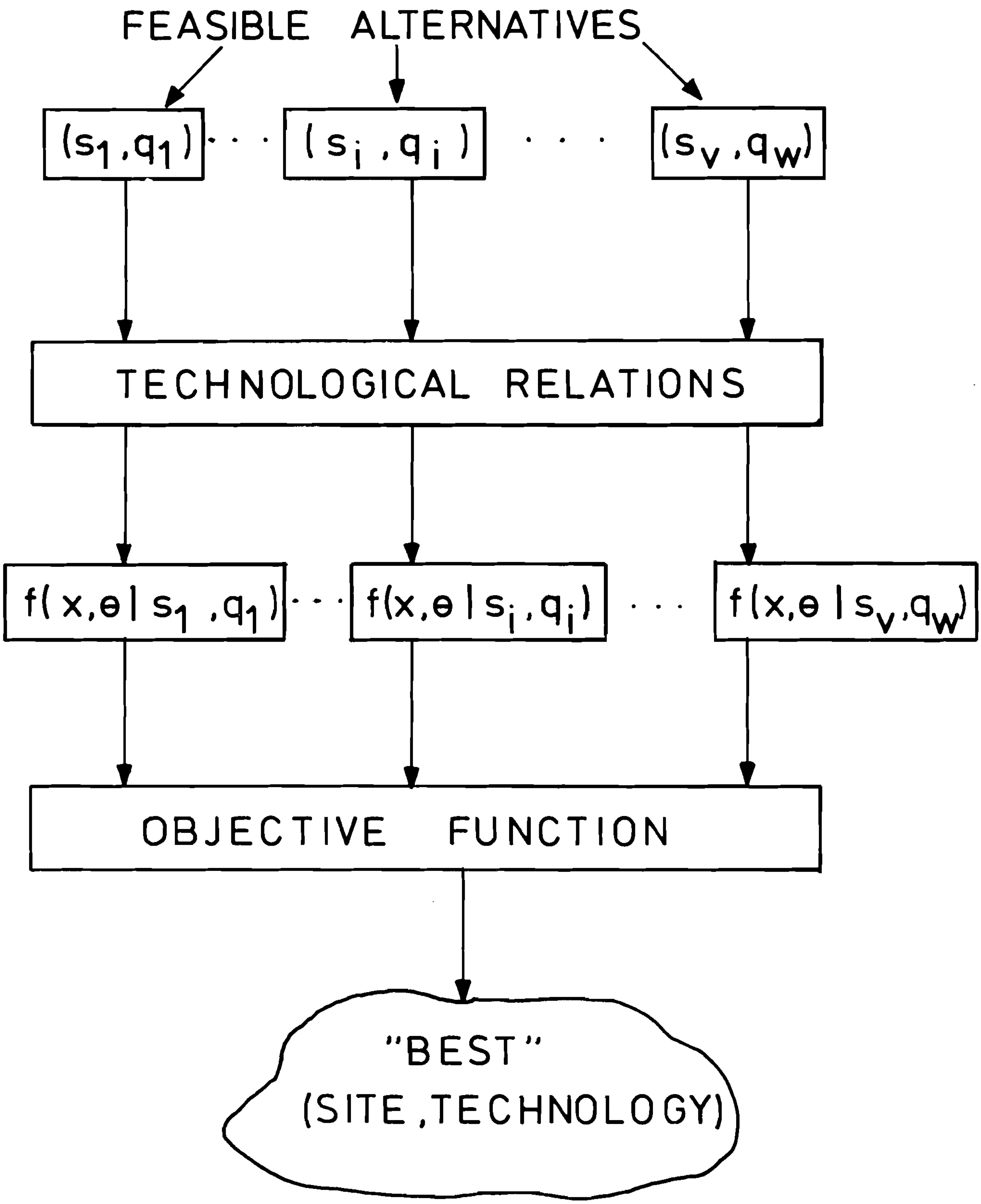
FEASIBLE ALTERNATIVES
(s_1, q_1) . . . (s_i, q_i) . . . (s_v, q_w)
TECHNOLOGICAL RELATIONS
$f(x, \theta \mid s_1, q_1)$ . . . $f(x, \theta \mid s_i, q_i)$ . . . $f(x, \theta \mid s_v, q_w)$
OBJECTIVE FUNCTION
"BEST"
(SITE, TECHNOLOGY)

FIGURE 6

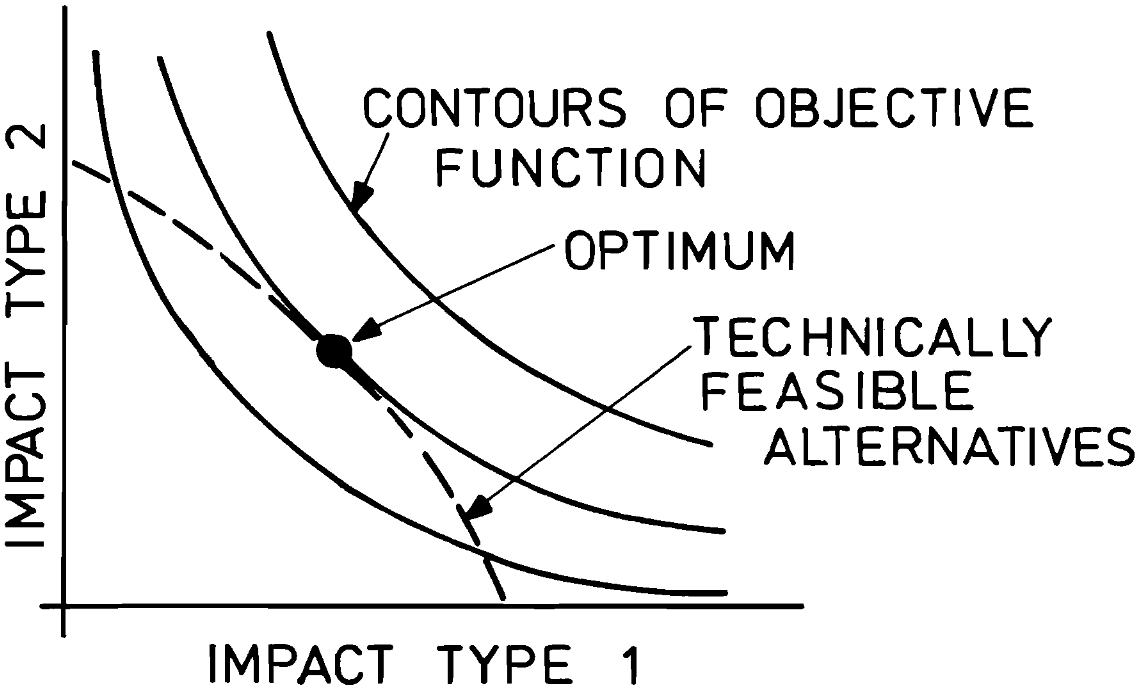
CONTOURS OF OBJECTIVE FUNCTION
OPTIMUM
TECHNICALLY FEASIBLE ALTERNATIVES
IMPACT TYPE 2
IMPACT TYPE 1

FIGURE 7

distinguishes evaluation methodologies from one another, and which is the focus of the present review.

1. Objectives

It is assumed here that objectives for siting decisions are known or can be generated. Some of these objectives are "to provide adequate service," "to minimize environmental degradation," "to minimize social disruption," and "to minimize adverse health and safety effects." Most of them can be identified on the basis of past decision-making (or the criticism of that decision-making) and from the siting literature. Certainly an extensive list of impacts that might be (and for nuclear power plants in the United States, must be) accounted for appears in *USAEC Guide 4.2* (1973).

The set of objectives should have several properties: it should be *complete*, in the sense that it contains all important considerations on which a decision has impacts; it should be *non-redundant* in the sense that "double-counting" is minimized, and it should be of *minimum size* to facilitate analysis.

Hierarchies of objectives exist; it is only at the lowest level that objectives become specific enough for one to grapple with them analytically. At high levels are such objectives as those cited above, which are too abstract to use in an actual decision. In constructing their hierarchy, one attempts to structure objectives so that each highest-level objective comprises sub-objectives which fully describe its important aspects and yet can be dealt with more straightforwardly. For example, within or below the objective "minimize environmental degradation" might be the sub-objectives "minimize adverse impact on aqueous life forms," "minimize adverse impact on terrestrial life forms," and "minimize aesthetic degradation of landscape and adverse aesthetics of water and air pollution"

(Figure 8). Specification of sub-objectives not only facilitates analytical treatment, but also *clarifies* and *defines* the upper-level objective for the purpose of analysis. Thus care must be taken to assure that the substrata of the objectives hierarchy do actually meet the intentions of the analyst or decision-maker. One mechanism for constructing the objectives hierarchy is to ask whether or not sub-objectives *do* completely describe upper-level objectives, and if they do not what additional sub-objectives must be provided so that they do.

It is not our purpose here to dwell on the question of how inclusive or finely divided the objectives hierarchy should be; this problem is treated elsewhere (e.g., Manheim and Hall, 1967; Keeney and Raiffa, 197X). Certainly, however, all sub-objectives that may change the result of analysis must be included, although sometimes they may be treated in sets to facilitate quantification (Ting, 1971). In the end, the point at which formalization stops is a judgemental problem.

2. Attributes

Since objectives, even at lower levels in the hierarchy, are usually not measurable concepts, indices must be specified over which impacts can be scaled; these are called attributes in the present paper. Given the sub-objective "minimize thermal pollution to receiving waters," a typical attribute might be "increase in temperature of receiving waters in degrees centigrade." Listings of typically applied attributes may be found in USAEC (1973) and in Keeney and Nair (1974). With each lowest-level objective some attribute is associated, which itself may be either a scalar or vector.

Individual attributes must be, in the terms of Keeney and Raiffa (197X), *comprehensive* and *measurable*. Comprehensiveness is the property that the level of impact as measured on

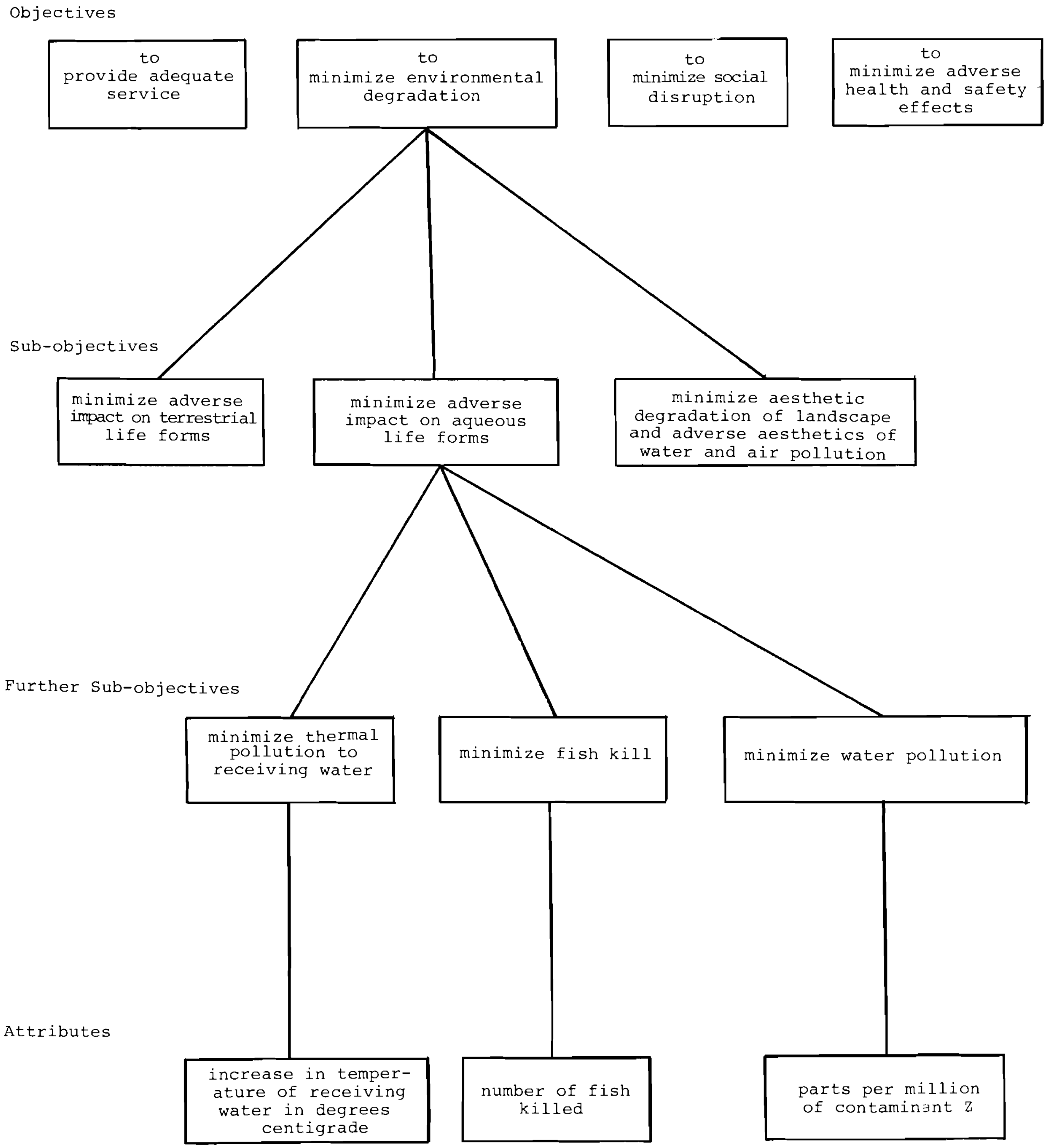

Figure 8

Example of an Objectives Hierarchy

an attribute fully expresses the degree to which the associated objective is achieved; measurability is the property that predictions can be made about the impact of a proposed site and technology alternative in terms of that attribute, and that the objective function (i.e., desirability) over values of the attribute can also be assessed.

The *set* of attributes should also display two properties, *non-redundancy* and *minimum size*. The set should be non-redundant so that impacts are not double-counted (e.g., see McKean, 1958) and of minimum size for analytical tractability.

The set of attributes associated with the objectives hierarchy and each attribute itself do not uniquely follow from the objectives, and only with a small fraction of the objectives considered do attributes immediately suggest themselves. Thus the selection of attributes may itself affect the outcome of analysis; one is well advised to proceed with great care and to assess retrospectively the sensitivity of analytical results to attribute selection.

Attributes that do follow immediately from an objective are said to be *natural* attributes. For example, if one sub-objective were to "minimize 'fish kill'," a natural attribute would be "number of fish killed." When an attribute does not follow immediately from the objective, as is normally the case, a *proxy* or *surrogate* attribute must be employed. For example, one might associate the attribute "parts per million of chemical contaminant Z" or "BOD" with the objective "minimize water pollution." These are not direct measures of the water quality the associated objective deals with, but rather are correlates, and may be chosen either because the primary property is inherently unmeasurable or because the natural measure is analytically intractable. To specify water pollution adequately, for example, would require a vector attribute of large dimension, so large that it could not be used in analysis.

A second reason for choosing a proxy attribute is that data may be more easily obtainable for it than for an attribute that seems to follow more naturally. This may be due to ways in which data have been historically collected or aggregated, because certain types of monitoring are cheaper or quicker than others, or because it is easier to specify the objective function over some attributes than others. In cost-benefit analysis and other methods which use money as a measure of desirability, this increased ease may arise because some attributes have closer analogs in the marketplace than others; and in methods such as utility analysis which use subjective valuations of desirability, because individuals find it easier to think about certain measures of impacts than about others.

In siting problems impacts arise for which even proxy attributes cannot be identified, either because adequate indices have yet to be developed for very complex phenomena, or because the impact seems inherently non-quantifiable. In such cases scenarios are often specified in qualitative terms and values of desirability assessed directly over the scenarios. This technique is receiving increasing attention in problems of facility siting, particularly with aesthetic impacts such as visual quality of the landscape (Jones et al., 1974; Burnham et al., 1974). At present these approaches generally specify a rating scale associated with adverbal descriptions and scenarios, rate impacts of contending alternatives along that scale, and subsequently assign desirabilities to the scale. As this work proceeds, proxy attributes or scales may be developed which better lend themselves to quantified description (Holling, 1973).

Money is often taken as an attribute with which to measure the impacts of site technology pairs. Indeed, with such methods as cost-benefit analysis there is a strong bias towards expressing as many impacts as possible in monetary terms since impacts are coalesced in monetary units. There is nothing improper about this approach, as long as impacts can be readily and comprehensively expressed in monetary units. Often, however, money is used not as the attribute of impact, but rather as the measure of desirability of an impact which is itself measured along another scale--for example, a monetary value is assigned to each fish killed by pollution. As desirability may be expressed in any consistent unit, again there is nothing innately improper in this approach. However, some units, such as money, may have interrelationships within the measure itself which are not shared by whatever one is trying to measure; the analyst must be careful that properties of the measure not reflected in the phenomenon are not employed in the mathematical analysis. This is an important point which will be developed later in this section.

3. Objective Functions

We have already said that the distinguishing characteristic of evaluation methodologies is the form of the objective function. We now turn attention to properties of objective functions that distinguish one from another. Figure 9 lists these properties.

Desirability of an impact may be measured to an ordinal, interval, or ratio scale (a brief review of scaling theory is presented in Appendix III). Admissible operations on measurements of desirability depend on the scale used. If desirability is measured to an ordinal scale, as with some matrix methods, then the operations of addition and multiplication necessary for aggregation are not permissible. Thus, aggregating ordinal data yields numbers whose relationships to one another have no meaning. If desirability is measured to an interval scale, then ratios of desirable to adverse impacts have no meaning. One is generally reticent about making

Level of Scaling
Linearity of Desirability over Individual Impacts
Independence or Non-independence among Impact
    Desirabilities
Analytical Treatment of Uncertainty
Marginal Rates of Preferential Substitution
"Objectivity"
Explicit Aggregation

Figure 9
Characteristics of Objective Functions

stronger assumptions than one must, but practical advantage can be realized by defining desirability to a higher scale than is theoretically necessary. Decisions among alternatives having multi-attribute but deterministic impacts require only that desirability be measured to an ordinal scale, and in fact Major (1974) has done so in water resources location problems. In practice, however, it may be much easier to assess and computationally handle desirability if it is measured to an interval or ratio scale. Of course, this ease of application is bought with more restrictive assumptions.

The level of scaling to which impacts are measured and that to which desirability is measured need not be the same. For example, financial costs of a project are measured in monetary units, that is by a ratio scale, yet the desirability of levels of cost may be only an interval measure. On the other hand, impacts such as visual aesthetics may be measured only to an ordinal or even nominal scale, yet the desirability may be measured to an interval scale, or even a ratio scale (e.g., "willingness-to-pay").

Given an interval or ratio scaling for desirability over one attribute, the objective function may be linear or non-linear (Figure 10). Assuming that each increment of impact is just as important as every other increment leads to linearity, as when one assigns a unit cost and multiplies by the number of units. Linearity means constant marginal rate of changes of desirability with unit increases in impact.

The desirability of impacts measured over multiple attributes may be either independent or non-independent. Stated another way, the level of desirability of an impact versus other impacts may or may not depend on the levels of the other impacts. For example, the decrease in desirability caused by a unit increase in project cost may or may not depend on the level of environmental impacts. If the unit cost increase is

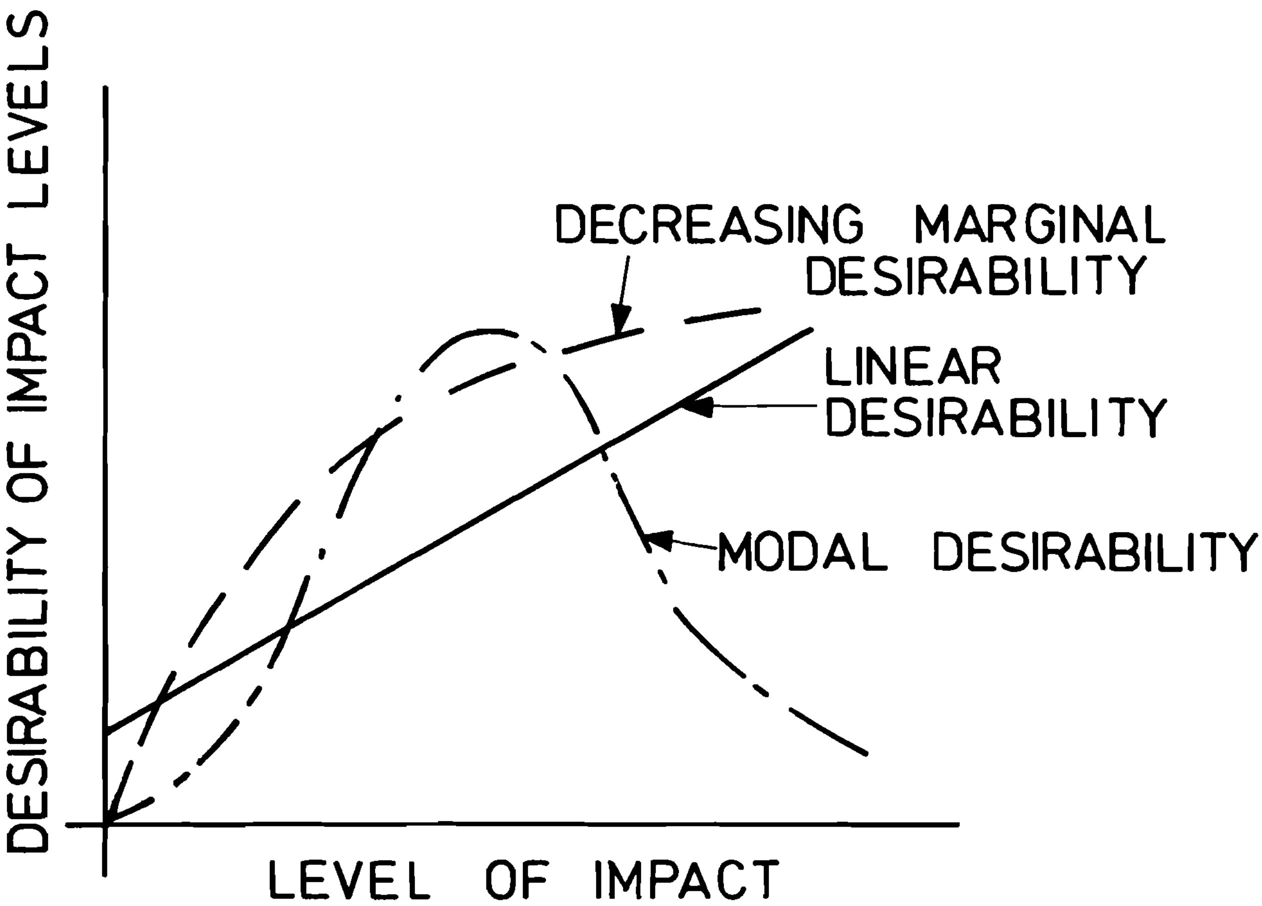
DESIRABILITY OF IMPACT LEVELS
DECREASING MARGINAL DESIRABILITY
LINEAR DESIRABILITY
MODAL DESIRABILITY
LEVEL OF IMPACT

FIGURE 10

considered less important for a project with very low environmental effects than for one with high environmental effects, then the desirabilities are non-independent; they do not follow the relationship

$$\mathcal{D}(\text{cost, environmental effects}) = \mathcal{D}(\text{cost}) + \mathcal{D}(\text{envir. effects})$$

Independence among the desirabilities of impacts must be distinguished from technical independence among them. Two impacts such as visual aesthetics and heat release may be technically independent in that the beauty (or lack thereof) of a facility might play no part in the level of pollutants released, or vice versa; while the marginal desirability of increases in pollution may depend on the desirability of visual aesthetics of the facility. Conversely, two impacts such as cost and pollution release may be technically dependent but preferentially independent; the *desirability* of a unit decrease in pollution release might be the same if the facility costs \$1.0 million or \$10 million. This is a simple but important distinction.

If an objective function specifies linear changes in desirability and independence between the desirabilities of different types of impacts, then the marginal rate of preferential substitution between impacts is constant over all impact levels. This would imply, for example, that if one were willing to increase the facility cost from \$10,000 to \$10,100 to lower effluent pollution concentrations from 2% to 1%, then one would be equally willing to invoke a cost increase of \$10 to \$110 to realize a pollution decrease from 10% to 9%. Similarly, if one were willing to increase cost by almost \$100 to realize a decrease in pollution of from 1.5% to 1.0%, then one should be willing to increase cost by another \$100 (and no more) to realize a further reduction to 0.5%.

Another characteristic of objective functions is whether they reduce evaluation to a single index. In other words, are all impacts aggregated? Methods such as cost-benefit analysis do aggregate, others, such as Bishop's Factor Profile (1972), do not. This represents a philosophical distinction between methods. Although human beings certainly do aggregate in reaching decisions, and politicians or decision-makers must aggregate in any public decision, the issue of dispute is whether or not this may be done explicitly and analytically or only through judgement. Adherents to the former position would say that only in explicitly aggregating can one recognize underlying assumptions and possible biases; adherents to the latter, that the judgemental process of aggregation is so complex that simplified analytical procedures cannot do justice to its full richness and texture. Both arguments have merit. Empirical evidence in experimental psychology (Edwards and Tversky, 1967) would indicate that even the rigorous constructs of rational decision-making represented by utility theory and Bayesian probability does not always perform as well as human judgement. It is difficult to know from historical records whether such theory would have improved decisions made with respect to civil works development (or anything else for that matter). On the other hand, falling back on the sanctity of judgement does open the door to personal biases, and perhaps more importantly to the attempt to grapple intuitively with more impacts than one can remember at any one time. Between these extremes is the idea of aggregating impacts at the sub-objective level in the objectives hierarchy (e.g., aggregating all environmental impacts), and judgementally aggregating across main objectives. This course has the advantage that political decision-makers, while being wary of explicitly weighting impacts against one another--for example, environmental against financial--for fear of political repercussions, may be willing to explicitly weight different environmental impacts with respect to one another.

Objective functions also differ in how they treat uncertainty in impact predictions. Uncertainty enters predictions in two ways: it may arise from the uncertainty of future conditions such as population density or geophysical phenomena (e.g., floods, earthquakes, tornados), or from an inability to predict (i.e., from lack of knowledge). Inadequate information, e.g., on health effects of radiation, is of the latter type. In terms of the siting decision these two types of uncertainty have identical consequences and are therefore the same. An objective function may either treat uncertainty analytically or leave it as an external for later consideration. In any event, to account adequately for the true net desirability of feasible alternatives, an objective function must explicitly (whether or not analytically) account for uncertainty.

Finally, objective functions differ in the degree to which they are "objective." In the sense we use the term here it means that the analyst's influence on measures of desirability is small. Plan evaluations are always subjective to the degree that they depend on the preferences of people, whether a small group of policy makers or the entire population. However, measures may depend to some extent on non-enumerated interpretations of the analyst, and this is what we take to be lack of objectivity. By this rule elections and many types of market data would be classified as almost purely objective, since little interpretation of the analyst is involved. Color coding schemes (e.g., Goeller, 1974) and the like are highly non-objective.

4. Assessment

All methods of evaluation which would compare favorable and unfavorable impacts of proposed facility sitings to arrive at some ranking rest ultimately on how the assessments of desirability are made. That is, they depend at their foundation on the procedure for collecting desirability data. We have already spoken of attributes as scales along which the impacts of a project can be measured; we must also speak of how to associate desirabilities with those scalings.

All assessment techniques infer desirability from behavior, whether it is expressed in the market-place or in replies to an analyst's questions. All assessment techniques make assumptions about the interrelationships of desirability, and then use the structure that derives from those assumptions to draw inferences from empirical data. Very roughly, analysts fall into one of two groups with respect to their philosophy of assessment. The philosophy of the first springs from economic planning theory and views assessment as inference from market data; the second, from sociology and "systems analysis" and views assessment as inference from the direct replies to an interviewer's questions. While these two views might be taken merely as opposite ends of a continuum, it is of interest to look at each in isolation.

A. Market Approaches

In a free-enterprise economy it is assumed that the desirability (or utility in an economic sense) of a commodity is reflected directly in the amount of money people are willing to spend for it at the margin. This is a strength of the market-place and the justification for using market prices in evaluating impacts of decisions. For direct impacts of siting, this approach to desirability valuation works well; we have substantial experience with it and understand its pitfalls. Further, the analyst's subjective input is minimized relative to other evaluation techniques, and is relatively easy to discern. Thus there are strong arguments for its use.

Briefly, market approaches first use the set of technological relations to predict impacts along a set of attributes (which need not be monetary units), then associate levels of impact on these attributes with monetary values. For example, if an impact attribute were "change of estuary temperature in ^{o}F," one would subsequently associate some monetary cost or benefit with each degree of temperature change. The mapping from attribute to money need not be linear, although in practice it often is. The assignment of monetary units derives from market data either directly or indirectly, and a spectrum of indirect techniques has been developed (e.g., Dorfman, 1965; Layard, 1972; Kendall, 1971).[3] Most of these techniques, however, have been developed to evaluate indirect benefits of a project, while at present techniques for handling indirect *costs* are perhaps insufficient for an adequate accounting (Joskow, 1974; Ross, 1974).

The deficiencies of market approaches, which have often been discussed in the cost-benefit literature (e.g., Dorfman, 1965), are summarized below.

1. Desirabilities of "non-market" objectives, such as equity, flexibility in future options, and "balanced" regional growth, cannot be evaluated and thus remain external to the analysis.[4]

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[3]These methods include shadow prices and opportunity costs, compensation costs, willingness-to-pay for or to avoid similar impacts, cost of providing benefits in other ways, and the like.

[4]One could argue, of course, that desirability can be expressed in monetary as well as any other units; so the degree to which these objectives are met can be associated with monetary desirability. However, this merely transforms the process to one of direct assessment, using money as a scale; it no longer remains a market approach.

2. The use of monetary units implicitly assumes certain interrelationships about desirability, whether they are intended or not--specifically, linearity over money, independence among impacts, and constant marginal rates of preferential substitution among impacts.

3. Some impacts are very difficult to evaluate because existing market mechanisms are distorted or non-existent (e.g., environmental impacts, health impacts), or because we have no experience with them.

4. Market approaches distort the real desirabilities of impacts toward their market-like facets. The real undesirability of water pollution, for example, may be only partly captured by its economic implications; similar arguments can be applied to reduction of mortality rate, regional development, and other impacts.

B. Direct Assessment

Direct approaches go straight to individuals and by means of questionnaires, simple games, and related techniques infer desirability of impacts. These approaches have been developed primarily in the literature of social research and public opinion surveying (e.g., Hansen et al., 1953; Hyman, 1954), and in that of applied decision theory (e.g., Raiffa, 1968).

Opinion sampling is well known, and has well-known pitfalls and biases (Webb et al., 1972); in general these need not be enlarged upon here. Opinion sampling yields qualitative sentiments about the desirabilities of impacts, and most often treats feelings about each type of impact in isolation. (Question: "How would you like to live next to a new highway?" Answer: "Not much.") Often, this means that the results of opinion surveys are difficult to interpret; only in rare cases do they yield quantitative data. The results of opinion surveys do give the analyst or policy maker a good general idea of the sentiments of groups involved, as well as identifying interests (Collins, 1973).

At the other end of the spectrum of direct approaches is the method of "preference assessment" which has been developed in the field of applied decision analysis (e.g., Raiffa, 1968). This approach is oriented toward evoking quantitative statements of preference for impacts and trade-offs among impacts. The method follows from the structure of preference assumed in decision analysis, which in that literature is called a "utility function" (Section VI). Accepting the axioms of preference upon which utility theory is based (Appendix VI.B) leads to an interval scaling of desirability whose mathematical properties can be derived. These properties often allow preferences over a range of impact levels to be estimated by making a small number of measurements.

The procedure for assessing utility functions is based on asking subjects to select preferred alternatives in hypothetical gambles (Appendix VI.A). By presenting hypothetical gambles with multi-attributed outcomes and by varying levels of probability associated with "winning" and "losing," one can have the subject make decisions that force him to implicitly express multi-impact desirability; one can then back-figure preference measures reflected in his answers. Normally, a certain level of redundancy is included in the questioning, and this process is iterated until internally consistent utility functions that the subject retrospectively agrees with are developed.

The strengths of direct methods vis à vis market approaches is that they allow treatment of impacts with which we have little or no economic experience; that they reflect opinions and feelings which are current (whereas market data are often years old); and that they allow treatment of as yet unrealized impacts, although the whole question of "hypotheticalities" in public or quasi-public decision-making remains a sticky problem.

Opinion surveys and the more quantitative methods of decision analysis are end-points of a spectrum of methods, whose use depends on available time, money, and resources, and on the level of precision required. The question resolves to one of investment in public sampling vs. error in resulting quantifications of desirability. The latter end of that spectrum consists of methods that bring out quantitative tradeoffs among the desirabilities of impacts; the data one receives from this end of the spectrum are much more useful than those from the other end, but cost more.

Several important deficiencies of direct approaches are listed below.

1. The ordering and even the wording of questions introduces bias errors of whose magnitude and direction the analyst is ignorant.

2. Subjects may have preferences for impacts but be unable or unwilling to verbalize them.

3. Even if, after great introspection, a subject can verbalize his preferences, are these the same as would be inferred from his behavior (i.e., in action) and how could you ever find out? If it is not, which is more proper? Clearly one would be measuring something different other than what is measured by market approaches.

4. Cost constrains the number of individuals interviewed and the depth of the interviews. This leads to larger "estimation errors" than market approaches which generally have larger data bases.

5. Assessment techniques involve hypothetical gambles and therefore depend not only on subjective preference but on subjective probability as well.

6. Non-naive subjects sometimes deliberately mislead interviewers in the hope of biasing decisions toward their true preferences (i.e., "gamesmanship," or what Swain (personal communication) calls the "garden path effect").

C. Combined Approaches

There is no reason why market and direct approaches cannot be combined for a better description of desirability than either approach leads to in itself. This is generally not done because analysts approach problems with a prechosen decision methodology, carrying with it a philosophy of assessment.

While work is needed to develop a combined approach, such an approach might use market techniques to measure economic impacts or impacts that are easily and justifiably treated with market data, and direct assessment to measure non-market impacts (and those which are difficult to measure behaviorally, such as mortality rate). Sets of assessments could overlap, and could be calibrated with respect to each other to reduce bias errors. A second approach would be based as this one, but use market data as prior information in the Bayesian sense, and modify those data by direct assessments in the normal Bayesian scheme of updating (Baecher, 1975).

APPENDIX

Measurement Theory

One assigns numbers and symbols to events and objects because mathematical relationships among properly defined numbers and symbols have been extensively studied and are well known. Since some of these relationships may be shared by the events and objects, one may by analogy infer properties of the events and objects that have not been observed or are not immediately obvious. However, one must be explicit about relationships among the events and objects, because numbers and symbols may be related in ways in which the events and objects are not (Ackoff, 1962).

The relationships one assumes to hold between the events and objects one assigns numbers to are implicit in the scale used. The following four scales are generally recognized.[5]

1. Nominal Scales group elements into classes; for example, a facility site might be either inland or coastal.
2. Ordinal Scales rank elements with respect to some dyadic relationshp (i.e., "greater or less than" relationships). The Mercalli scale of earthquake intensity is an ordinal scale.
3. Interval Scales introduce a unit of measurement; distances between elements on the scale represent distances between them in some relationship defined over them. The Centigrade temperature scale is an example.

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[5]Stevens (1959) and Stevens & Galanter (1958) suggest others, but they are primarily of theoretical interest.

4. Ratio Scales introduce the property of absolute zero in addition to interval properties; ratios of scale values represent ratios in the relationship defined over the elements. Money is a ratio scale.

The scale to which events or objects are measured also defines permissible mathematical and statistical operations on the resulting measurements (Table 1). Because the scale specifies allowable operations, the operations required by an evaluation methodology dictate the level of scaling required. Simple comparison of deterministic impacts requires only ordinal scaling (e.g., indifference curves--Section VII); analytical inclusion of uncertainty requires interval scaling (e.g., von Neumann-Morgenstern Utility--Section VII); ratios of desired to adverse impacts require ratio scaling (e.g., cost-benefit analysis--Section V). Applying inadmissible operations to measurements result in numbers whose relationships to one another have no meaning. For example, if different alternatives have impacts against some objective whose desirability we can ordinally scale (best, second best, ..., worst), and if we assign the numbers 1,2,...,n to those desirabilities, then we cannot add the desirabilities together nor weight them to form an aggregate average.

Table 1

(after Stevens, 1959)

Scale	Empirical Operations	Group Structure	Measure of Location	Dispersion
Nominal	determination of equality	permutation group $x' = f(x)$ where $f(x)$ is any one-to-one substitution	mode	information, H
Ordinal	determination of greater or less than	isotonic group $x' = f(x)$ where $f(x)$ is any monotonically increasing function	median	percentiles
Interval	determination of the equity of intervals or differences	linear group $x' = ax + b$ $a > 0$	arithmetic mean	standard deviation
Ratio	determination of equity of ratios	similarity group $x' = cx$ $c > 0$	geometric mean harmonic mean	percent variation

IV. Cost-Benefit

Ever since Dupuit observed that more general benefits accrue to society than are manifested in revenues, decision-makers have been searching for techniques that can include all of these in one analysis. Perhaps the most-used technique is cost-benefit analysis. Here, a project is analyzed by summing economic benefits to all of society and comparing them with economic costs; if the former exceed the latter, then the project is either deemed favorable for investment or ranked against alternatives. Cost-benefit has been subject to debate and refinement for decades. The purpose here is not to present the spectrum of opinion, but to review some basic or implicit assumptions of the technique, to discuss the ease of applying it for site evaluation, and to compare it to other methods of analysis.[6]

During the New Deal era, cost-benefit analysis was adopted in the United States as a tool to evaluate public works programs. The returns on these projects were often insufficient to interest private investment, but were attractive to the government because total benefits often exceeded costs. The Flood Control Act of 1936 institutionalized the use of cost-benefit analysis, which has remained the primary tool for evaluating public works programs ever since. This Act set the important precedent for U.S. government policy that benefits "to whomsoever they accrue" should exceed costs, and did not require an enumeration of the recipients. Since the Act, the U.S. government has made major efforts to incorporate modifications and extensions into the general procedure (see U.S. studies of 1965, 1971),

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[6]More detailed reviews and discussions of cost-benefit theory and its problems are given in Prest and Turvey (1955), Mishan (1971), Maass et al. (1962), Marglin (1967), Eckstein (1958), and UNIDO (1972).

and cost-benefit techniques have been applied to decisions in such disparate fields as public health, outdoor recreation, and defense, and in both the public and private sectors (Dorfman, 1965).

In cost-benefit analysis the only criterion of decision is economic efficiency. This criterion has traditionally been taken either to be the ratio

$$B/C = \frac{\sum b_i}{\sum c_i} > 1.00 \quad , \tag{3}$$

or the difference

$$B\text{-}C = \sum b_i - \sum c_i > 0 \quad , \tag{4}$$

where the b_i's and the c_i's are benefits and costs, respectively, expressed in monetary terms.

Benefits are commonly separated into direct and indirect. The former include the immediate products or services of the project, often expressed by direct revenues; the latter include all other benefits accruing from the proposed project, such as increases in regional economic development, flood protection, etc. Costs can be similarly divided, and again the summation includes both.

When used to generate an ordinal ranking of plans, the alternative with the largest benefit to cost ratio or benefit less cost difference is preferred, followed by the one with the next-highest, and so on. In public expenditure practice, however, cost-benefit analysis often serves as an admissibility test in which all alternatives with a $B/C < 1.0$ are screened out and decisions among those which remain are made on other bases (Sewell, 1973). When an ordinal ranking is generated, the benefit/cost ratio and benefit-cost difference can lead to different orderings of alternatives, as the ratio criterion favors low-cost alternatives (disregarding economies of scale) while the difference criterion favors high-cost ones (Figure 11). Given several projects with constant total budget, the ratio criterion can easily be shown to maximize net return; while for any one project with no cost constraint, the difference criterion obviously maximizes net benefit.

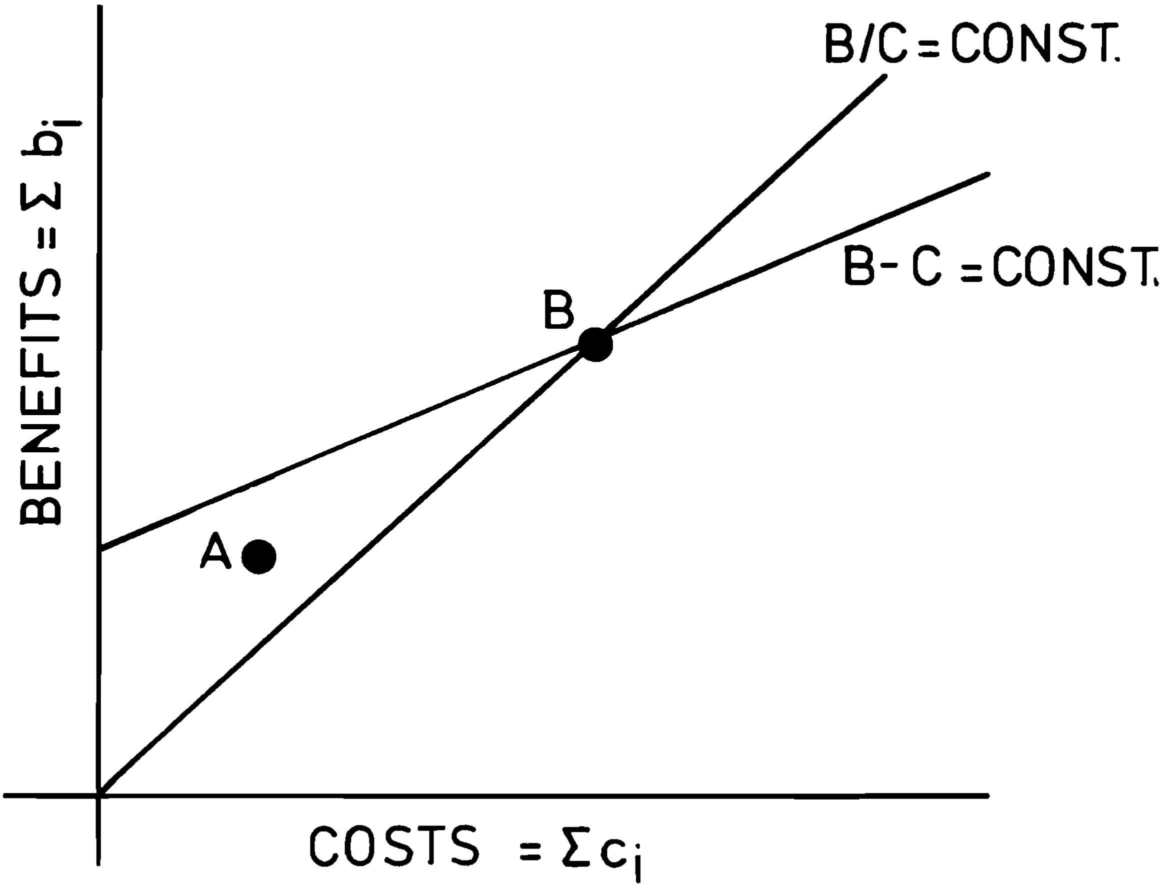
Siting decisions are different from the usual budget allocation problem in that the value of benefits is usually considered to be independent of the site considered. Therefore, after the decision has been made to build the facility, the problem is more nearly a cost minimization problem than a true cost-benefit problem. Perhaps this can best be characterized as a cost-effectiveness approach.

The primary advantages of the cost-benefit technique relative to other decision tools are:

1) It is conceptually simple and readily understandable, and decision-makers have experience in using it;
2) It has a basis in general welfare theory, although it is normally used more pragmatically (Broadway, 1974);
3) It reduces multi-dimensional impacts to one scalar index for easy comparison of alternatives;
4) It attempts to be objective, limiting the analyst's influence on the results.

The disadvantages are:

1) The use of monetary units for all impacts places restrictive assumptions on the preference structure and does not allow inclusion of more than one group's values or more than one averaging of "society's" values;
2) It does not include many social objectives;
3) It lacks a satisfactory way of treating uncertainties in impact predictions;



(SITE A HAS A GREATER BENEFIT/COST RATIO BUT LESSER BENEFIT-COST DIFFERENCE THAN SITE B)

FIGURE 11

4) By reducing impacts to monetary units, it leads to market-like approaches to evaluation, which often involve complex schemes not fully capturing the true desirability of impacts.

In cost-benefit analysis, all impacts are expressed in monetary units. Two restrictive and probably unrealistic assumptions about the preference structure result:

1) Desirability is a linear function of impact level for each impact.
2) The desirability of any impact level is independent of the levels of other impacts.

These implicit assumptions result in restrictions on the marginal rate of substitution between impacts (i.e., it is assumed constant).

The disadvantages listed as Nos. 2 and 4 deal with what are known in cost-benefit analysis as *externalities*. These are impacts that, while important, cannot be included in the decision analysis in ways which adequately reflect their true importance. Some of these are noise, health and safety impacts, environmental degradation, and social disruption. To the extent that externalities relate to important objectives, cost-benefit analysis is incomplete and can be only one of several factors in reaching a final decision.

Economists have been clever in including in the cost-benefit framework impacts that would seem at first appearance to be inexpressible in monetary units (noise, for example; Heath, 1971). Often, however, such impacts are treated by establishing legal standards or constraints that must be met in decision-making rather than treating the impacts as merely another variable. This suggestion has been made by Joskow (1974), for example, with respect to siting nuclear facilities. The approach is not at all satisfactory, because it simply transfers responsibility for decisions to another place, in this case to regulatory agencies. If they are making their standard-setting decisions with the same cost-benefit methodology (see, e.g., Majone, 1974) we are still left with the problem.

1. Equity

Implicit in cost-benefit analysis is a disregard for the distribution of impacts. An alternative that greatly benefits a few people while adversely affecting many or even most, is perfectly admissible as long as its benefits to society as a whole exceed its costs. In siting decisions, these questions of equity refer to the distribution of effects both over the strata of society and over spatial groups.

There have been many attempts to include questions of equity in the cost-benefit framework. A common approach is to list efficiency calculations alongside equity (and other "non-scientific" criteria) in presenting alternatives to decision-makers, who are then called on to make subjective comparisons. This approach was used by the Roskill Commission (1970) on siting the Third London Airport, and was recommended by the Water Resources Council (1971) for U.S. government projects. By including equity considerations in this manner, cost-benefit analysis becomes similar to some of the matrix methods discussed in the next section.

Marglin (1962) suggests the use of constraints on costs and benefits accruing to groups. The problems with this method, however, are that constraints must be chosen arbitrarily, and that there is no provision for trade-offs between efficiency and equity (Weisbrod, 1968). A second method is to apply weighting factors to benefits and costs for each group, and then take a weighted sum over all groups. Values of the first weights would correspond to values that groups themselves attach to changes in particular impacts, and the second set of weights would correspond to the importance of each group having its preferences satisfied (i.e., political weights). Weisbrod has suggested that the political weights might be inferred from past government decisions.[7] Weights of this type assume independence among the groups.

On the other hand, many applications of cost-benefit analysis simply ignore equity. Justifications of this are usually taken to be (Layard, 1971):

1. The so-called "Hicks-Kaldor criterion," which says that one should be concerned only that beneficiaries *could* compensate losers even if in reality they don't; a concept often extended by the concept that adverse distributional effects can be undone by purely redistributional projects;

2. The impropriety of undertaking interpersonal comparisons of the marginal value of benefits and costs;

3. A multiplicity of projects will tend to even out distributional effects.

2. Uncertainty

Siting decisions involve uncertainties, with respect not only to health and safety impacts, but also to a range of social, environmental, and even monetary costs; and any rational decision process must provide a means of accounting for them. Uncertainties result from (a) random events, such as weather conditions, future population levels, and equipment failures, and (b) lack of information on long-term consequences. As we have already argued, these should be treated similarly.

A satisfactory method of handling uncertainty in cost-benefit analysis has yet to be developed (Dorfman, 1962),

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[7]This method circumvents a value judgement by the analyst by using the value judgement of politicians. The interesting objection has been made by Layard (1972) that if past decisions were consistent and rational, why not continue in the same process; and if they were not, why pretend that they were?

although several methods have been explored and applied. Among these are: using expected values of impacts, trying to assess certainty equivalents, and using discount factors.

The most straightforward approach is to use an impact's expected value in cost-benefit analysis. This corresponds to linear preferences for money in uncertain situations; while expected value may be legitimate over small uncertainty ranges, it is unlikely to be legitimate over large ones. Thus expected monetary value is not the same as expected desirability, and we have the intuitive contradiction that distributions of possible impact values are equally desirable as long as their mean values are the same. The second approach is to specify a certain impact for which one would be indifferent to the choice between it and the uncertain impact. Much of the "risk evaluation" work in nuclear power uses this approach (Otway et al., 1971; Starr, 1970). Often, however, certainty equivalents are determined on an *ad hoc* basis, and cannot be back-figured using utility functions and economic data. A critical discussion of this approach is found in Dorfman (1962). A common heuristic technique is to discount the expected value of impacts by some measure of the uncertainty; a typical factor is $(1 + k\sigma)^{-1}$ where k is a positive constant and σ is the standard deviation.

The drawbacks of all three methods are that they are simply rules-of-thumb (Eckstein, 1961; Dorfman, 1962) with no sound theoretical basis.

V. Matrix Approaches

Given the multi-attribute nature of impacts from siting large facilities and what is seen to be an inherent non-comparability of impacts of different types, several methods of project evaluation have been developed which list impacts separately in a table or matrix (Figure 12). These methods hope to circumvent apparent non-comparabilities by allowing

Sector and Instrumental Objective	Measure	Differences (£ m.) from Cublington			
		Cublington	Foulness & Luton	Nuthampstead	Thurleigh
PRODUCERS OPERATORS					
Air and Surface Transport					
British Airports Authority					
Airport Construction	£	0	+32	- 4	-18
Operating Costs	£	0	-22	- 5	-15
Airline Operators					
Meteorology	£	0	- 5	- 3	- 4
Airspace Movements	£	0	5	31	26
Accident Hazards	£	0	2	0	0
Highway Authorities					
Capital Costs	£	0	4	4	5
Public Transport Authority					
Capital Costs	£	0	+23	+ 9	- 3
DISPLACED OR AFFECTED PRODUCERS					
Defence	£	0	-29	-24	+32
Public Scientific Establishments	£	0	- 1	+20	+26
Private Airfields	£	0	- 7	+ 6	+ 8
Schools, Hospitals & Public Authority Buildings	£	0	- 2	+ 4	+ 2
Agriculture	£	0	+ 4	+ 9	+ 3
Commerce and Industry	£	0	+ 2	+ 1	+ 2
Producers: Total:	£	0	+ 6	+48	+64
CONSUMERS					
TRAVELLERS AND FREIGHT SHIPPERS					
Passengers					
(a) On Surface: British residents	£	0	131	28	17
: Foreign residents	£	0	36	7	5
(b) In the Air (included in 1.2)					
Freight Shippers	£	0	14	5	1
Other Travellers (included in 2.1)					
DISPLACED OR AFFECTED CONSUMERS					
Residents Displaced	£	0	-11	- 3	- 5
Residents Not Displaced					
-Noise: 55 NNI+	£	0	0	2	3
50-55 NNI	£	0	- 1	- 1	0
45-50 NNI	£	0	- 1	+ 3	- 4
40-44 NNI	£	0	- 1	+19	- 5
35-40 NNI	£	0	- 2	+27	0
-Recreation	£	0	-13	- 6	- 6
RATEPAYERS, TAXPAYERS AND GENERAL PUBLIC		-	-	-	-
Consumers: Total:	£	0	+152	+81	+ 6
Overall Total:	£	0	+158	+129	+70

Figure 12

Balance Sheet of Development
(after Lichfield, 1971)

the decision-maker to choose a best decision alternative judgementally after reviewing the spectrum of differing impacts.

While several "matrix" approaches have been developed, they spring from the same philosophy: impacts against different types of objectives are inherently non-comparable; it is true that people do make decisions that require implicit trading-off of one type of impact for another, but schemes to analyze such trade-offs quantitatively invariably stumble over the necessary simplifying assumptions. While trade-off relations might be developed on subjectivist theory, as in utility theory, the analysis cannot do justice to the full complexity of judgemental decision-making, and some impacts of large facilities simply bar quantification.

In this section we will present four groups of matrix techniques which embody a range of those proposed, and conclude by summarizing the advantages and limitations of non-aggregating approaches to siting.

1. Lichfield's Planning Balance Sheet

Lichfield's (1968, 1971) planning balance sheet method is an outgrowth of cost-benefit analysis which received renewed attention in the wake of controversy over the Roskill Commission's analysis of sites for the Third London Airport. This method attempts to separate from one another both impacts considered inherently non-comparable, and those against different groups within society. Typically, a planning balance sheet might look like that schematically illustrated in Figure 12, in which monetary units are used for impacts that may be readily so quantified, and non-monetary units for the remainder. If an impact is judged to be non-quantifiable numerically it is assigned qualitive descriptions. Impacts expressed monetarily are aggregated as in normal cost-benefit analysis, and a decision is made judgementally by weighting the net monetary cost or benefit against the spectrum of other impacts and their distribution across groups.

The advantage of Lichfield's method over traditional cost-benefit is that it explicitly enumerates impacts that seem "unmeasurable" (and thus are not normally included) and specifies the distribution of impacts over affected groups. However, it gives no guidance to how these might be incorporated in a decision, other than that impacts on groups might be weighted to account for equity considerations.

2. Goals-Achievement Matrix

The "goals-achievement" approach developed by Hill (1973) is perhaps the most widely publicized of the various matrix techniques. Hill uses the term *goal* in precisely the same way as we have used the term *uppermost objective*; sub-objectives, lower in the hierarchy, he merely called *objectives*.

The essence of the goals-achievement approach is to establish separate accounts for impacts generated by contending sites and technologies as they bear against each important goal and each of several groups within society. Achievements toward each goal and impacts against each group are given weights on judgemental bases, and those levels of goal achievement (multiplied by their appropriate weight) which are in commensurable units are combined, leaving a reduced but still multi-dimensional array to be reviewed in reaching a final decision. The method is one step closer to aggregation than simple impact display tables, but again breaks down when the number of unaggregated impacts becomes too large for intuitive treatment.

The procedure for generating a goals-achievement matrix is the following. First, each goal of importance is identified, and attributes with which to measure achievements against each is selected. If a quantitative index cannot be associated with each goal, a qualitative description of predicted impact is substituted. Second, weights are judgementally assigned to each goal on the basis of its importance; each population group affected by the proposed project is identified, and the importance of impacts on each group with respect to each goal is weighted. Finally, these are arranged in matrix format as shown in Figure 13 (in which capital letters represent costs and benefits, in a generic sense, accruing to each affected group). Costs and benefits with respect to each goal must be in similar units, and if these are quantified predictions, the weighted sum over all affected groups can be formed yielding an aggregated impact with respect to the one goal. If all impacts can be expressed in commensurate units and if the aggregation over affected groups is "meaningful," then a "grand cost-benefit summation" is possible.

The goals-achievement matrix, like other matrix approaches, includes no analytical way of treating uncertainty. Although Hill readily admits (1973, p. 27) that "uncertainty concerning anticipated consequences is best treated by probability formulation," the most that is currently done is to include ranges of possible impacts rather than point estimates. "In general, allowance for uncertainty should be made indirectly by use of conservative estimates, requirement of safety margins, continual feedback and adjustment and a risk component in the discount rate" (1973, p. 28). This does not seem satisfactory.

To this point the goals-achievement matrix is only a vehicle for displaying predicted impacts of site and facility technology alternatives. Given this listing, how is a decision or ranking of alternatives made? Hill suggests three techniques of varying levels of aggregation. The simplest is just to let the decision-maker review the matrix and arrive judgementally at a decision; at this level the

Goal Description		α			β			γ			δ	
Relative Weight		2			3			5			4	
Incidence	Relative Weight	Costs	Ben.	Relative Weight	Costs	Ben.	Relative Weight	Costs	Ben.	Relative Weight	Costs	Ben.
Group a	1	A	D	5	E	-	1	-	N	1	Q	R
Group b	3	H	-	4	-	R	2	-	-	2	S	T
Group c	1	L	J	3	-	S	3	M	-	1	V	W
Group d	2	-	-	2	T	-	4	-	-	2	-	-
Group e	1	-	K	1	-	U	5	-	P	1	-	-
		$\sum$	$\sum$					$\sum$	$\sum$			

Figure 13

<u>The Goals-Achievement Matrix</u>
(after Hill, 1973)

method is primarily bookkeeping. The next level is to aggregate impacts using the weightings assigned to goal achievement and group impact, but here the method adopts those very inadequacies it was developed to mitigate. According to Hill (p. 37), "the combined weight of the objectives and their incidence is assigned to the measures of achievement of the objectives. The weighted indices of goals-achievement are then summed and the preferred plan among the alternatives compared is that with the largest index." Clearly, this approach differs little from traditional cost-benefit analysis except that units other than money may be employed and that relative weightings of goals may be specified explicitly rather than being hidden in specified monetary values. The explicit weighting of impacts on groups is similar to Lichfield's planning balance sheet and Weisbrod's (1968) suggestions for traditional cost-benefit analysis.

The central problem with aggregation of impacts in this way is that it assumes interrelationships in the objective function (i.e., in the desirability of impacts relative to one another) that may not be reflected in reality. Namely, it assumes that the degree to which we should desire a certain level of an impact is independent of the levels of all other impacts, and of the level of that impact against that same goal relative to other groups; and is a linear function of absolute level with a defined zero point. It is not at all clear that these even approximate valid assumptions; and so the goals-achievement approach contributes little to overcoming the limitations of cost-benefit assumptions.

Hill goes on to say that although not every impact may be scaled on cardinal indices, the goals-achievement method may be modified to handle ordinally scaled impacts. His proposed method would assign the value +1, 0, or -1 to each impact on each group, depending on whether it enhanced, left unchanged, or detracted from goal achievement. These *ordinal* values would be combined by multiplying each by both the goal and the group weight and summing to determine a final aggregate index of goal attainment. This is blatantly erroneous: if impact data are specified to an ordinal scale they do not allow multiplication and addition, so the final index is meaningless.

Hill's final proposal is based on Ackoff's (1962) notion of transformation functions which map one impact scale onto another, and approaches the concept of measurable utility which is treated in Section VI. Hill suggests that impacts that are measurable to either an interval or ratio scale be transformed onto one common scale through some (not necessarily linear) transformation. In the two-impact case this would mean expressing levels of one impact in units of the other. As the correspondence between increments of impacts is not necessarily constant over the ranges of those impacts, these transformations might not be linear. In the multi-impact case the easiest proposition might be to scale all impacts in terms of a single impact, perhaps money. In this case, Hill's proposal once again reduces to a form of cost-benefit analysis, except that non-linearities in the evaluation of impact levels would be allowed. This does not circumvent other assumptions of independence or allow one to treat analytically impacts defined to less than an interval scale, as discussed previously. Given that this approach attempts to express quantitatively trade-offs between the desirability of different impacts and non-linearities in the desirability of levels of one impact, there seems little reason not to go over entirely to a utility analysis, which makes few additional assumptions and is more theoretically sound.

3. Environmental Impact Matrix

Leopold et al. (1971) of the U.S. Geological Survey have presented what they call an "environmental impact matrix" for use in compiling environmental impact statements as required by the Environmental Policy Act of 1969. This technique is primarily intended to provide a uniform procedure for coalescing impacts and presenting them, rather than being a decision-making tool in itself. As the authors state their intention,

> "The heart of the system is a matrix which is general enough to be used as a reference checklist or a reminder of the full range of actions and impacts on the environment that may relate to proposed actions."

Their hope is to provide "a system for the analysis and numerical weighting of probable impacts" which would "not produce an overall quantitative rating but portrays many value judgements."

In essence the environmental impact matrix is intended to be a tabular summary of project impacts which would accompany environmental impact statements. But as this method attempts to scale impacts, and as some workers have attempted to use it as a decision tool, a few remarks are in order.

The matrix is constructed by listing aspects of a proposed alternative that might produce impacts along one axis, and types of impacts along the other (Figure 14). In each resulting square of the matrix with which significant impacts are associated, two numerical entries are made: the upper, a measure scaled on the integer range (1,10) indicating the magnitude of impact; and the lower, again a measure on the integer range (1,10), indicating importance of impacts. Although these numbers are assessed judgementally, to the extent possible they "should be...based on factual data rather than preference." Although the authors are not specific about how this should be done, they suggest that such

	Industrial sites and buildings	Highways and bridges	Transmission lines	Blasting and drilling	Surface excavation	Mineral processing	Trucking	Emplacement of tailings	Spills and leaks
Water quality					2/2	1/1		2/2	1/4
Atmospheric quality						2/3			
Erosion		2/2			1/1			2/2	
Deposition, Sedimentation		2/2			2/2			2/2	
Shrubs					1/1				
Grasses					1/1				
Aquatic Plants					2/2			2/3	1/4
Fish					2/2			2/2	1/4
Camping and hiking					2/4				
Scenic views and vistas	2/3	2/1	2/3		3/3		2/1	3/3	
Wilderness qualities	4/4	4/4	2/2	1/1	3/3	2/5	3/5	3/5	
Rare and unique species		2/5		5/10	2/4	5/10	5/10		
Health and safety							3/3		

Figure 14

Environmental Assessment Matrix
(after Leopold et al., 1971)

a quantification "discourages purely subjective opinion." This does not seem immediately true; more likely, such quantification requires the analyst to be more honest in his subjective evaluation of impacts, which will be uncompromisingly stated in his report and open for direct questioning--as with any quantification. The environmental impact matrix provides no mechanism for treating uncertainty, and the authors make it very clear that one should not try to compare impacts from square to square on the same matrix.

As a summary chart this method is not without merit, except that quantification as presented here can easily be misinterpreted. Some workers (e.g., Beer, 1974) have attempted to coalesce these impact measures by forming the weighted sum of matrix entries (the very thing cautioned against in Leopold et al., 1971), which not only presumes the assumptions of additive desirability but takes impact indices to be intervally rather than ordinally scaled.

4. Bishop's Factor Profile

Bishop's "factor profile" (1972) is in essence a graphical technique for displaying project impacts. However, it has received some mention as a decision-making tool (e.g., Fischer and Ahmed, 1974) and so will be briefly reviewed. A typical factor profile is shown in Figure 15. In this profile each non-financial impact is scaled on an (-100, +100) interval range on the basis of its relative desirability, -100 being the least desirable and +100 the most desirable of the impacts of contending alternatives against that goal. A decision is reached via a four-step procedure:

1) the economic impact of each alternative is determined in benefit to cost ratios,
2) factor profiles are constructed for each alternative,
3) dominated alternatives on both the factor profile and benefit/cost ratio are eliminated,

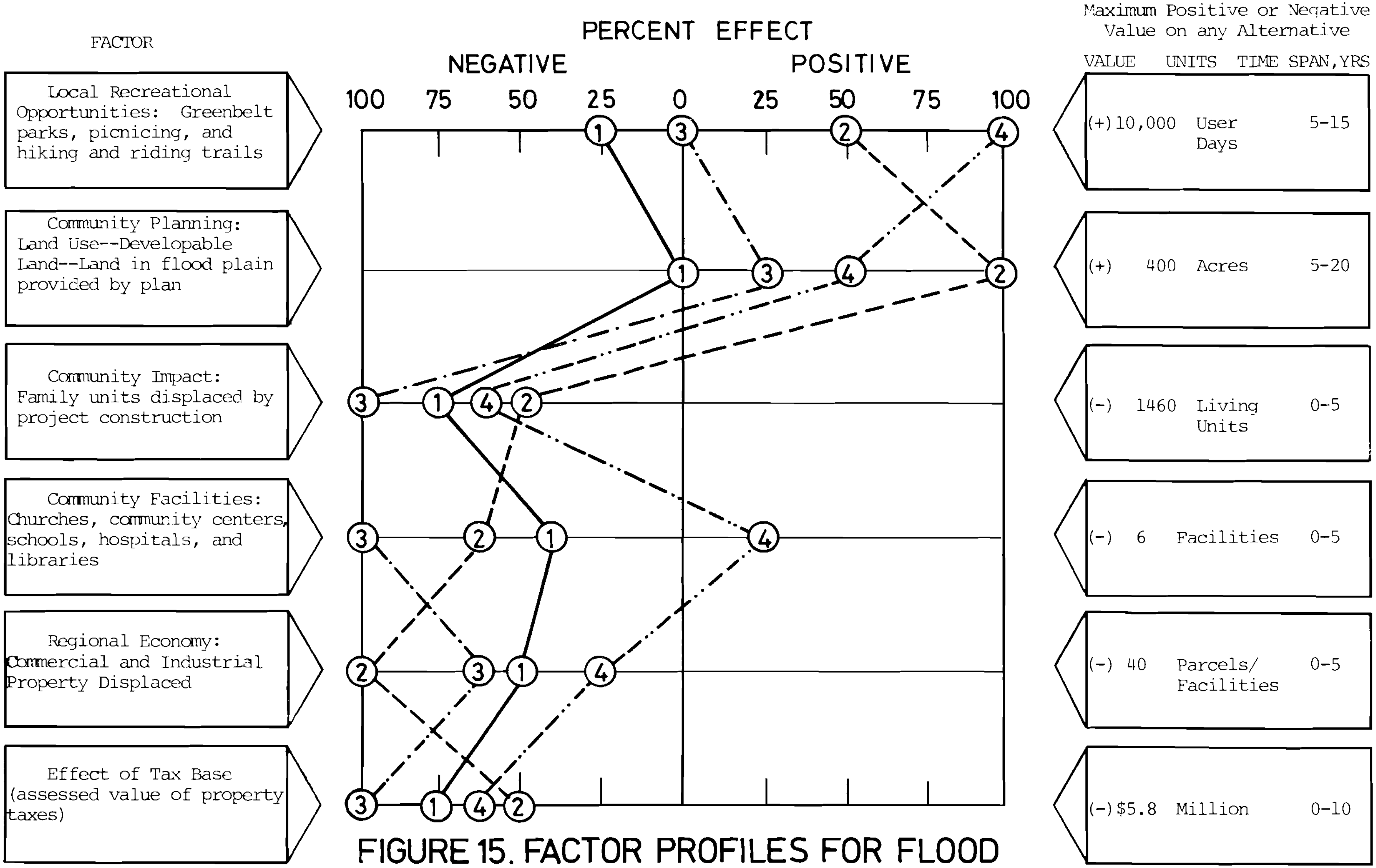

FIGURE 15. FACTOR PROFILES FOR FLOOD CONTROL ALTERNATIVES (after Bishop, 1972)

4) pair comparisons are made on the remainder to assess relative desirability (judgementally), and an ordinal ranking is thus generated.

Factor profiles are more a graphical display device than a decision tool, thus offering little that Lichfield's balance sheet does not. Although Bishop does not extend factor profiles to the separation of group impact, this could be accomplished with minor alteration. The assumption of interval scaling seems more restrictive than necessary, as ordinal scaling is all that is required.

5. Advantages and Disadvantages of Matrix Methods

The advantages of the matrix methods reflect the disadvantages of cost-benefit analysis that they were designed to overcome. Their primary advantage is that they allow the explicit inclusion on non-efficiency objectives in an analysis, although they do not indicate how one should trade off achievement of economic and non-economic objectives. However, many proponents of matrix methods would say that such trade-offs are inherently non-quantifiable and thus can be made only in a purely judgemental way. This works satisfactorily when the number of non-aggregable impacts is small, but not when it is large: still then there is a danger of biasing a decision toward economic objectives as the spectrum of impacts is so large that a fuller integration is conceptually difficult.

Secondary advantages of matrix methods are that they are good vehicles for presenting impacts to decision-makers, and that they do not require quantification of certain impacts, such as aesthetic ones, that are difficult to scale.

The central disadvantage of matrix techniques is that they do not tell one how a decision should be made, and when secondary procedures are used for considering the totality of impacts they often lead to misinterpretations. In particular, the schemes that have been used to aggregate matrix entries usually assume that there is independence among the desirabilities of impacts, and that one may perform mathematical operations with what are often ordinally scaled quantities.

VI. Preference Theories

The methods discussed so far assign desirability to impacts and thus generate objective functions based on economic impact or simple weighting schemes. Although some of these methods carefully scale relative desirabilities of levels of single impacts, none adequately accounts for interaction among impacts. That is, they assume that marginal changes in the desirability of levels of one impact do not depend on levels of associated impacts; these desirabilities are independent.[8]

There does exist a set of methodologies, however, in which the desirabilities of multi-attribute impacts are rigorously handled, including interdependencies among impacts. These methodologies are based on a set of simple axioms of preference, and from this axiomatic foundation mathematical properties of multi-attribute objective functions are derived. In this way interrelationships are explicitly stated, in contrast to previously discussed methods in which they were implicit and therefore often neglected.

These methods are explicitly based on the tenet that desirability of impacts derives from subjective preferences rather than so-called "objective" criteria, citing the failure of general welfare theory to provide that objective valuation.

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[8]An argument could be made that cost-benefit analysis circumvents this interaction, because in economic efficiency terms the desirabilities of impacts <u>are</u> independent; but this is a narrow case and leads to the common objection that we should make evaluations on broader grounds.

We will discuss the theoretical foundations of three levels of axiomatically based preference functions, and then turn to their application in siting and a discussion of their advantages and disadvantages relative to other methodologies.

If one assumes that a preference ordering can be assigned for any pair of impacts or impact levels (that is, if for any pair of impacts A and B, either A is preferable to B, or B is preferable to A, or A and B are equally preferable), then a preference ordering over an entire set of impacts can be constructed. Further, if the preferability of pairs of impact levels can be assessed relative to other pairs of impact levels (that is, if given two types of impacts X and Y and two levels of each impact X_i, X_j and Y_i, Y_j, the relative preferability of the pairs (X_i,Y_i), (X_j,Y_j) can be assessed), then a family of "indifference curves" can be generated (Figure 16) with the property that any two pairs of impact levels on the same indifference curve should be equally preferable (e.g., (X_i,Y_i), (X_j,Y_j)). Applying similar arguments, one can generate indifference surfaces in higher-order spaces (Fishburn, 1970) and thus an ordinally scaled objective function for evaluating the desirability of specified sets of impact levels.

The important thing to note here is that indifference surfaces are ordinally scaled; the normal operations of multiplication and addition are not defined over them, and common procedures of reducing the work of assessment and evaluation are not allowed. To assess a set of indifference curves requires individual assessment of the relative preferability of each point in the multi-dimensional space and entails substantial effort--too much, in fact, to be reasonable for more than, say, three or so impact attributes. Further, there is no rigorous way to include uncertainty in the analysis, again because the ordinal scaling does not allow arithmetical operations.

INDIFFERENCE CURVES

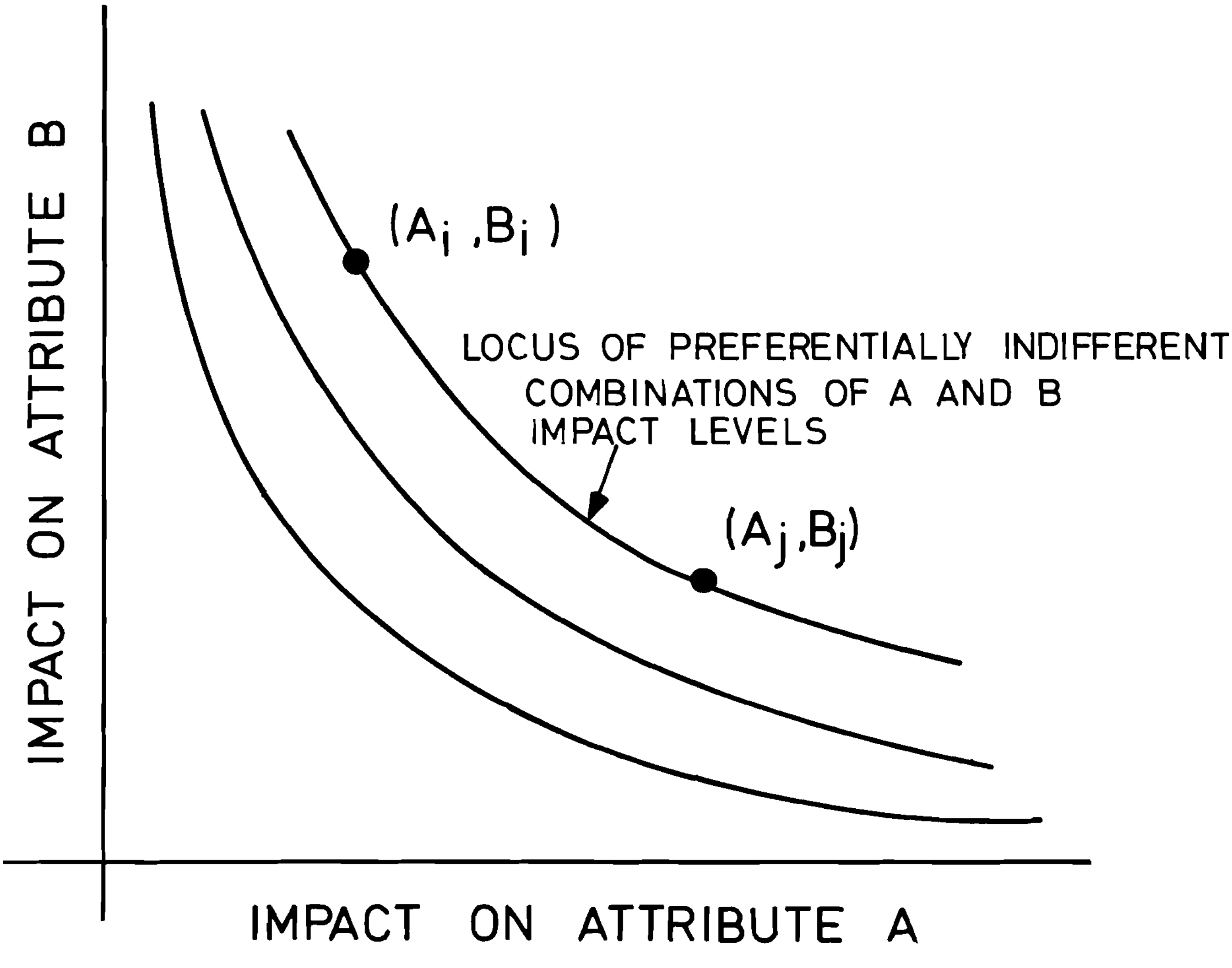

FIGURE 16

Despite these drawbacks in implementation, indifference surfaces have been used in siting and project evaluation, most notably in the work of Major (1974) and MacCrimmon (1968). MacCrimmon and Toda (1969) have also described a procedure for obtaining indifference surfaces. An advantage of indifference surfaces is that the additional assumptions necessary to develop integrally scaled functions need not be introduced, yet varying marginal rates of preferential substitution among impacts can be represented.

1. Value and Utility Functions

If an expanded set of axioms on preferability between impacts is introduced, integrally scaled preference functions can be derived. This results in a function similar to indifference surfaces but for which each surface represents a contour of preference which can be assigned a numerical value, and for which the differences between these numerical measures carry meaning. This allows the mathematical operations defined on integral scales to be performed on the preference function; such functions are generally called "value functions."

By increasing the set of axioms (Appendix VI.B) and by modifying the procedures of assessment, value functions can be expanded to apply to cases in which impact levels are uncertain but can be described by probability distributions. The latter function has become widely known as *utility*, or sometimes *measurable utility*, in differentiation to the classical concept of utility in economics.

Smith (1956) has presented a historical summary of utility theory. Although beginnings of the theory can be traced as far back as Daniel Bernoulli, it has seen the bulk of its development in the past 25 years. A rigorous treatment of the foundations can be found in Fishburn's writings (e.g., 1964, 1970).

2. The Utility-Based Decision Model

Given the axioms of utility theory, an optimum decision is that which leads to a maximization of expected utility (Pratt, Raiffa and Schaifer, 1965). In the notation introduced in Section III, the set of decision alternatives leading to the most preferred set of impact levels is that which maximizes

$$E|u| = \int \int u(\underline{x},\underline{\theta}|s,q)\ f(\underline{x},\underline{\theta}|s,q)\ d\underline{x}d\underline{\theta} \quad , \qquad (5)$$

where $u(\underline{x},\underline{\theta}|s,q)$ is the utility function. Although this is conceptually straightforward, in practice the process is made difficult because the utility function itself can become complicated unless certain properties of the structure of preference are shown to apply, and because assessment of utility functions is an involved task. Given also that utility theory is based on subjective preference, the question of whose preference structure to use is more explicit here than in other methods, even though one can forcefully argue that none of the methods are truly "objective"; thus "whose objective function to use" is always a problem.

3. Form of the Utility Function

Unless certain restrictive properties of the interdependence of preference over different types of impacts can be assumed to apply in a particular case, the mathematical form of the utility function can be quite complicated and even approach intractability. Keeney (1972) has reviewed forms of multi-attribute utility functions, and has shown that two "independence properties" are of critical importance in establishing the appropriate form. These are called *value independence* and *utility independence*. Value independence is the more restrictive of the two and is a sufficient condition for utility independence; utility independence is only a necessary condition for value independence.

Value independence is the property that preferences for gambles depend only on the marginal (i.e., single variable) probability distributions of impacts and not on their joint (i.e., multivariate) probability distributions.

Utility independence is the property that preferences for gambles involving uncertainties in one impact, conditioned on known values of the other impacts, do not depend on what those other values are.

We will not dwell on definitions of these properties, for they are presented elsewhere (e.g., Keeney, 1973). The important thing to note is that only if value independence holds is the simple additive form of the multi-attribute utility function appropriate:

$$u(\underline{x}) = \sum_{i=1}^{n} k_i u_i(x_i) \quad . \tag{6}$$

If utility independence holds sufficiently often, then either the additive form or the multiplicative form,

$$1 + ku(\underline{x}) = \prod_{i=1}^{n} [1 + kk_i u_i(x_i)] \quad ,^{9} \tag{7}$$

may be appropriate, depending on whether value independence also holds. Again, *unless one of these properties holds, the additive or multiplicative forms of the multi-attributed utility function are not applicable.*

This greatly increases the difficulty of assessment and, if the decision structure contains continuous variables, also reduces the mathematical tractability of optimization.

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[9] Both k and k_i are constants with the properties $\sum_{i=1}^{n} k_i = 1$ in the additive form, and $\sum_{i=1}^{n} k_i \neq 1$ in the multiplicative form.

In the siting and environmental impact literature, additive forms of the utility function are widely used and only infrequently justified by attempts to demonstrate value independence--or at times even to mention it. The whole set of decision methodologies which use rating scales for individual impacts and a weighted sum for aggregation are forms of additive utility and incorrect in preferential terms unless the restrictive condition of value independence holds.

A problem with applying utility theory to siting decisions is assessing utility functions. This can be a long process and requires some degree of familiarity with the technique by individuals whose preferences are being assessed. Further, a satisfactory procedure for measuring group utility functions, when they are to be used, has yet to be developed. These drawbacks were discussed in Section III.

4. Application

While cost benefit and matrix methods have been used extensively in plan evaluation and siting, utility models have been used only infrequently. An initial application of utility to siting public facilities was made by de Neufville and Keeney (1974) on the problem of siting the new Mexico City Airport. In that work the authors used an impact set consisting of six objectives and attributes, of which three dealt with cost and service and three with social/environmental effects: safety, social disruption (as measured by the number of people displaced by construction), and noise pollution. In the final analysis, however, the problem was seen to be an innately political one dealing with phasing levels of commitment to opposing sites.

An attempt to apply utility models with a limited set of objectives to power plant siting in New England was made by Gros (1974), who also addressed the problem of differing interest groups having different utility functions. However, in neither the de Neufville-Keeney nor the Gros study were utility functions directly assessed for groups affected by siting decisions; they were assessed either for government decision-makers, or for representatives of interest groups.

Keeney and Nair (1974) and Fisher and Ahmed (1974) have discussed the use of utility theory for siting power plants, though without actually reporting application of the method. Dee et al. (1973) have developed an "environmental evaluation system" for water resource projects, which is a set of non-linear single-attribute utility functions over 78 attributes of environmental impact which are aggregated by a weighted sum, of the form of Equation 6, and thus in essence is a multi-attribute utility function for environmental impacts of the additive form.

5. Advantages and Disadvantages of Preference Methods

The advantages of utility analysis over the methods previously discussed spring from its rigorous handling of preference for impacts and uncertainty. It is the only one of the evaluation methods that adequately accounts for dependence among the desirabilities of different impacts and for uncertainty in impact predictions. The method allows differences in desirability as perceived by different groups to be introduced, and theory is currently being developed to incorporate varying group utility functions analytically in decision-making (Kirkwood, 1974).

The disadvantages derive mainly from problems of application: assessing utility, dealing with sometimes messy mathematics, and lack of conceptual simplicity. The problem of coalescing the utility functions of different groups into one function is more explicit with utility models, but is a problem inherent in siting and not in a particular method. Other methods either ignore this question or treat it judgementally. Perhaps the major problem is measurement: what are we measuring when we assess over large groups, and does whatever we measure accurately reflect individuals' "true" preferences or merely their momentary whims? The procedures of utility assessment seem better on this point than opinion surveys generally, as they confront a subject with decisions involving trade-offs among impacts rather than simply asking opinion-type questions; however, the objection of economists that surveys and market behavior represent qualitatively different things and that the latter may be more valid and reliable still plagues the effort. The answer to this problem is not immediately apparent, and certainly a closer look at the measurement problem might prove more helpful than much of the current effort to expand the mathematical base of utility theory.

APPENDIX A

Utility Assessment[10]

The assessment of utility functions involves having the subject whose preferences are to be assessed choose among various alternatives with uncertain and certain outcomes; then an interval scaling of his preferences is back-figured from his answers. As an example, consider the choice between a certainty of receiving $5,000, and the wager with equal chances of winning $10,000 and $0. For convenience, we scale the utility function so that u($10,000) = 1 and u($0) = 0. The expected utility value of the wager is

$$0.5\ u(\$10{,}000) + 0.5\ u(0) = 0.5 \quad .$$

If the subject chooses the sure $5,000 over the wager, then we can infer that the utility of $5,000 must be greater than the expected utility of the wager, which is 0.5. Similarly, if the subject, faced with the choice between $3,000 and the wager, chooses the wager, then the utility of $3,000 must be below 0.5. Questioning would continue until a value is established for which the subject is indifferent.

A similar procedure would be used in multi-attribute problems. A series of choices is presented to establish whether preference independence properties hold, and whether a sum or product form is appropriate. If either is appropriate, the problem reduces to assessing single-attribute scalings, followed by simple multi-attribute questions to obtain scaling constants among impacts. If the simple forms are not appropriate, more complicated series of questions must be used.

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[10]Full descriptions of utility assessment can be found in Schlaifer (1959). Practical assessments are discussed in Gros (1974) and Keeney (1972). Also, interactive computer programs are available (Schlaifer, 1971; Keeney & Sicherman, 1975).

APPENDIX B

Axioms of Utility Theory

Utility function analysis depends on seven axioms. Before stating them, it is helpful to define some notation. A simple lottery, written $L(x_1,p,x_2)$, is the event where there is a chance p that x_1 will occur and a chance 1 - p that x_2 will occur. The symbol > means that, when faced with the choice between the event to the right and that to the left of the symbol, the latter is preferred. The symbol ~ means that the decision-maker is indifferent to the choice between the two events, and ≤ means that the event to the left is not preferred to that on the right. Thus, the statement $x_1 \sim L(x_2,p,x_3)$ says that the decision-maker is indifferent to the choice between the x_1 for certain, and the lottery yielding either x_2 with probability p or x_3 with probability 1 - p. We can now formally state the axioms, based on those used in Pratt, Raiffa and Schlaifer (1965).

Axiom 1: *Existence of Relative Preferences.* For every pair of values x_1 and x_2, the decision-maker will have preferences such that either $x_1 \sim x_2$, $x_1 > x_2$, or $x_2 > x_1$.

Axiom 2: *Transitivity.* For any lotteries L_1, L_2, and L_3, the following holds:

i) if $L_1 > L_2$ and $L_2 > L_3$ then $L_1 > L_3$

ii) if $L_1 \sim L_2$ and $L_2 \sim L_3$ then $L_1 \sim L_3$

and so on.

Note that any deterministic value x_i can be expressed as a degenerate lottery, so Axiom 2 requires transitivity between deterministic events also.

Axiom 3: *Comparison of Simple Lotteries.* If for the decision-maker $x_1 > x_2$, then

i) $L_1(x_1,p_1,x_2) \sim L_2(x_1,p_2,x_2)$ if $p_1 = p_2$,

ii) $L_1(x_1,p_1,x_2) > L_2(x_1,p_2,x_2)$ if $p_1 > p_2$.

Axiom 4: *Quantification of Preferences.* For each possible consequence x, the decision-maker can specify a number $\pi(x)$, $0 \lesssim \pi(x) \lesssim 1$, such that $x \sim L(x^*,\pi(x),x_*)$, where x^* is the most preferred and x_* the least preferred outcome. The value $\pi(x)$, the indifference probability of the lottery, is a measure of utility.

Axiom 5: *Quantification of Judgemental Uncertainties.* For each possible event E which may affect the consequence of a decision, the decision-maker can specify a probability P(E), $0 \lesssim P(E) \lesssim 1$, such that he is indifferent between $L(x^*,P(E),x_*)$ and the situation where he receives x^* if event E occurs and x_* if it does not.

Axiom 6: *Substitutability.* If a decision problem is modified by replacing one lottery or event by another which is equally preferred, then he should be indifferent between the old and the modified decision problems.

Axiom 7: *Equivalence of Conditional and Unconditional Preferences.* Let L_1 and L_2 designate lotteries that are possible only if event E occurs. After it is known whether or not E occurred, the decision-maker must have the same preference between L_1 and L_2 as he had before it was known whether E occurred.

VII. Conclusions

We have reviewed three methodologies which apply multi-objective decision techniques to site selection problems for large constructed facilities. Our major observations are the following.

1. The methodologies are distinguished by having different objective functions. One must be aware of the assumptions underlying objective functions, and select that which best fits the decision problem considered.
2. Only certain mathematical operations on preference measures are permissible. One should keep in mind the scale on which preference measures have been made, and the mathematical operations that are appropriate. Failure in this respect can result in numbers that have no interrelational meaning.
3. Sensitivity analyses should always be performed. Uncertainty in the parameter values of the objective function, along with uncertainties in impact prediction, lead to uncertainties in objective function values. One should check how sensitive results are to these uncertainties.
4. Siting decisions are inherently political. The analyst's role in this process should be to eliminate all but the two or three "best" sites, and then to detail impacts for these, aggregated against the major objectives of cost, environmental degradation and social disruption.

References

[1] Ackoff, R.L., S.K. Gupta and J.S. Minas. Scientific Method: Optimizing Applied Research Decisions. Wiley, N.Y. 1962.

[2] Baecher, G.B. "Sampling for Interest Group Preferences." IIASA RM-75-00. International Institute for Applied Systems Analysis, Laxenburg, Austria. Forthcoming 1975.

[3] Beer, P. "Quantification of Siting Factors for Rational Selection of Alternative Sites." ANS Conference on Power Plant Siting, 1974, p. 12, ff.

[4] Berkman, R.L. and W.K. Viscusi. Damming the West. Grossman Publications, N.Y. 1973.

[5] Bishop, A.B. "Approach to Evaluating Environmental, Social and Economic Factors." Water Resources Bull. 8, 4 (August 1972), 724.

[6] Broadway, Robin W. "The Welfare Foundations of Cost-Benefit Analysis." The Economic Journal (December 1974), 926-939.

[7] Brewer, G.D. Politicians, Bureaucrats and the Consultant: A Critique of Urban Problem-Solving. Basic Books, N.Y. 1973.

[8] Buehring, William A. "A Model of Environmental Impacts from Electrical Generation in Wisconsin." Ph.D. Thesis Title (tentative), University of Wisconsin, Nuclear Engineering Department, August 1975.

[9] Burnham, J.B. et al. "A Technique for Environmental Decision Making Using Quantified Social and Aesthetic Values." BNWL-1787, Battelle Pacific Northwest Laboratories, Richland, WA. February 1974.

[10] Collings, J.B. "Urban Priorities and Attitudes: Socio-Economic and Lifestyle Determinants." Vancouver Urban Futures Project, Report #6, University of British Columbia, 1973.

[11] Dee, N. et al. "An Environmental Evaluation System for Water Resources Planning." Water Resources Research, 9 (1973), 523-539.

[12] deNeufville, R. and R.L. Keeney. "Use of Decision Analysis in Airport Development for Mexico City." In Analysis of Public Systems. Eds. A.W. Drake et al. MIT Press, Cambridge, MA. 1972.

[13] Dorfman, R. "Formal (Mathematical) Models in the Design of Water Resources Systems." Water Resources Research, 1 (1965), 329.

[14] Dorfman, R. Ed. Measuring Benefits of Government Investments. Brookings Institution, Washington, D.C. 1965, pp. 429.

[15] Dorfman, R. "Basic Economic and Technologic Concept: a General Statement." In A. Maass et al. Design of Water Resource Systems. Harvard University Press, Cambridge, MA. 1962.

[16] Eckstein, O. "A Survey of the Theory of Public Expenditure Criteria." In Ed. J.M. Buchanan, Public Finances: Needs, Sources and Utilization. Princeton University Press, Princeton, N.J. 1961.

[17] Eckstein, O. Water Resources Development. Harvard University Press, Cambridge, MA. 1958.

[18] Edwards, W. and A. Tversky, Eds. Decision Making. Penguin, London, 1967.

[19] Fishburn, P.C. Utility Theory for Decision Making. Wiley, N.Y. 1970.

[20] Fishburn, P. Decision and Value Theory. Wiley, N.Y. 1964, p. 451.

[21] Fisher, A.C. and J.V. Krutilla. "Valuing Long Run Ecological Consequences and Irreversibilities." Jour. Environmental Economics and Management, 1 (1974), 96-108.

[22] Fischer, J.A. and R. Ahmed. A Systematic Approach to Evaluate Sites for Nuclear Power Plants. Transactions of the ANS Conference on Nuclear Power Plant Siting, August 25-28, 1974, Portland, OR. pp. 7-8.

[23] Goeller, B. "San Diego Clean Air Project." Rand Report R-1362-SD, Santa Monica, CA. 1974.

[24] Gros. Jacques. "A Paretian Environmental Approach to Power Plant Siting in New England." Ph.D. Thesis, Harvard University, May 1974.

[25] Häfele, W. "Hypotheticality and the New Challenges: the Pathfinder Role of Nuclear Energy." Minerva, 12, 3 (1974), 303-322.

[26] Hansen, M.H., W. Hurwitz and W. Madow. Sample Survey Methods and Theory. Wiley, N.Y. 1953.

[27] Heath, J.B. "Cost-Benefit Analysis and Airport Location." In Ed. M.G. Kendall. Cost-Benefit Analysis. The English Universities Press, London, 1971, pp. 395-304.

[28] Hill, Morris. Planning for Multiple Objectives. Monograph #5, Regional Sci. Res. Inst., Philadelphia, PA. 1973.

[29] Holling, C.S. "Resilience and Stability of Ecological Systems." IIASA RR-73-3. International Institute for Applied Systems Analysis, Laxenburg, Austria, 1973.

[30] Hyman, H.H. Interviewing in Social Research. University of Chicago Press, Chicago, IL. 1954.

[31] Jones, G.R., B.A. Gray and J.B. Buniham. A Method for the Quantification of Aesthetic Values for Environmental Decision Making. Transactions of the ANS Conference on Nuclear Power Plant Siting, August 25-28, 1974, Portland, OR., pp. 49-50.

[32] Joskow, P.L. "Approving Nuclear Power Plants: Scientific Decision or Administrative Charade?" Bell Journal of Ec. & M. Sc., 5 (1974), 320-332.

[33] Keeney, R.L. "Concepts of Independence in Multiattribute Utility Theory." In Eds. J.L. Cochrane and M. Zeleny. Multiple Criteria Decision Making, 1973, pp. 62-71.

[34] Keeney, R.L. "Multiplicative Utility Functions." Technical Report No. 70, Operations Research Center, MIT, Cambridge, MA., March 1972.

[35] Keeney, R.L. and K. Nair. "Decision Analysis for the Siting of Nuclear Power Plants: The Relevance of Multiattribute Utility Theory." Technical Report No. 96, Operations Research Center, MIT, Cambridge, MA., June 1974.

[36] Keeney, R.L. and H. Raiffa. Decision Analysis with Multiple Conflicting Objectives. Wiley, N.Y. (forthcoming).

[37] Keeney, R.L. and A. Sicherman. "An Interactive Computer Program for Assessing and Analyzing Preferences Concerning Multiple Objectives." IIASA RM-75-12, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

[38] Kendall, M.G. Cost-Benefit Analysis. The English University Press, London, 1971.

[39] Kirkwood, C.W. Group Decision Making Under Forced Uncertainty. Technical Report No. 74-5, The Department of Industrial and Operations Engineering, The University of Michigan, Ann Arbor, Michigan, October 1974.

[40] Koopmans, T.C. "Stationary Ordinal Utility and Impatience." Econometrica, 23 (1960), 287-309.

[41] Krutilla, J.V. Ed. Natural Environments: Studies in Theoretical and Applied Analysis. Johns Hopkins Press, Baltimore, Md., 1972.

[42] Krutilla, J.V., C.J. Cicchetti, A.M. Freemen III and C.S. Russell. "Observations on the Economics of Irreplaceable Assets." In Eds. A.V. Kneese and B.T. Bower. Environmental Quality Analysis. Johns Hopkins Press, Baltimore, Md., 1972.

[43] Layard, R. Cost-Benefit Analysis: Selected Readings. Penguin, 1972.

[44] Lee, D.B. Jr. "Requiem for Large-Scale Models." Journal of the American Institute of Planners, 39, 3 (1973), 163-78.

[45] Leopold, L.B., F.E. Clarke, B.B. Hanshaw and J.R. Balsley. "A Procedure for Evaluating Environmental Impact." Geological Survey, Circular No. 645 (1971), 1-13.

[46] Lichfield, N. Cost-Benefit Analysis in Planning: A Critique of the Roskill Commission. Regional Studies, 5 (1971), 157-183.

[47] Lichfield, N. "Evaluation Methodology of Urban and Regional Plans: A Review." Regional Studies, 4 (1970), 151-165.

[48] Lichfield, N. "Economics in Town Planning." Town Planning Review, 39 (1968), 13-15.

[49] Maass, A. et al. Design of Water-Resource Systems. Harvard University Press, Cambridge, MA., 1962.

[50] MacCrimmon, K.R. Decision Making Among Multi-Attribute Alternatives: A Survey and Consolidated Approach. RAND RM-5877 DOT, Santa Monica, CA. 1968.

[51] MacCrimmon, K.R. and M. Toda. The Experimental Determination of Indifference Curves. The Review of Economic Studies, 36 (1969), 433-450.

[52] McKean, R. Efficiency in Government Through SA with Emphasis on Water Research Development. Wiley, N.Y., 1958.

[53] Majone, G. On the Logic of Standard Setting in Health and Related Fields. Paper presented at the International Institute for Applied Systems Analysis conference on "Systems Aspects of Health Planning" held at Baden, Austria, August 20-22, 1974.

[54] Major, D.C. Multiobjective Redesign of the Big Walnut Project. Systems Planning and Design, Prentice-Hall, Englewood Cliffs, N.J. 1974.

[55] Manheim, M.L. and F. Hall. Abstract Representation of Goals. Department of Civil Engineering, MIT, Cambridge, MA., 1967.

[56] Marglin, S.A. Public Investment Criteria. MIT Press, Cambridge, MA., 1967.

[57] Marglin, S.A. "Objectives of Water-Resource Development: A General Statement." In A. Maass et al. Design of Water-Resource Systems, Harvard University Press, Cambridge, MA., 1962.

[58] Meyer, R.F. "On the Relationship Among Utility of Assets, the Utility of Consumption and Investment Strategy in an Uncertain, but Time Invariant World." Proc. 4th IFORS Conference, Venice, Italy, 1969.

[59] Mishan, E.J. Cost-Benefit Analysis. Geo. Allen & Unwin Ltd., London, 1971.

[60] Olson, M. The Logic of Collective Action. Harvard University Press, Cambridge, MA., 1965.

[61] Otway, H.J., R.K. Lohrding and M.E. Battat. "A Risk Estimate for an Urban-Sited Reactor." Nuclear Technology, 12 (1971), 173-184.

[62] Pratt, J.W., H. Raiffa and R.O. Schlaifer. Introduction to Statistical Decision Theory. McGraw Hill, New York, N.Y., 1965.

[63] Prest, A.R. and R. Turvey. "Cost-Benefit Analysis: A Survey." Economic Journal (1965).

[64] Raiffa, H. Decision Analysis. Addison-Wesley, Reading, MA., 1968.

[65] "Roskill Commission on the Third London Airport." Her Majesty's Stationery Office, London, 1970.

[66] Ross, M. "London's Third Airport: Quantitative Decision-Making." Ekistics, 218 (1974), 27-44.

[67] Schlaifer, R.O. Computer Programs for Elementary Decision Analysis. Harvard, Cambridge, MA., 1971.

[68] Schlaifer, R.O. Probability and Statistics for Business Decisions. McGraw-Hill, New York, N.Y., 1959.

[69] Sewell, W.R.D. Broadening the Approach to Evaluation in Resources Management Decision-Making. Journal of Environmental Management, 1 (1973), 33-60.

[70] Smith, N.M. Jr. "A Calculus for Ethics: A Theory of the Structure of Value." Behavioral Science, 1 (1956), 111-186.

[71] Stanley, J.K. "A Cardinal Utility Approach for Project Evaluation." Socio-Econ. Plan. Sci., 8 (1974), 329-338.

[72] Starr, C. "Benefit-Cost Relationships in Socio-Technical Systems." Paper presented at the Symposium on Environmental Aspects of Nuclear Power Stations, UN Headquarters, New York, N.Y., August 14, 1970.

[73] Stevens, S.S. "Measurement, Psychophysics, and Utility." In Eds. C.W. Churchman and P. Ratoosh. Measurement: Definitions and Theories, Wiley, New York, N.Y., 1959.

[74] Stevens, S.S. and E.H. Galanter. "Ratio Scales and Category Scales for a Dozen Perceptual Continua." Journal of Experimental Psychology, 54 (1958), 377-411.

[75] Swain, H. "Evaluating Growth Proposals." IIASA internal paper, April 1975.

[76] Ting, H.M. "Aggregation of Attributes for Multiattribute Utility Assessment." MIT Center, Technical Report #66, MIT, Cambridge, MA., 1971.

[77] UNIDO. "Guidelines for Project Evaluation." United Nations, New York, N.Y., 1972.

[78] US Atomic Energy Commission. "Directorate of Regulatory Standards." Preparation of Environmental Reports for Nuclear Power Plants, Regulatory Guide 4.2, Washington, D.C., March 1973.

[79] Walters, C.J. "Foreclosure of Options in Sequential Resource Development Decisions." IIASA RR-75-12, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

[80] US Water Resources Council. "Proposed Principles and Standards for Planning Water and Related Land Resources." US Federal Register, 36, 245, Part II (1971).

[81] US Water Resources Council. "Procedures for Evaluation of Water and Related Land Resource Projects." US Government Printing Office, 1965.

[82] Webb, E.J., D.T. Campbell, R.D. Schwartz and L. Sechrest. Inobtrusive Measures, Rand McNally, Chicago, IL. 1972.

[83] Weisbrod, B.A. "Income Redistribution Effects and Benefit-Cost Analysis." In Ed. S.B. Chase, Jr. Problems in Public Expenditure Analysis. The Brookings Institute, 1968.