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POWER PLANT SITING: A PARETIAN ENVIRONMENTAL APPROACH

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Several different interest groups are involved in the siting decision process for nuclear power plants. Their inputs and how the final decision affects them are usually not explicitly included in mathematical analyses. Paretian analysis is a technique which attempts to identify the preferences of each of the interest groups involved in the decision-making process, and to illuminate the trade-offs among these groups. The specific problem studied is the deployment by a regional power plant siting agency of nuclear base-load power plants to coastal sites in New England. Four interest groups participate in power plant siting decisions; utility functions can represent their preferences. Techniques to find Pareto-admissible decisions are described.

1. Introduction

A host of administrative, regulatory, judicial and advisory bodies at the federal, state and local levels participate in the process of site selection and licensing of major power facilities. They - along with various private and public intervenors, as well as the power utilities - take part in a complex decision-making process with a highly controversial set of choices. Yet state and local agencies have a severely limited capacity to conduct their own analyses of many of the issues they are called on to decide. At present, the power utilities conduct extensive studies of system design and operation before deciding the type, size and location of a new generating plant or transmission line. In general, the analysis is done by Westinghouse or General Electric, as a contracted service, using computer packages developed by these large equipment manufacturers. Unfortunately, the results do not fulfil the needs of regulatory agencies and other interested parties in siting disputes. The computer packages are designed to tell a utility which development pattern is in its best interest and to provide guidance for day-to-day management of the preferred system. Consequently, they supply a great deal of detail about forecasting loads, network reliability, scheduling of maintenance, system load dispatching, system costs, and financial considerations. According to published accounts, however, the studies rarely consider broad trade-offs among the different interests that are in conflict over any siting plan. After all, siting has become an adversary process, and power utilities can be expected to use the analysis to support their own position.

In this situation, public officials who must weigh the trade-offs between power cost and environmental damage are more or less at the mercy of the analysis provided by the utilities. Power systems are complex, and without an independent source of information it is not easy for these officials to question proposed plans or to evaluate the implications of possible modifications in plant location or design. Administrative bodies setting environmental standards (e.g. the maximum end-of-pipe temperature) must also work with little or no independent analysis of the effect of different emissions standards on system cost or of the trade-offs that must be made among different environmental values.

Environmental groups are in a similar predicament. Most want to be responsible critics and are trying to minimize the environmental cost of the inevitable growth in power facilities. But since they lack the capacity to analyze choices and trade-offs, their natural response is to oppose each and every plant and to fight for tighter environmental standards whenever the opportunity arises. It seems clear that even the power utilities would benefit if analytical capacity were more generally available - though they should not necessarily be expected to provide it and might inevitably be suspect if they tried. What is needed is a flexible, low-cost analytic package that will allow public agencies and private groups to conduct their own analyses of major choices. The analysis should cover the principal siting and design decisions and evaluate their consequences for the various interested parties. A carefully focused modeling effort will be required to meet this need.

An excellent framework for research on the topic is provided by the approach we refer to as Paretian environmental analysis [1]. This type of analysis, in which the interested parties are considered explicitly, resembles what is called 'multi-objective planning' in the literature on applied microeconomics and benefit-cost analysis. The two types of analyses are similar mathematically, but differ in that conventional multi-objective planning usually considers trade-offs among abstractly defined social objectives (such as national income or income distribution), whereas Paretian analysis considers the interested parties that are actually involved in trying to influence a public decision, or that are affected by it, and calculates the preference function values as perceived by these parties. In this paper Paretian analysis is applied to the problem of the deployment of 1000 MW nuclear base-load units to coastal sites in New England.

2. The Paretian model

The Paretian model can be described algebraically as follows. Let the decision vector be X, a vector whose elements are the variables relevant to the particular public decision. For example, in an application to a power plant siting problem with n sites, X can be represented as $(Q_1, Q_2, \ldots, Q_n, x_1, x_2, \ldots, x_n)$, where Q_i is the thermal pollution level at site i when there is thermal pollution abatement equipment x_i at the site. Assumptions about the possible policy options help to determine the feasible elements of X. The quality levels $Q = (Q_1, Q_2, \ldots, Q_n)$ and the thermal pollution abatement equipment options $x = (x_1, x_2, \ldots, x_n)$ are related. Let the set of equations $T(X) = 0$ describe the technological relation. There may be a set of constraints on the decision process, such as $Q \leqslant Q^*$, where Q^* is a vector of the quality standards. Summarize all these technological, economic, legal and political constraints and relations by $\Phi(X) \leqslant 0$, where $\Phi(X)$ is a vector of the relevant transformations.

Let $NB^i(X)$ correspond to the preference ordering for the ith interest group from decision X, with $NB^i(X) > NB^i(Y)$ if X is preferred over Y. Suppose that X and Y are two feasible decisions and that $NB^i(X) > NB^i(Y)$ for all interest groups i. Decision Y should not be adopted because every participant will prefer decision X. Similarly, if $NB^i(X) \geqslant NB^i(Y)$ for all interest groups, and if $NB^i(X) > NB^i(Y)$ for at least one of them, then Y should not be chosen, since another decision exists that is preferred by some interest groups and is not detrimental to the interests of any other interest group. Such a decision Y is said to be inadmissible. On the other hand, a decision Y is Pareto admissible if it is feasible and if there does not exist any alternative feasible decision X for which $NB^i(X) \geqslant NB^i(Y)$ for all interest groups i, with strict inequality holding for at least one of them. The set of Pareto-admissible decisions constitutes the Pareto frontier.

To find the Pareto-admissible points a set of auxiliary problems is defined as follows. Choose a set of positive numbers w_i, one for each interest group, and use these numbers to form the objective function $W = \Sigma_i w_i NB^i(X)$. Then find a decision X with a feasible outcome $[\Phi(X) \leqslant 0]$ that makes W as large as possible. Decision X is a Pareto-admissible point. The numbers w_i are called political weights since their values reflect the relative marginal weighting of the net benefits of interest groups in the determination of the particular Pareto-admissible decision.

The application of Paretian analysis requires six steps: definition of the problem, identification of the interest groups, determination of the technological relations, estimation of the preference functions, determination of the Pareto frontier, and analysis of the results. In the discussion that follows emphasis will be put on the method of determining the preference functions.

2.1. Definition

The public decision studied in this paper is the design and deployment by a regional power plant siting agency of 1000 MW nuclear base-load units to coastal sites in New England. In this analysis, the decision is twofold: whether to use a particular site and what thermal pollution abatement system to build at the site. Much of the difficulty in defining the public decision is in specifying the available policy alternatives and the constraints. For example, federal water quality standards limit the set of available control measures for regulating thermal pollution. But these standards can change while the decision is being made, or before the decision is implemented. Therefore, the results of Paretian analysis will depend on both the standards and the variability of the standards. One aim of this analysis is to make it possible to model the uncertainty in some simple fashion.

2.2. Identification of interest groups

Step two in Paretian analysis is the identification of the interest groups that are affected by the decision or that take part in the decision process. The attempt to identify these groups and to quantify their preference functions distinguishes Paretian analysis from other types of analyses. A difficult problem in Paretian analysis is deciding to what extent the interest groups should be identified. It would be nice to represent as an explicit interest group each real-world group which has a distinct preference function that is affected by the decision. Unfortunately, too large a number of interest groups makes the analysis and interpretation of the Pareto frontier very awkward; it is therefore necessary to aggregate and simplify the interest groups. For the Paretian analysis of power plant siting, four interest groups that participate in the decision process have been identified: electric utilities, regulatory agencies, environmentalists and local interests. Each of these interest groups consists of organizations with different concerns.

2.2.1. The electric utilities

A total of 147 organizations - investor-owned utilities, municipally-owned utilities, and cooperatives - are involved in providing electricity in New England. The interests of these organizations vary. Investor-owned companies are interested in maintaining an adequate profit level and in meeting demand and avoiding outages, fish kills, etc.; municipals and cooperatives are less profit-oriented than the investor-owned companies. Companies that generate electricity obviously have different interests than those that buy. Another conflict, more common in the past, is between small and large utilities. Small utilities were excluded by the larger ones from part ownership of large, efficient base-load plants. The small utilities could not build such large plants themselves because they could not use so much additional capacity, so they were forced either to buy bulk electricity from the large utilities or to generate their own electricity in less efficient plants.

There is much more cooperation among utilities on siting matters now than in the past†. Under the NEPOOL agreement utility companies are now planning their investment decisions together. As a result, large electric companies are spreading their generation capacity over a sizable number of plants, either by part ownership or by long-term contract, instead of building large plants entirely for themselves. Utilities are no longer constrained to build plants in their own service areas; for example, Boston Edison's Pilgrim Nuclear Station is in the service area of the New England Gas and Electric Association. The electric companies of New England have formed a new organization, the Yankee Atomic Electric Company, to supervise the design and construction of nuclear plants throughout New England. For this analysis, the electric utility industry has been treated as one interest group.

2.2.2. Regulatory agencies

This interest group includes the many state and federal agencies that regulate the electric utility industry, each of which has its own particular interest. The Massachusetts Department of Public Utilities, for example, is concerned with the financing of the electric

† To achieve economies of scale in generation and economies in system dispatch, New England utilities have started region-wide planning. The major investor-owned utilities and some of the municipals and cooperatives are parties to the New England Power Pool (NEPOOL) Agreement. The objectives of NEPOOL are 'joint planning, central dispatching, cooperation in environmental matters and coordinated construction, operation and maintenance of electric generation and transmission facilities' in order to attain an efficient and reliable regional power supply. Regional coordination of planning depends on a set of interutility committees supported by a shared planning staff (NEPLAN). Centralized load dispatching has been achieved through a New England Power Exchange (NEPEX).

companies and the erection of transmission lines. Other agencies, such as the Division of Marine Fisheries, are concerned with particular environmental effects. In most cases these agencies can only act forcibly when the utility applies for permits after a plant has been built. The threat of regulatory action after a plant has been built has given the regulatory agencies some influence over design and siting decisions. The various state agencies' views are coordinated in Massachusetts by the newly formed technical committee, which has asked utility companies for studies of environmental effects of existing and proposed plants. The attitudes of state agencies toward specific siting decisions are also effectively coordinated by a staff member from the state's attorney general's office who represents the state at federal hearings.

The regulatory agencies and laws of different states often conflict with each other. For example, the Vermont Yankee Nuclear Power Station is located in Vermont but the cooling water comes from New Hampshire and heated cooling water flows through Massachusetts. Each of these states has different thermal pollution regulations and there has been litigation to determine which state's regulations should be followed.

2.2.3. Environmentalists

This is a catchall category for groups with a number of different concerns. In New England at least three subcategories of people and organizations are worth mentioning:

(1) those concerned with nuclear hazard, such as the Union of Concerned Scientists;

(2) those concerned with air and water pollution, such as the Sierra Club; and

(3) those opposed to power facilities on aesthetic grounds - for example, local groups organized around a specific issue.

This interest group should not be associated exclusively with its more vocal spokesmen, however. There is a general public concern with environmental protection with deserves to be accounted for.

On the issue of nuclear power plant siting, a local group usually leads the environmental effort and hires counsel to represent its viewpoint at the local AEC hearings. (Because of the expense, there is usually only one environmental counsel at the hearings.) All of these local groups are similar, although they are active in different geographical regions and participate in the decisions for different plants. They are often represented by the same law firm, hire the same expert witnesses, share information, and aid each other in formulating strategy. Unfortunately, these groups first participate in the decision process at the hearings on a particular plant, after many of the design decisions have already been made. Under most proposed power plant siting legislation, the environmental groups would participate earlier in the decision process, when alternative designs are still feasible.

2.2.4. Local interests

Often state and local governments like to have large power generating facilities located within their boundaries because they are a source of tax revenue. A local community in which a nuclear plant is built is obviously affected, as are the surrounding towns. Plant construction has immediate environmental and aesthetic impacts, and once the plant is built there are further effects, such as the increase in the end-of-pipe temperature of the plant and the greater danger of high radiation levels. The economic effects are also considerable: in addition to the higher tax base, employment opportunities and general commerce increase; however, the plant may interfere with established commercial activities such as fishing, lobster trapping and Irish Moss harvesting. A local community must choose whether to support or to fight a proposed plant, whose presence in the community may evenually change its character completely [2].

The influence of local jurisdictions in siting decisions should diminish in the future as state government agencies get increased powers to overrule local zoning decisions.

Once the interest groups have been identified, a related problem is: who should be interviewed to determine their preferences? For each interest group a knowledgeable observer familiar with many of the group members' preferences was chosen to assess the preference function for the group. The functions were verified for reasonableness by group members.

2.3. Analytic techniques and technological relations

To better explain the relevant technological relations and the need for preference functions I will describe an analytic technique used to obtain Pareto-admissible decisions. The model described in this paper is a long-run model. It covers nuclear base-load units only, and does not reflect the fact that the power system of New England serves different states or that it is made up of different companies. The model is based on the following assumptions:

(1) All power plants will consist of four 1000 MW units, with two years between the construction of units at a site. At present nuclear base-load units exhibit economies of scale up to around 1000 MW; new power stations in the early 1980s will be of approximately this size. Construction costs are minimized if units are built two years apart, since one construction crew can then build all four units. Let v, the vintage of the plant, refer to the year of commissioning of the first unit at a site.

(2) All the monetary costs and environmental effects can be assigned to the plant site. This means, for instance, that the cost of the transmission link to the New England high-voltage grid must be added to plant cost. It is also necessary to estimate the difference in transmission losses among sites and correct the capital and operating costs accordingly. It should be possible to estimate these quantities within a small margin of error, perhaps 1-2%. Localizing environmental effects to the generating site means that the environmental effects from one site do not change the level of the environmental effects from another site.

With these assumptions, the long-run power plant siting problem can be expressed as an assignment linear programming problem. Data management and specification of the objective function may present problems, but the computation costs are low on a digital computer; it is the kind of model a public agency could afford to maintain and operate.

The model can be set up as follows. A site k is defined as a place that can accommodate one plant consisting of four 1000 MW electric generating units. At each site in each vintage year v a number of configurations of pollution abatement equipment can be considered. However, for each combination (k, v) it is possible to identify the best plant design j since all the monetary costs and environmental effects can be assigned to the plant site and the objective function for this decision depends only on the conditions at the site (and not on the conditions at the other sites).

Therefore the problem breaks conveniently into two parts: (1) determine the best plant type for each site and vintage (the design decision); and (2) decide what combination of site developments over time is preferable (the deployment decision).

The plant types considered at any site will differ from one another in the stringency of controls on heat discharge to natural waters. Because of the difficulties of preparing data, it is not feasible to work with configurations of equipment for the continuous range of heat discharge; we must work with discrete alternatives in choosing plant designs. Thus we shall develop designs by setting alternative constraints on thermal pollution and solving for the minimum-cost design that will meet these conditions.

We can then take these designs and evaluate each under the objective function for the auxiliary problem of Paretian analysis to define

$$A_{kjv} = \sum_{i=1}^{4} w_i P_i(k, j, v)^{\dagger},$$

where w_i is the political weight and $P_i(k, j, v)$ is the preference function value for interest group i for the plant of vintage v, design j, at site k. The term A_{kjv} can be described as the contribution of a particular installation to a Paretian objective function. The best design for site k of vintage v can be found by taking $\max_j A_{kjv}$; the objective function value for this best design under the assumed conditions can be denoted A_{kv}. Naturally, the value of A_{kv} and associated plant designs may be different for different political weights.

† The above equation is for conditions of certainty. Consider the scenario where with probability p the federal government will restrict the generating units to closed cooling systems. Let us assume, for convenience, that the government will decide whether to require closed cooling systems after the deployment decision is made, but in enough time for plant designs to change without a severe cost penalty. Under this scenario,

$$A_{kjv} = p \sum_{i=1}^{4} w_i P_i' (k, j', v) + (1-p) \sum_{i=1}^{4} w_i P_i(k, j, v),$$

where $P_i'(k, j', v)$ is the preference function value for the situation in which the restriction to closed cooling systems is in effect (design j' is for closed cooling systems), and $P_i(k, j, v)$ is the preference function value for the situation in which the restriction is not in effect. (The restriction is not in effect with probability $1 - p$.)

The long-run planning problem can now be stated as follows:

$$\max \sum_k \sum_v A_{kv} Y_{kv},$$

subject to a constraint that specifies the number of new base-load plants N_v that must be committed in each period v, $\Sigma_k Y_{kv} = N_v$†, and subject to a constraint that allows only one plant at each site, $\Sigma_v Y_{kv} = 1$, where $Y_{kv} = 0$ or 1. To accommodate sites that are not used in the planning period, enough additional years are included so that each site is 'used' at some time. If the solution indicates that a site should be used after the planning period, then the site remains undeveloped.

The third step in applying Paretian analysis is the determination of the relevant technological relations, that is, the effects of the decision alternatives on each of the interest groups. As should be apparent from the discussion of the analytic technique used, the technological relations include the effects of various kinds of thermal pollution abatement equipment as well as the costs of transmitting electricity. Costs and thermal effects of using once-through cooling and spray canals are calculated using a computer routine developed by Shiers and Marks [3]. The cost of transmitting electricity is the sum of the capital and operating costs of the transmission lines and the transmission losses.

2.4. *Preference function theory*

Siting decisions involve more than just monetary costs; surrounding population, ambient water conditions and existing development at the site are also important inputs to the decision. Thus in modeling the power plant siting decision process the analyst must obtain an objective function including the multiple attributes which describe the effectiveness of a decision. Such an objective function would indicate the relative ranking of consequences and identify the trade-offs among various levels of the different attributes. In a risk-free environment, the optimal decision would be the one that maximizes the objective function.

But the power plant siting decision problem can involve uncertainties. For instance, the regulatory process which governs such decisions may change in some unpredictable fashion. This type of uncertainty should be considered in the modeling effort and the objective function should allow the uncertainty to be handled easily. One approach is to design an objective function such that the decision which maximizes the expected value of the objective function is the optimal decision. Such an objective function is usually called a utility function; because of the possible confusion in referring to the utility function for utility companies, I will often call it a preference function.

There are several ways of assessing a utility function. A direct approach would have the assessor consider this multidimensional problem as a whole, assessing preferences for sets of attributes in the several years. This is an enormously time-consuming process, with no guarantee of consistency, since people have trouble visualizing trade-offs in more than one dimension. To have the assessment made in less time the problem should be broken down into its simpler components and then reconstructed.

By asking simple questions about trade-offs between quantities, the decision analyst can find a preference function that can serve as a guide in decision making. If the consequences chosen satisfy certain independence properties, the assessment problem is simplified. The two independence properties to be considered are preferential independence and utility independence.

Let us define a set of consequences which describe the effects of power plant siting decisions. Let $X = X_1 X_2 X_3 \ldots X_N$ be a consequence space, where each X_i, the ith consequence, can represent an attribute in one year, a set of attributes, etc.; let x_i represent a particular value of the consequence. Let the complement of consequence X_i, denoted X_i', be the space defined by all the consequences except the ith consequence. This complement can be written as

$$X_i' = X_1 X_2 X_3 \ldots X_{i-1} X_{i+1} \ldots X_N.$$

Similarly, the complement of two consequences, X_i and X_j, can be written as

$$X_{ij}' = X_1 X_2 X_3 \ldots X_{j-1} X_{j+1} \ldots X_{i-1} X_{i+1} \ldots X_N.$$

† Because of the cost structure of the electric power industry (low cost of transmission relative to generation), there is no incentive to install base-load plants before they are needed, so it is reasonable to express the constraints as shown, instead of as the inequality $\Sigma_k Y_{kv} \geqslant N_v$.

Consider the situation in which the decision-maker is asked to rank values of pairs of consequences. In particular, consider the case in which consequences i and j can vary over their complete range of values and the other consequences have an arbitrary (fixed) set of values. If the ranking of values of consequences i and j does not depend on the fixed value of the other consequences, this pair of consequences is said to be preferentially independent of the other consequences. Formally, the consequence pair X_iX_j is said to be *preferentially independent* of its complement X'_{ij} if the preference order for consequences (x_i, x_j, x'_{ij}) with X'_{ij} held fixed does not depend on the fixed amount x'_{ij}. Thus the conditions necessary for preferential independence to hold, express a property of the decision-maker's preference for choices between definite (certain) consequences†.

The conditions for utility independence, on the other hand, depend upon the decision maker's preference for lotteries involving uncertainty. Consider the situation in which the decision maker is asked to rank lotteries on the ith consequence. For each specific lottery, let the value of the ith consequence be determined by a specific random variable, while all other consequences have an arbitrary (fixed) set of values. A set of random variables yields a set of lotteries. If the ranking of these lotteries on the ith consequence does not depend on the fixed value of the other consequences, the ith consequence is said to be utility independent of the other consequences. Formally, consequence X_i is said to be *utility independent* of its complement X'_i if the preference order for lotteries with only X_i varying, represented as $(\tilde{x}_i, x'_i)$ with X'_i held fixed, does not depend on the fixed amount x'_i.

If each consequence is utility independent of its complement, and each pair of consequences is preferentially independent of its complement, then the multi-consequence utility function $U(X)$ takes either of two special forms [4]:

pure product

$$1 + cU(X) = [1 + cc_1U_1(X_1)]\,[1 + cc_2U_2(X_2)]\ \ldots\ [1 + cc_NU_N(X_N)]\,;$$

pure sum

$$U(X) = c_1U_1(X_1) + c_2U_2(X_2) + \ldots + c_NU_N(X_N).$$

In both equations, $U(X)$ and $U_i(X_i)$ are utility functions scaled from zero for the worst state to one for the best state; the c_i's are scaling constants with $0 < c_i < 1$; and $c > -1$ is a scaling constant. The two pure forms correspond to different preference orderings for multi-consequence lotteries. Let us consider lotteries involving just the best outcome and worst outcome of each consequence. Let there be a lottery, lottery 1, in which the values of the N consequences are determined by *N independent two-pronged lotteries,* each giving a chance p at the preferred outcome and a chance $(1 - p)$ at the worst outcome. Let there be a second lottery, lottery 2, in which the values of the N consequences are determined by *a single two-pronged lottery,* with a chance p of getting the preferred outcome of each consequence and a chance $(1 - p)$ of getting the worst outcome of each consequence. A preference for lottery 1 over lottery 2 shows a kind of risk aversion; that is, the assessor would rather have a mix of 'best' and 'worst' consequence values than an 'all-or-nothing' proposition [5]. Multivariate risk indifference means the assessor has no preference for either lottery, while multivariate risk-seeking corresponds to a preference for lottery 2 over lottery 1. The pure product form of the multi-consequence preference function exhibits multi-consequence risk-aversion or risk-seeking; the pure sum exhibits multi-consequence risk indifference.

The same information is needed to specify both the pure product and pure sum forms. In each case, N single-consequence utility functions $U_i(X_i)$ and N scaling constants c_i must be obtained. When X_i is a continuous consequence, the single-consequence utility function $U_i(X_i)$ can be obtained as follows. Determine the feasible range of values from the most preferred value (denoted x_i^*) to the least preferred value (denoted x_{i*}) so that the single-consequence utility function is scaled from zero to one; let $U_i(x_{i*}) = 0$ and $U_i(x_i^*) = 1$.

† Consider, for example, a young child deciding what to order at a restaurant. The child is to choose an appetizer, an entrée and a dessert from the menu. Let us assume that the child is, as most children are, most interested in what he/she is having for dessert. He/she therefore considers the first dessert and considers (ranks) all combinations of appetizers and entrées. The process is repeated with the second dessert, etc. If the ranking of pairs of appetizers and entrées is independent of the dessert being considered, then the consequence pair (appetizer, entrée) is preferentially independent of dessert.

Next, consider the lottery with a 0.5 chance of obtaining x_i^* and a 0.5 chance of obtaining x_{i*}. Find a value x_i^+ such that the decision-maker is indifferent to a choice between the lottery and the certain consequence. (Since X_i is utility independent of its complement, this indifference point x_i^+ can be obtained with each of the other consequences set at any arbitrary value.) Since the expected utility of the lottery is 0.5, the indifference point x_i^+ has a utility value of 0.5. Repeating the process using indifference point x_i^+ and the most preferred value x_i^* in a lottery, the consequence value with 0.75 utility value can be found. Similarly, using the least preferred value, the consequence value with 0.25 utility value can be found. These five points (the points with utility value 0, 0.25, 0.5, 0.75 and 1) define a utility curve for a single consequence. Standard techniques are available to make consistency checks and to fit piecewise continuous functions to the points [6, 7].

When X_i has only discrete values, this method for assessing $U_i(X_i)$ cannot be used, since there is no guarantee that the indifference points will be at one of the values of the ith consequence. When X_i is a discrete consequence, the single-consequence utility function $U_i(X_i)$ can be obtained as follows. Determine the feasible set of values from the most preferred value (x_i^*) to the least preferred value (x_{i*}). As before, let $U_i(x_{i*}) = 0$ and $U_i(x_i^*) = 1$. Consider the following two alternatives: (1) the lottery with a chance p of obtaining x_i^* and a chance $(1 - p)$ of obtaining x_{i*}; and (2) the certainty of obtaining x_i^+. The problem is to find the odds which make the decision-maker indifferent to the choice between these two alternatives. Since the expected utility of the lottery is p, x_i^+ has a utility value of p. The process is repeated with other triplets of consequence values until enough indifference probabilities have been obtained to specify a utility value for each discrete consequence value.

To combine the single-consequence utility functions obtained by the above procedure into a single, multi-consequence utility function of the pure sum or pure product form, a set of scaling questions could be devised. Such a scaling question for c_i would ask: 'For what probability p is the decision-maker indifferent to the choice between:

(1) the situation with all consequences but the ith at their least preferred values, and the ith consequence at its most preferred value; and

(2) an alternative with two possible results: all consequences at their most preferred values with probability p, or all consequences at their least preferred values with probability $(1 - p)$?'

The utility value of the first alternative is c_i, since x_i is at its most preferred value ($U_i(x_i^*) = 1$), and all other consequences are at their least preferred values ($U_j(x_{j*}) = 0, j \neq i$); the expected utility of the second alternative is p, since there is a chance p of obtaining the most preferred situation (which has a utility value of 1), and a chance $1 - p$ of obtaining the least preferred situation (which has a utility value of 0). For the decision-maker to be indifferent to the choice between these two alternatives the utility value of the first alternative must equal the expected utility of the second alternative. Therefore, $c_i = p$, and c_i is a positive number less than 1.

If $\Sigma_{i=1}^N c_i = 1$, the utility function is of the pure sum form and has been totally specified. If $\Sigma_{i=1}^N c_i \neq 1$, the pure product form is appropriate and a value for c must be obtained. The utility function $U_i(X_i)$ for each consequence is scaled from 0 to 1; c is needed so that $U(X)$ may also be scaled from 0 to 1. $U(X)$ should be 1 for the most preferred condition, when each of the $U_i(X_i)$ equals 1, and $U(X)$ is 0 when each of the $U_i(X_i)$ equals 0; therefore c must satisfy $1 + c = \Pi_{i=1}^N (1 + cc_i)$. If $\Sigma_{i=1}^N c_i > 1$, the multi-consequence utility function exhibits multi-consequence risk aversion, and $-1 < c < 0$; if $\Sigma_{i=1}^N c_i < 1$, the utility function exhibits multi-consequence risk seeking, and $c > 0$.

2.5. *Preference function assessment*

The preference assessment process was divided into two parts. The first dealt with the effects in one year (described by a set of attributes), while the second covered intertemporal preferences. The preference function for each interest group was assessed over the following four attributes:

X_1 = capacity at a site, measured by the number of 1000 MW units at a coastal site;

X_2 = incremental dollar costs, measured by the cost of thermal pollution abatement equipment plus transmission cost expressed as a percent of the minimum cost plant;

X_3 = radiation hazard, measured by the population within 15 miles of the nuclear facility times the number of units affecting the population (referred to as population equivalent); and

X_4 = thermal pollution level, the end-of-pipe temperature of the nuclear facility measured in °F.

These attributes were defined on the basis of information provided by a number of individuals who had previously participated in siting controversies, and they cover the important factors involved in the deployment of nuclear power plants to coastal sites. The second attribute, for instance, includes the costs of lowering pollution - the cost of lowering thermal pollution by having a better thermal pollution control system and the cost of lowering radiation hazard by moving a plant away from its load. (The minimum-cost plant is a plant with once-through cooling and no long-distance EHV transmission.) The third attribute covers radiation effects from normal plant operation and from an uncontrolled plant, and its definition is based on the fact that the effects of radiation on an individual are proportional to the level of radiation, and the level of radiation from a plant is proportional to the number of units in the plant; the probability of abnormal occurrences (reactor uncontrolled) is approximately proportional to the number of units. Fifteen miles is the maximum lethal distance cited in the most widely distributed report considering nuclear plant accidents [8] †. The last attribute, end-of-pipe temperature, was chosen because it is what is measured now in the monitoring of coastal sites.

To obtain the preference assessments, I had two meetings with each of the knowledgeable observers. At the first meeting I explained the choice of attributes, outlined the procedure to be followed at the second meeting (when the formal preference assessment was to be made), and discussed the concepts of utility independence and preferential dependence. I asked a series of single-attribute assessment questions (the remaining attributes were set at different values) to determine whether one of the attributes was utility independent of its complement. It usually was, to a good approximation, and the assessor generally thought that it was reasonable to assume that the other attributes were also utility independent of their complements; however, I did not have time to ask assessment questions to confirm that utility independence holds for each attribute. In addition, several questions were asked to determine if pairs of attributes were preferentially independent of their complements.

At the second meeting we began the assessment process by considering incremental dollar costs. Incremental dollar costs are calculated as the ratio of the sum of thermal pollution abatement costs and transmission costs (discounted at 10%) to the costs of the minimum-cost plant. (The minimum-cost plant is a plant with once-through cooling and no long-distance transmission necessary between the plant and its load.) The ratio is in units of percent, its values ranging from 0 to 30%; 30% is an upper limit to the ratio, corresponding to a plant as far away as possible with an expensive, closed cooling system. I started by supposing that someone (exactly who depended on who was being questioned) has two plant designs - the most expensive (30%) and the cheapest (0%) - that are equivalent in all other attributes. He/she will decide between them by flipping a coin: heads - most expensive, tails - cheapest (the lottery). The alternative to the lottery is a plant design costing 5%. The knowledgeable observer, when asked to choose between the lottery and the alternative, usually picked the alternative. When a second alternative - a plant costing 25% over the minimum - was offered instead of the lottery, the lottery was usually preferred. Similar questions were asked until an indifference point was determined; that is, the cost no more nor less desirable than the lottery. This indifference point has a preference value of 0.5. Using that indifference point and the best value (the value corresponding to the cheapest plant design), the cost with 0.75 preference value was obtained; similarly, using the worst value (the value corresponding to the most expensive plant design), the cost with 0.25 preference value was obtained. The five points defined a preference curve for one attribute. Consistency checks were performed and computer programs were used to fit curves to these points [7]. Fig. 1 presents the single-attribute preference functions for the environmentalist interest group. The number of units at a site is a discrete attribute, all others are continuous, and each curve covers the range of interest of the attribute. The prefer-

† This is not to say that everyone within 15 miles of a plant site will be affected equally badly by radiation from the plant; those close to the plant will be affected more than those farther away. The population within 15 miles of a site is a representative density around this site; it provides a means of comparing the population densities surrounding different sites.

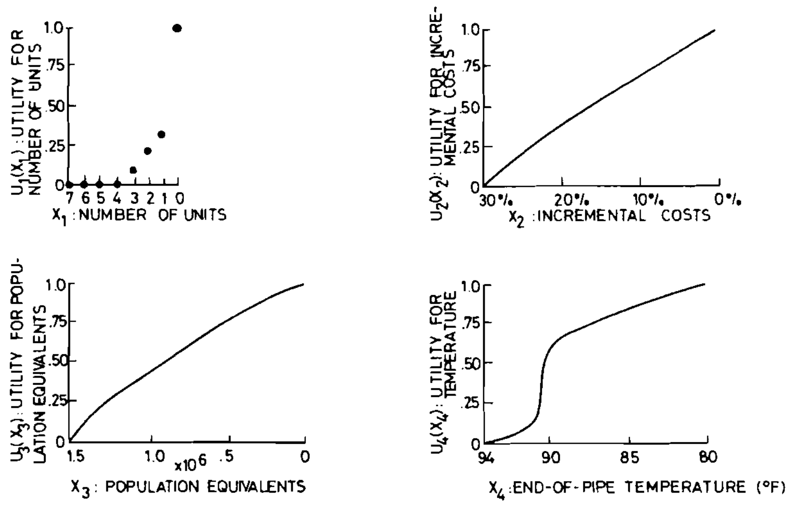

Fig. 1. Single-attribute preference functions for environmentalist interest groups.

ence functions for incremental costs and population equivalents exhibit the risk aversion that was expected. The shape of the curve for temperature is consistent with the safety of the fish species menhaden (the most economically important, endangered fish species indigenous to New England coastal waters). If the water temperature is above 90° F, menhaden are killed; below 88° F, they are safe; while between 88 and 90° F the fish are endangered, and their condition deteriorates rapidly. The environmentalist interest group's multi-attribute preference function describing effects in one year is

$$U(X) = [1 - \{1 - 0.3125 \times 0.23\ U_1(X_1)\}$$
$$\{1 - 0.3125 \times 0.1\ U_2(X_2)\}$$
$$\{1 - 0.3125 \times 0.3\ U_3(X_3)\}$$
$$\{1 - 0.3125 \times 0.5\ U_4(X_4)\}]/0.3125.$$

Preference functions were also assessed for the other three interest groups.

I was also interested in preferences over the 40 yr time horizon of the power plant siting study. For each of the knowledgeable observers, the preferences for lotteries in any individual year were utility independent of preferences for lotteries over the other years. In addition, preferences for the attributes in each pair of years were found to be preferentially independent of preferences for the attributes in the other years. Hence the 40 yr preference function was either the pure sum or pure product form. Because of the knowledgeable observers' desire to spread risks over the years, the multi-year, risk averse, pure product form was selected as appropriate.

3. Conclusions and further considerations

The model identified a variety of Pareto-admissible deployment decisions, and some sites were found to dominate the others for most sets of political weights†. The model can best be used to separate those sites that deserve further consideration from those that don't; it is low in cost and analyzes many of the broad trade-offs involved in the deployment of nuclear power plants to coastal sites. The application of analytic techniques to the problem of power plant investment decision making is not a new one. Many other studies have considered such units, but what makes this one unique is its inclusion of many interest groups in one analysis. The preference assessments described are a first step toward obtaining preference functions that will be useful in considering the broad trade-offs in nuclear power plant siting decisions. An advantage of the quantification is that the analyst does not have to specify levels of

† A total of 30 Pareto-admissible decisions were found for the scenario under certainty. For the second scenario, under which the federal government may restrict units to closed cooling systems, 27 Pareto-admissible decisions were found. Details on these decisions are described in ref. [9].

environmental indicators, such as end-of-pipe temperature, as constraints; the preference functions can be used to specify the optimal levels for different situations.

Because of time limitations, however, a number of issues could not be considered in the formal preference assessment. To begin with, the preference assessment did not touch on differences among the interest groups of the six New England states. Some states may have weak environmental groups and regulatory agencies; the utilities may exploit this weakness and locate additional generating units in these states. The model presented in this paper makes no distinction among the states: the same preference functions and political weights are used for the interest groups no matter in which state a site is located. A more reasonable - and more time-consuming - approach would be to assess the preferences for each site separately, and assign a different set of political weights to each site. Another consideration is the uneven distribution of sites among the New England states. Maine, with the longest coastline, has half of the proposed sites, and under some of the Pareto-admissible deployment schemes Maine would have three of the first five new generating plants - many more plants than would be required to satisfy its own needs. Maine's reaction to such plans was not considered in the model.

All preference assessments quantify a person's attitudes toward change in the value of a set of proxy variables. In this study several of the proxy variables cover more than one environmental effect. Population equivalent, for instance, covers radiation effects from normal plant operation as well as from an uncontrolled plant. Another approach to the assessment problem would be to consider each of these environmental effects separately so that there would be no confusion about what the proxy variable refers to. For normal plant operation the knowledgeable observer could assess the amount of radiation affecting the population; for an uncontrolled plant, the number of people killed in an accident and the associated probability of an uncontrolled unit could be used in the assessment. A similar case can be made for separating the effects of end-of-pipe temperature. The knowledgeable observer for electric utilities could assess separately the preference values of different amounts of fish killed and of the different effects of temperature on electric system operation. (The amount a power plant is derated depends on the plant's end-of-pipe temperature.)

To obtain the preference function for each interest group, I chose a knowledgeable observer familiar with many of the group members' preferences. Each knowledgeable observer assessed the preference function for one interest group, considering just the point of view of that particular group. Alternatively, these preference functions could include the preferences of other interest groups. For instance, an electric utility company is interested in satisfying its customers' preference for energy, in minimizing the conflict with environmentalists and regulatory agencies, and in maximizing the net benefits of its facilities to the local communities. These additional inputs into the electric company's decision process could be handled either explicitly or implicitly. The preference function for electric utilities could include the preference function values of the other interest groups in its arguments, or the knowledgeable observer could be asked to consider the influence of the other interest groups when he/she makes the assessments.

These and other problematic features of the assessment need to be considered in future modeling efforts.

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