Balancing Apples and Oranges: Methodologies for Facility Siting Decisions

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METHODOLOGIES FOR FACILITY SITING DECISIONS

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September 1975

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 facil-
ities. 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 appara-
tus for discounting the future becomes nonsensical. Improve-
ments 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.

Harry Swain
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Contents

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 method-
ologies. 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 empha-
sized 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 con-
structed facilities requires comparing impacts of
different levels and different types to establish
desirable yet feasible balances. Currently employed
and proposed methodologies for evaluating the desir-
ability of sets of impacts generated by large facil-
ities 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

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 ulti-
mately 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 desir-
   ability 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 seeming-
ly 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 environ-
mental degradation, undesired land-use alterations, and inequity
in the distribution of net benefits. This process of elimi-
nating 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 prob-
ability 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
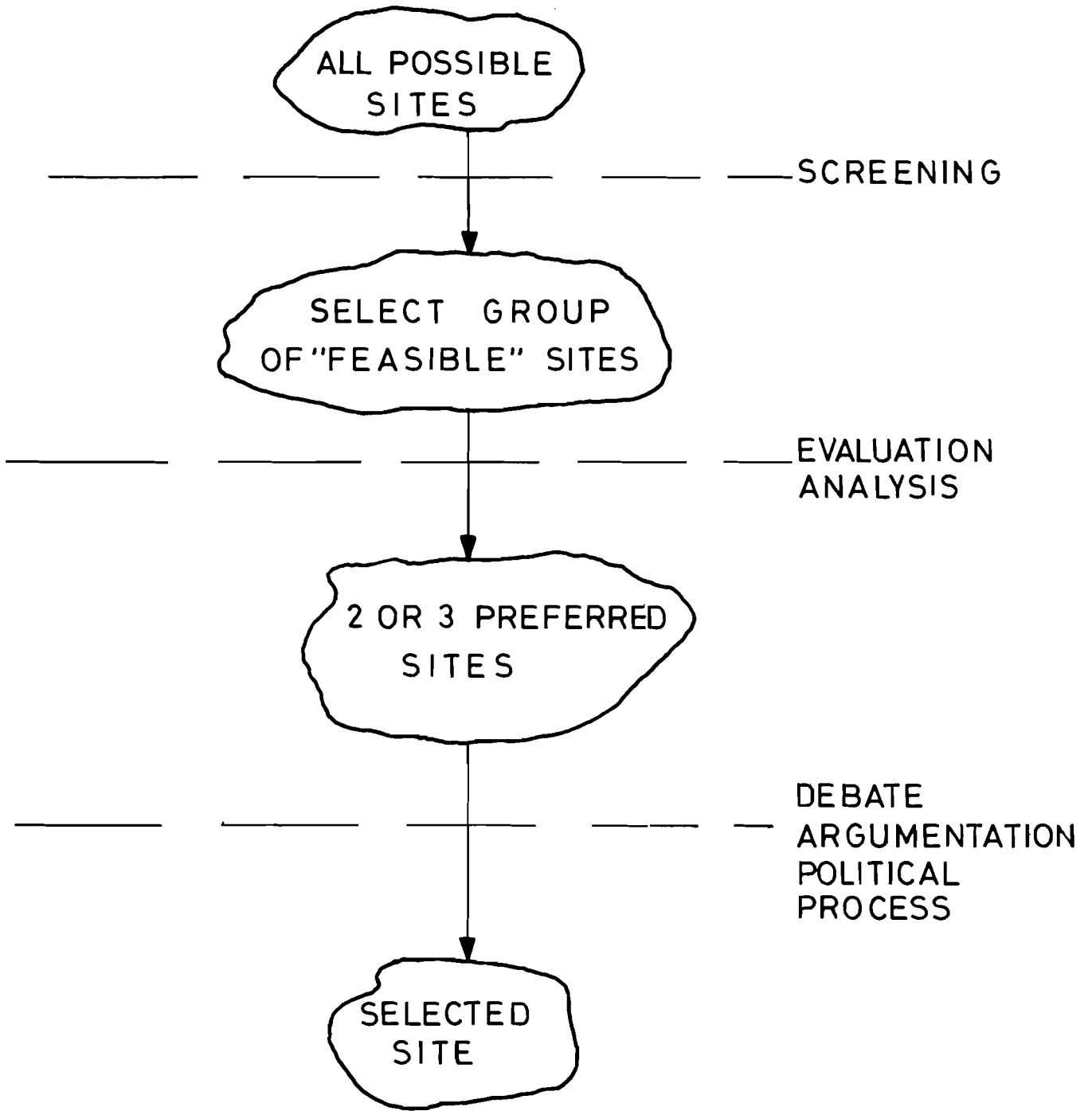
FIGURE 1

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 inter-
actions 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 in-
clude 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 iden-
tifying 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 pref-
erences 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 consider-
able 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 accom-
plish their mandate, impacts generated by siting a facility
should be evaluated for their compatibility with these pre-
ferred 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 desir-
able 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 respon-
sibility, 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, settle-
ment, 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 inter-
actions 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 develop-
ment (e.g., increases in tax base, increases in real income
flow) can be used as positively correlated measures of desir-
ability. At present even the desirability of regional devel-
opment 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 devel-
opment 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 impos-
sibility 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 pre-
ferred by at least one. In Figure 2 no sites are available
which, for the several impacts they generate, are more pref-
erable 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.
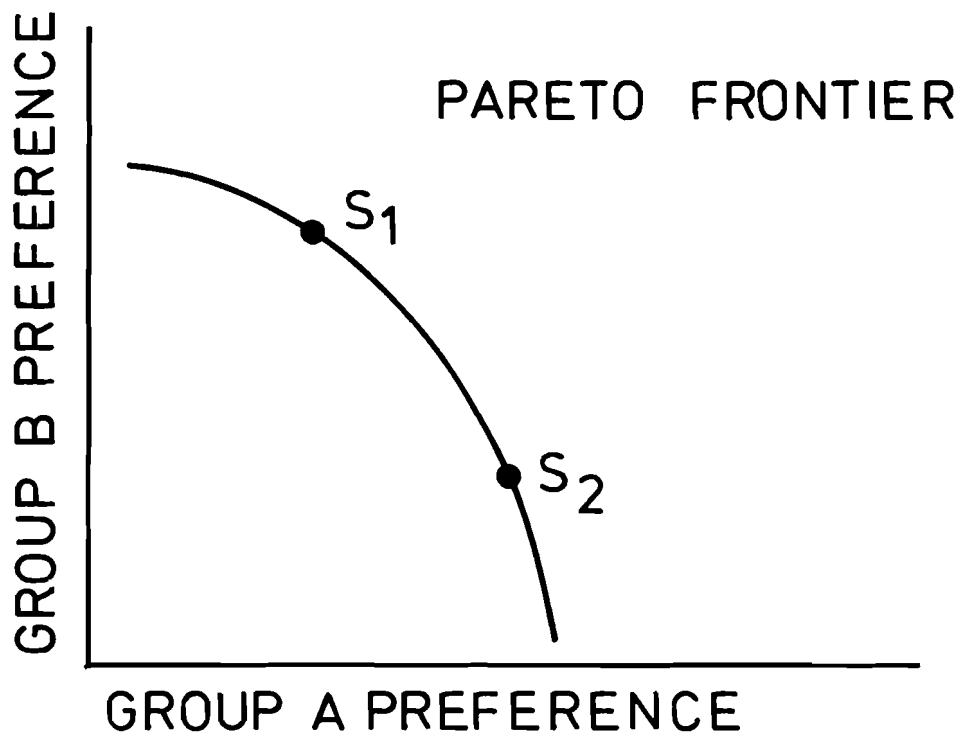
FIGURE 2

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).
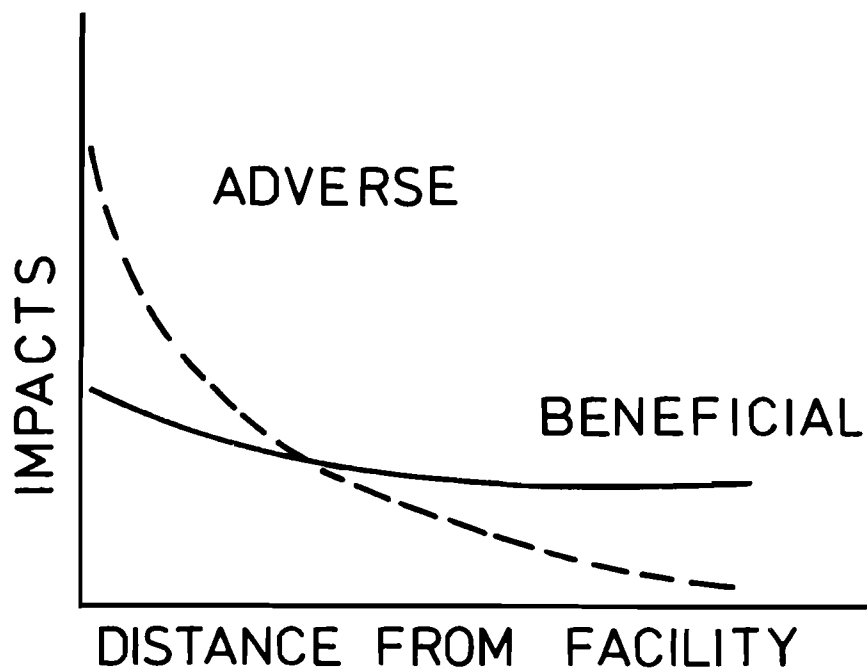
FIGURE 3
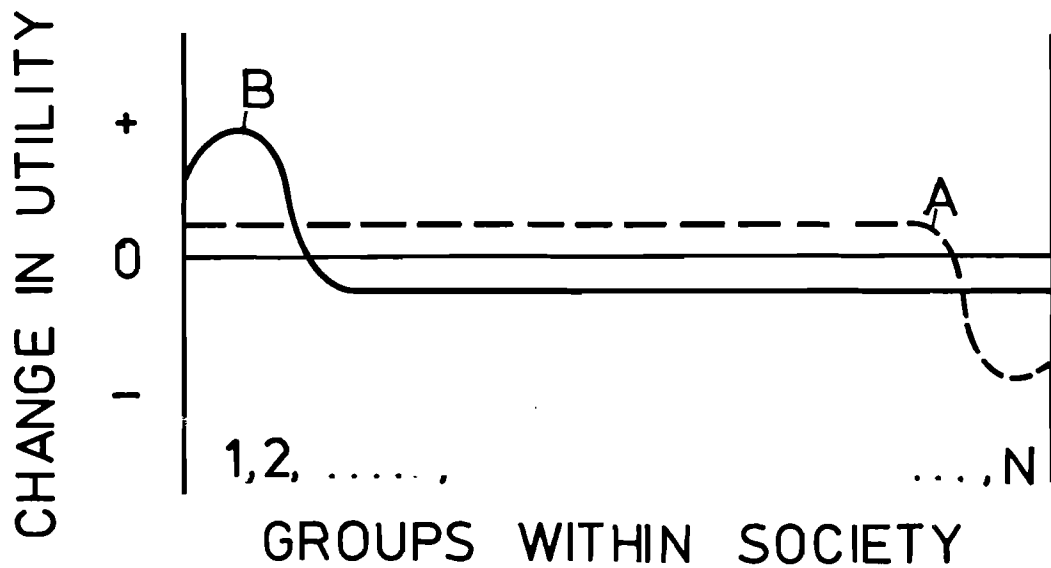
FIGURE 4

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 theoret-
ically 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 fluc-
tuate 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 sensi-
tivity 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 dis-
counting 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 appar-
ently 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 associ-
ates 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 fore-
closure, resilience, and incrementalism. One type of irre-
versibility, 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 scarce with time. Some of these
might be open space, environmentally undisturbed wilderness,

or non-renewable resources (Krutilla, 1972). Option fore-
closure 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 incre-
mental 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 unfore-
seen 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 fore-
closure 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:

GROUP G_1 : 1.0
GROUP G_2: 0.0

(a) G_1 : 0.5
     G_2: 0.5

G_1 : 0.0
G_2: 1.0

SITE B

G_1 : 0.9
G_2: 0.9

(b) G_1 : 0.45
     G_2: 0.45

G_1 : 0.0
G_2: 0.0

EXPECTED UTILITY
WITH RESPECT TO
G_2

(c)

A

B

PARETO FRONTIER

EXPECTED UTILITY WITH RESPECT TO G_1
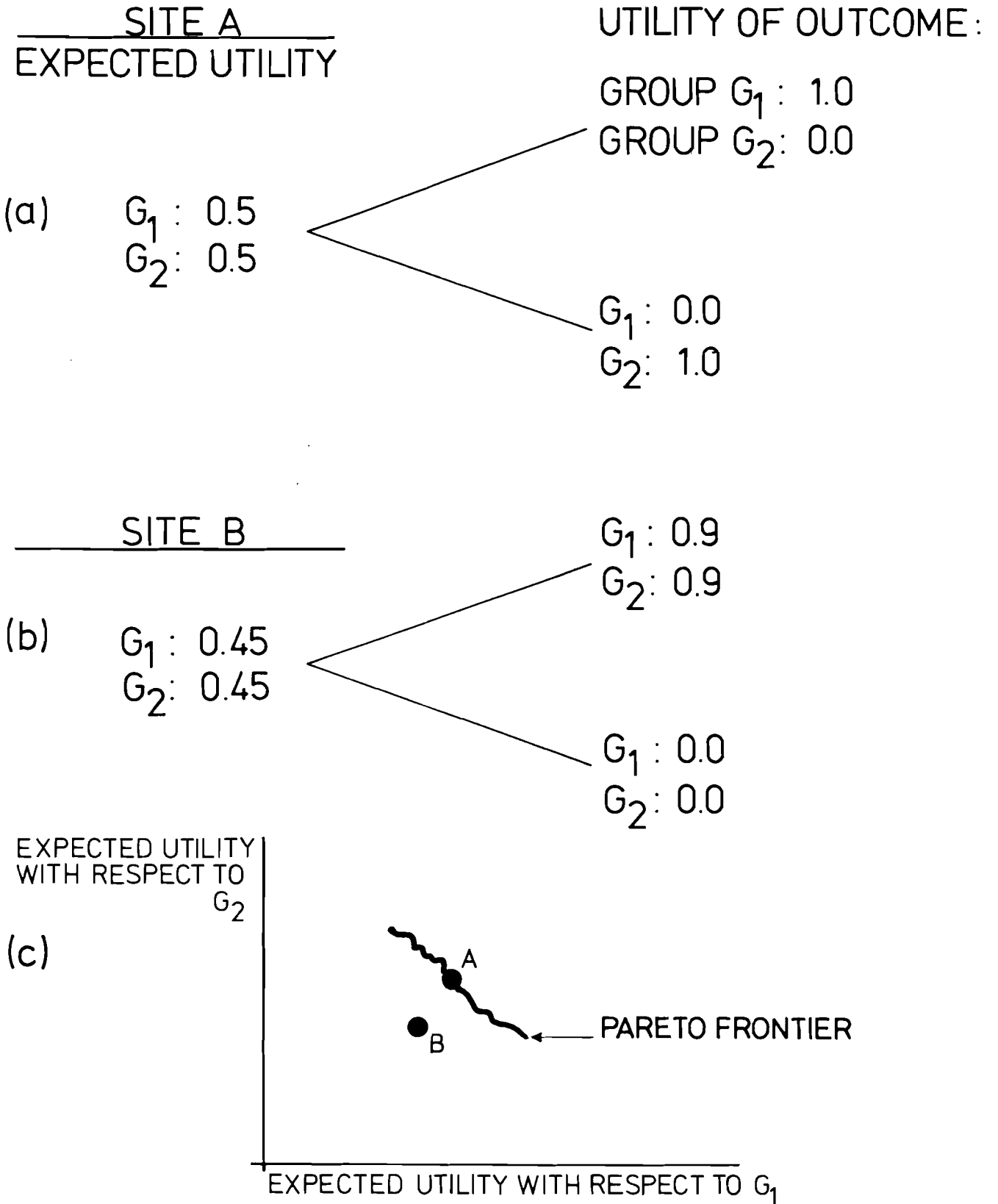
FIGURE 5

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

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

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)
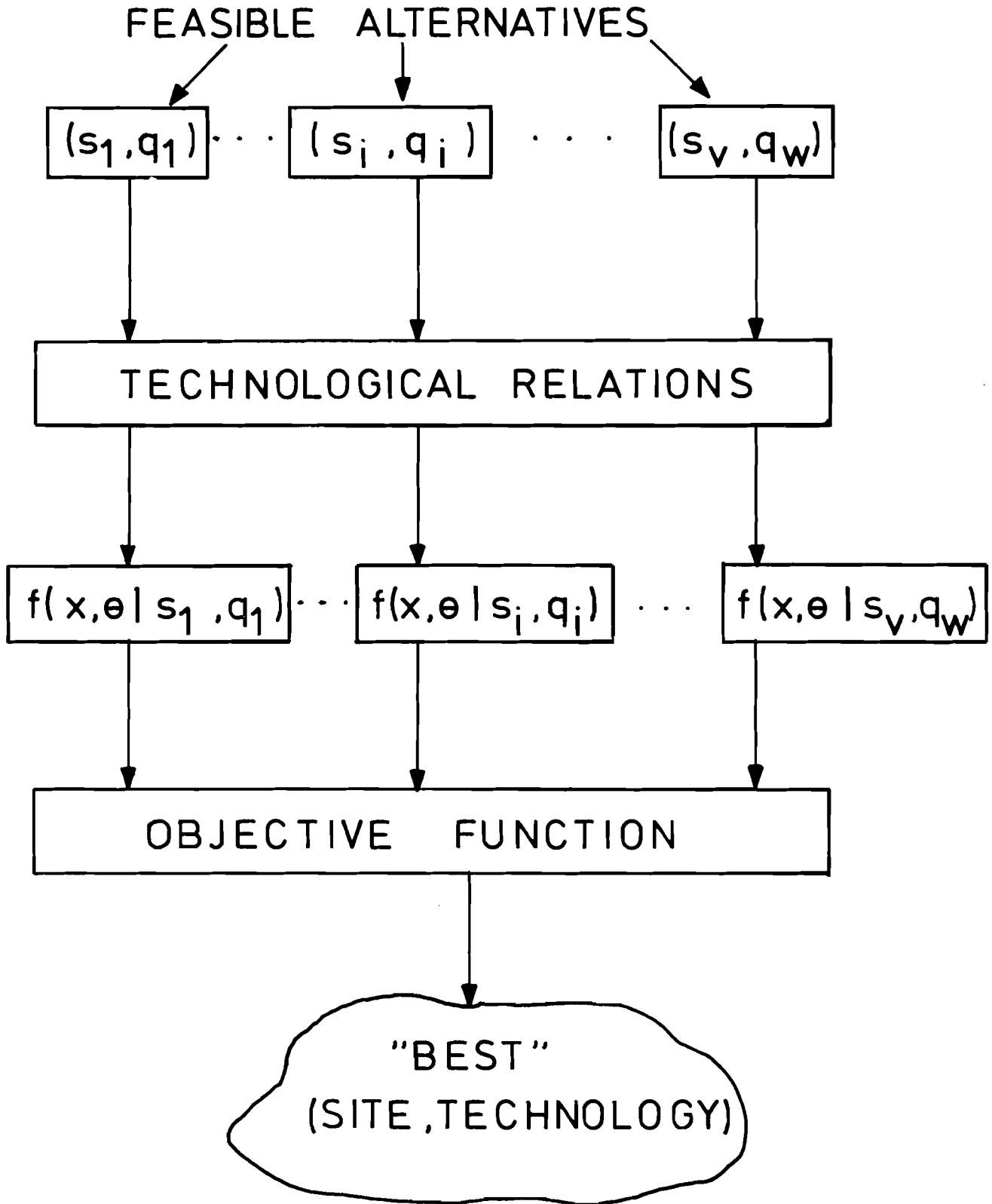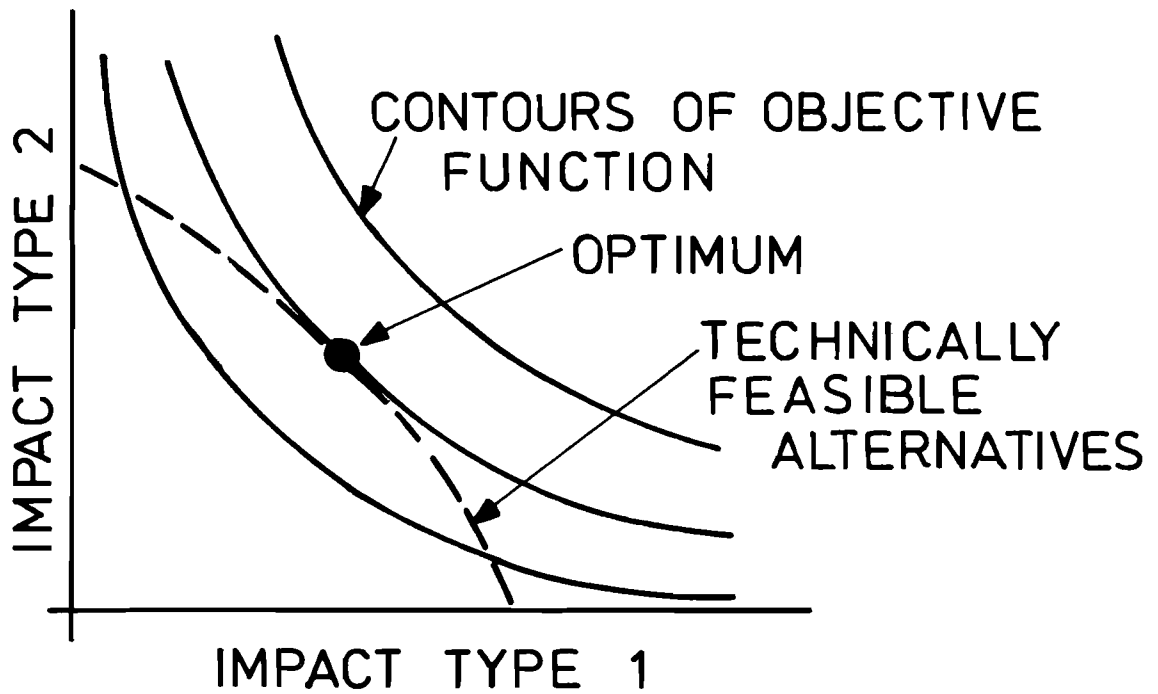
FIGURE 6

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

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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 attrib-
ute that seems to follow more naturally. This may be due to
ways in which data have been historically collected or aggre-
gated, 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 market-
place 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 meth-
ods 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

LEVEL OF IMPACT

DECREASING MARGINAL
DESIRABILITY

LINEAR
DESIRABILITY

MODAL DESIRABILITY
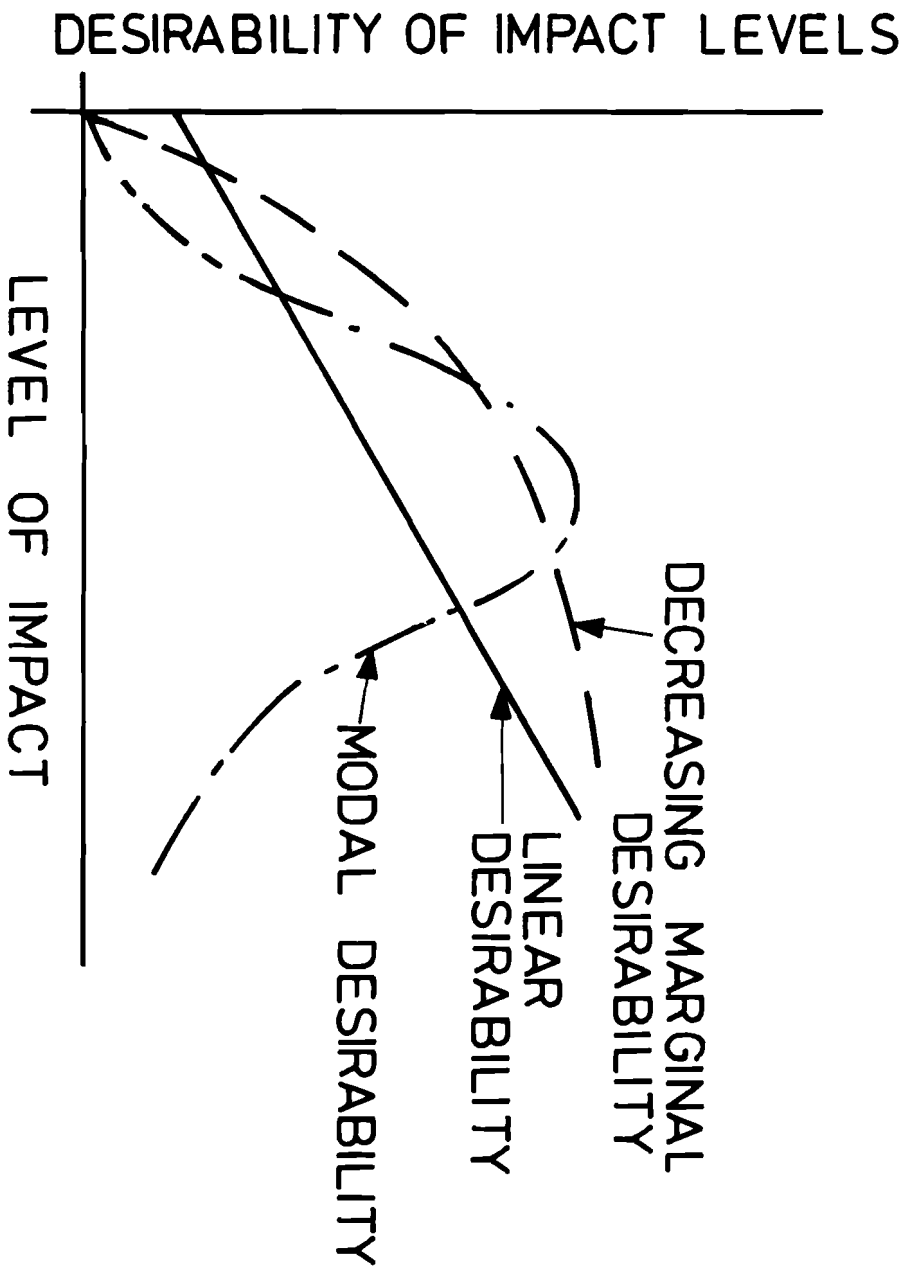
FIGURE 10

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

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

Independence among the desirabilities of impacts must be distin-
guished 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 prefer-
entially 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 prefer-
ential 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 mini-
mized relative to other evaluation techniques, and is rela-
tively easy to discern. Thus there are strong arguments for
its use.

Briefly, market approaches first use the set of techno-
logical 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 map-
ping 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 han-
dling 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 iden-
tifying interests (Collins, 1973).

At the other end of the spectrum of direct approaches
is the method of "preference assessment" which has been devel-
oped 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 proper-
ties 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 hypo-
thetical 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 implic-
itly 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 "hypo-
theticalities" 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 spec-
trum consists of methods that bring out quantitative trade-
offs 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 intro-
duces 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 "esti-
mation 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 Dupuiᴛ 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 tech-
nique 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 institution-
alized 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. govern-
ment 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

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

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 dif-
ference 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. There-
fore, 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 char-
acterized 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;
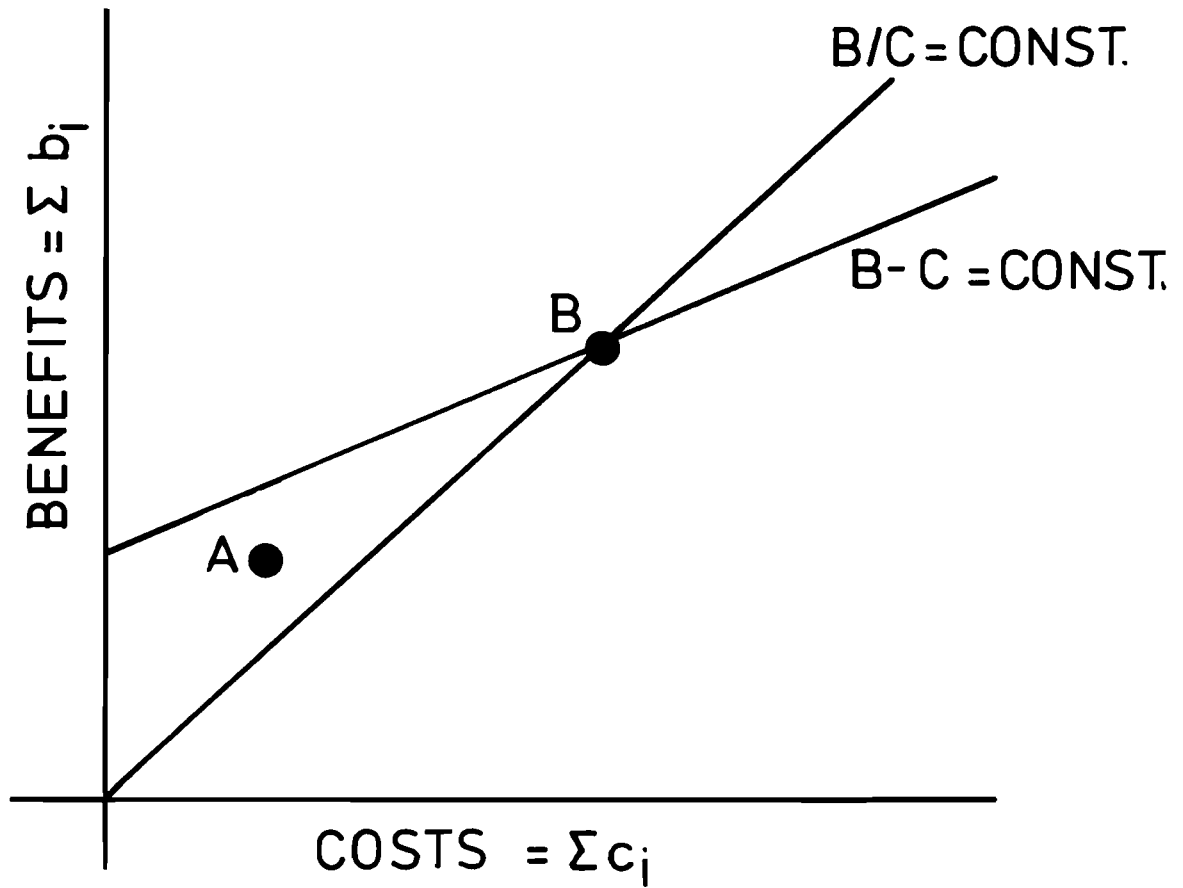
(SITE A HAS A GREATER BENEFIT/COST RATIO
BUT LESSER BENEFIT-COST DIFFERENCE THAN
SITE B)

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 method-
ology (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 arbi-
trarily, 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 impor-
tance of each group having its preferences satisfied (i.e.,

political weights). Weisbrod has suggested that the polit-
ical 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 com-
parisons 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 ratio-
nal 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 conse-
quences. 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),

---

[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	£	0	− 2	+ 4	+ 2
Buildings					
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 incor-
porated 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 *objec-
tives*.

The essence of the goals-achievement approach is to
establish separate accounts for impacts generated by contend-
ing 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 achieve-
ment (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 identi-
fied, 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 judge-
mentally 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 concern-
ing 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 indi-
rectly 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	–	–
		Σ	Σ					Σ	Σ			

Figure 13

The Goals-Achievement Matrix
(after Hill, 1973)

method is primarily bookkeeping. The next level is to aggre-
gate impacts using the weightings assigned to goal achieve-
ment 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 over-
coming 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,

FACTOR	PERCENT EFFECT	Maximum Positive or Negative Value on any Alternative

PERCENT EFFECT

NEGATIVE — POSITIVE

Maximum Positive or Negative Value on any Alternative

VALUE   UNITS   TIME SPAN,YRS

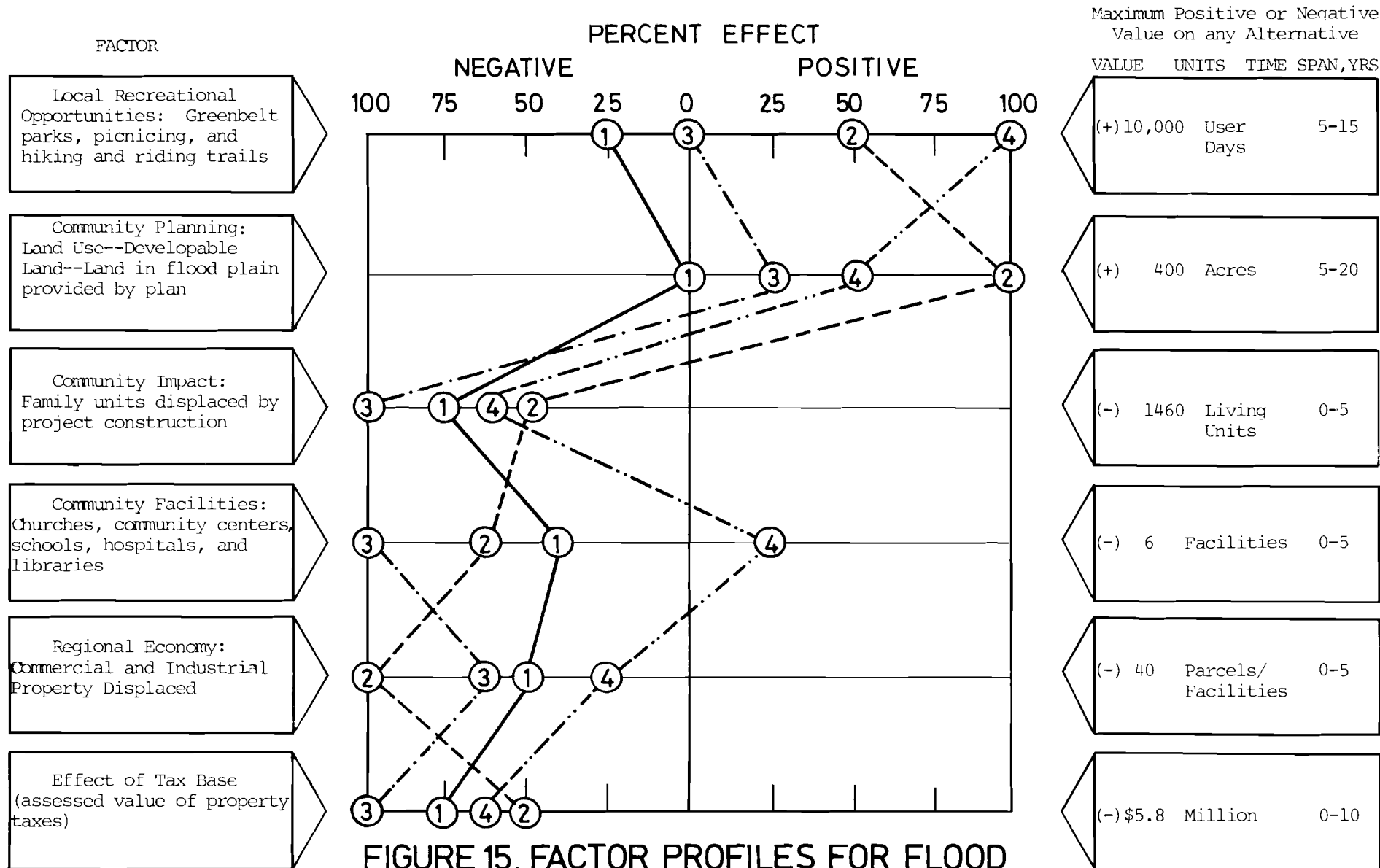| FACTOR	VALUE	UNITS	TIME SPAN,YRS
Local Recreational Opportunities: Greenbelt parks, picnicing, and hiking and riding trails	(+)10,000	User Days	5-15
Community Planning: Land Use--Developable Land--Land in flood plain provided by plan	(+) 400	Acres	5-20
Community Impact: Family units displaced by project construction	(-) 1460	Living Units	0-5
Community Facilities: Churches, community centers, schools, hospitals, and libraries	(-) 6	Facilities	0-5
Regional Economy: Commercial and Industrial Property Displaced	(-) 40	Parcels/ Facilities	0-5
Effect of Tax Base (assessed value of property taxes)	(-)$5.8	Million	0-10

Scale: 100 75 50 25 0 25 50 75 100

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 pro-
files to the separation of group impact, this could be accom-
plished 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 dis-
advantages 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 achieve-
ment 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 partic-
ular, 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 are 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 indif-
ference 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 prefera-
bility 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

IMPACT ON ATTRIBUTE B (vertical axis)

(A_i, B_i)

LOCUS OF PREFERENTIALLY INDIFFERENT COMBINATIONS OF A AND B IMPACT LEVELS
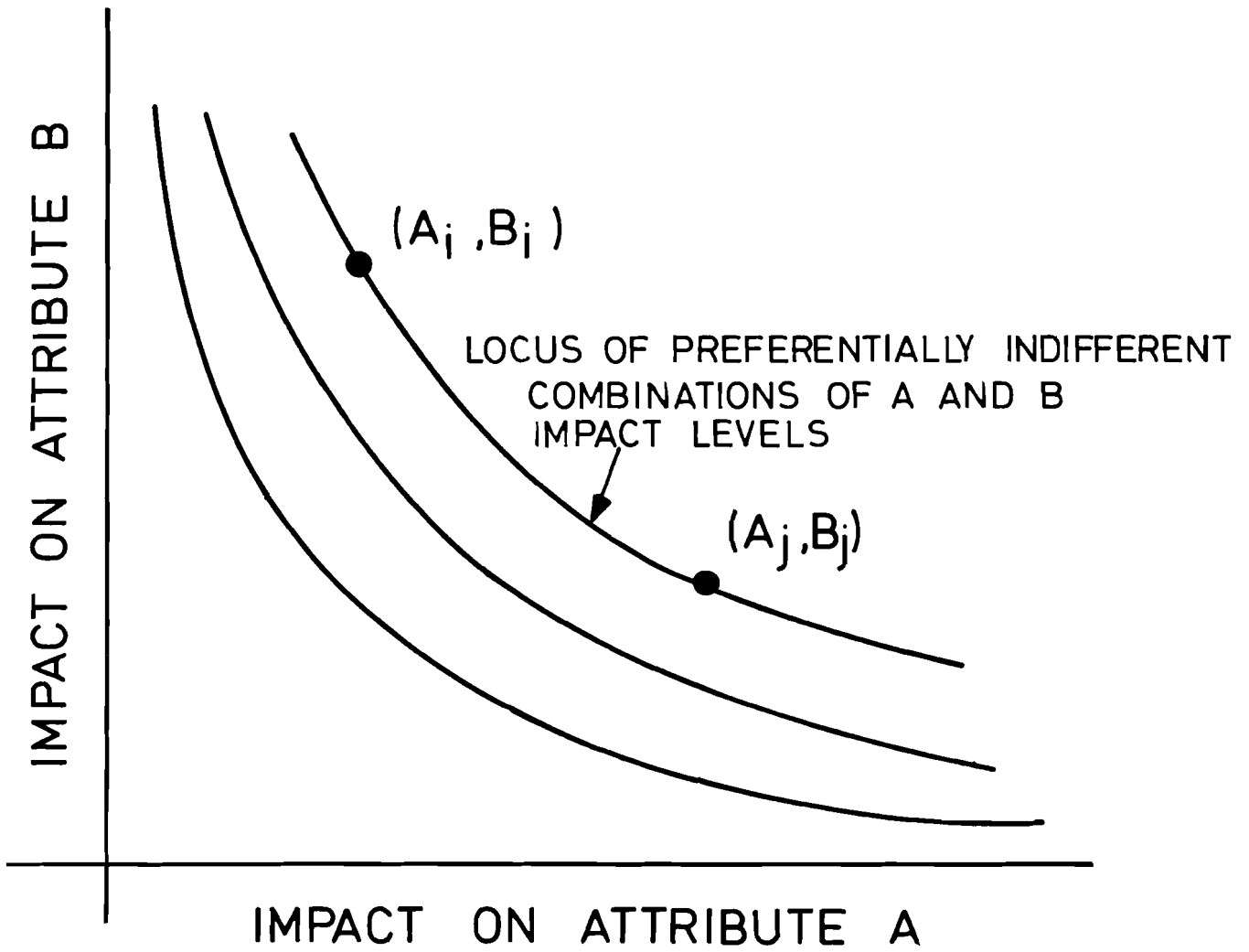
(A_j, B_j)

IMPACT ON ATTRIBUTE A

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:

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

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

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

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 indi-
vidual 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 consist-
ing 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 commit-
ment 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 prob-
lem 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 ~ $L(x_2,p,x_3)$ 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 ~ 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 ~ L_2 and L_2 ~ L_3 then L_1 ~ 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 $\pi(x)$, $0 \leq \pi(x) \leq 1$, 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 $P(E)$, $0 \leq P(E) \leq 1$, 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. <u>Conclusions</u>

We have reviewed three methodologies which apply multiobjective 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.

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