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DECISION MANAGEMENT FOR THE HANFORD ENVIRONMENTAL DOSE RECONSTRUCTION PROJECT

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ABSTRACT

The Hanford Environmental Dose Reconstruction (HEDR) Project is in the process of developing estimates for the radiation doses that individuals and population groups may have received as a result of past activities at the Hanford Reservation in Eastern Washington. A formal decision-aiding methodology has been developed to assist the HEDR Project in making significant and defensible decisions regarding how this study will be conducted. These decisions relate primarily to policy (e.g., the appropriate level of public participation in the study) and specific technical aspects (e.g., the appropriate domain and depth of the study), and may have significant consequences with respect to technical results, costs, and public acceptability.

BACKGROUND

Activities resulting in releases of radionuclides have been conducted at the Hanford Reservation in Eastern Washington since the mid-1940's. The Hanford Environmental Dose Reconstruction (HEDR) Project was initiated in 1988 by Battelle Pacific Northwest Laboratory (PNL) to develop estimates of the radiation dose to any concerned individuals, as well as to specific population groups.[1,2] An independent Technical Steering Panel (TSP), consisting of experts in the relevant disciplines and representatives of the States of Washington, Oregon and Idaho and of Native American tribes, establishes policy for the HEDR Project, which is then executed by PNL technical staff. The HEDR Project has been funded by the U.S. Department of Energy (DOE); administration of the project is being transferred to the Center for Disease Control.

A variety of decisions must be made in conducting this project, which will have consequences with respect to the technical results, the costs, and ultimately public acceptability. These decisions can be categorized broadly as being related to either "policy" or "technical" aspects:

- Policy-type decisions include those that deal with public communication, public participation, participation of potentially affected Native American tribes, public access to historical information, and documentation of the study.
- Technical-type decisions, at the broadest technical level, relate primarily to the appropriate "domain" and "depth" of the study. The "domain" of the study includes the spatial area, time periods, radionuclides, pathways, and population subgroups to be explicitly considered. The "depth" of the study includes the degree of approximation and simplification in such analyses, as well as the amount of data obtained.

For example, the HEDR Project has been organized and managed to actively promote public communication, public participation, participation of potentially affected Native American tribes, public access to historical information, and documentation of the study.[1] However, there are many levels and approaches that can be taken in any of these areas, each of which will impact project costs and the study results (especially in terms of credibility, acceptance and usefulness).

As another example, the ways in which individuals within the population may have been exposed to radionuclides from Hanford activities are illustrated in Figure 1 in terms of various "pathways". Such pathways can be modeled numerically in terms of specific parameters (e.g., radionuclide release and transport factors, in conjunction with demographic factors, as a function of time) to determine the combined dose an individual or set of individuals received, as a function of their location history. In some cases, where adequate monitoring data exists (e.g., for river concentrations), some parts of the model can be effectively replaced by that data. However, in either case, the models are necessarily imperfect representations of the real world, incorporating a variety of simplifications (e.g., possibly ignoring less significant radionuclides and/or pathways, as well as second-order effects, and assuming uniformity of conditions across subareas). Similarly, the model input parameters (including monitoring data) cannot be known exactly, due to an inherently imperfect data base. These modeling limitations result in uncertainty in the dose estimates. Decisions must be made regarding models (especially their degree of simplification), the use of monitoring data in such models, and the methods for assessing the model input parameters, which will impact project costs and the study results (especially in terms of the uncertainty in dose estimates).

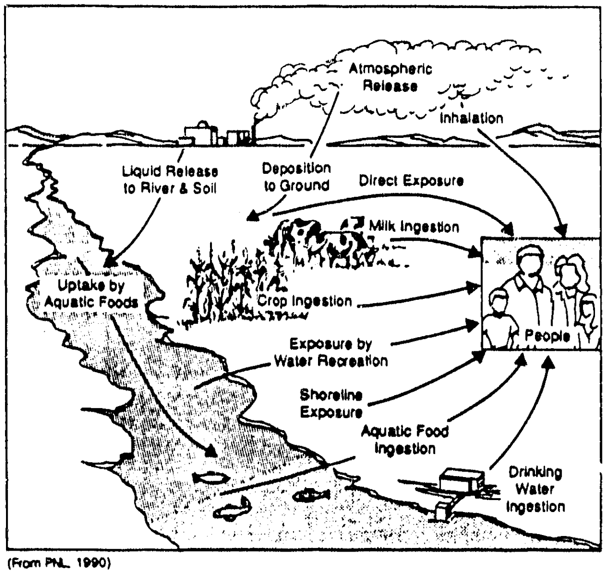

Figure 1. Possible Hanford Radionuclide Exposure Pathways

As still another example, the area within which preliminary dose estimates were explicitly made during Phase I of the study (i.e., the spatial domain) is shown in Figure 2.[1] This area consisted essentially of the adjacent and nearby counties potentially most affected by radionuclide releases from Hanford. Similarly, the air pathway was evaluated only for the time period of 1944-1947, whereas the river pathway was evaluated only for the time period 1964-1966, both for a limited set of radionuclides, all of which were considered to be the domir nt contributors to dose. However, doses vary by orders of magnitude as a function of distance, direction, pathway, radionuclide and time period, and are not necessarily zero outside the range of parameters studied in Phase I. Consequently, decisions must be made regarding which areas, time periods, radionuclides and pathways to study, which will impact project costs and the study results (especially in terms of the completeness and comprehensiveness of the dose estimates).

Policy-type decisions to increase public communication, public participation, participation of potentially affected Native American tribes, public access to historical information, and/or documentation of the study, will enhance the credibility, acceptance and usefulness of the study results, albeit at a significant cost. Similarly, technical decisions to increase the "domain" (i.e., spatial area, time periods, radionuclides, pathways, and population subgroups considered) and/or "depth" (i.e., rigor, accuracy, detail, and data) of the study, will enhance the accuracy, completeness and comprehensiveness, and acceptability of the study results, also at significant cost. With limited funds available, tradeoffs will be required in making such policy and technical decisions.

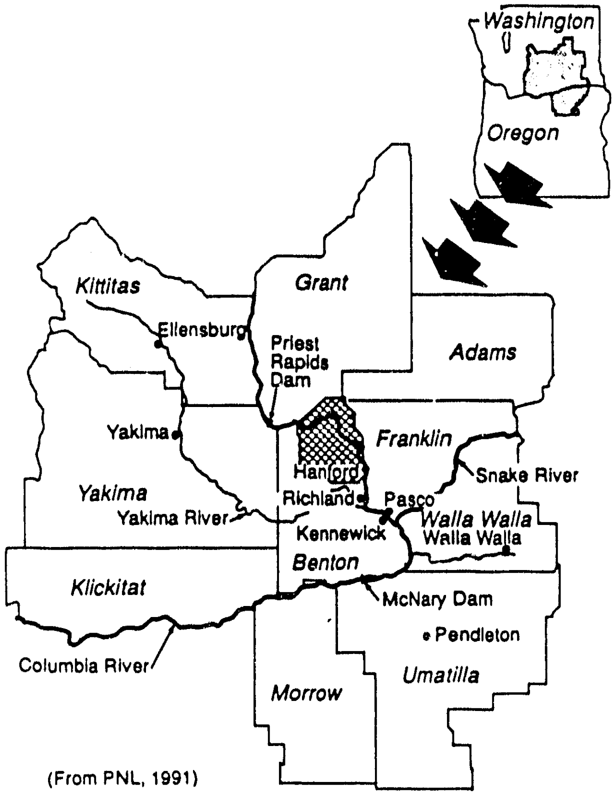

Figure 2. Spatial "Domain" of Study

DECISION ANALYSIS METHODOLOGY

A formal decision-aiding methodology has been developed to assist the HEDR Project in making the significant decisions discussed above in the context of interactions among project staff, the TSP, and the public. As illustrated schematically in Figure 3, this decision-aiding methodology is formal, rational, comprehensive, explicit and quantitative (and thus defensible), while still being practical and efficient. This methodology is comprised largely of concepts and techniques adopted from the field of decision analysis, especially "multi-attribute utility theory".[3]

Development

Development of the decision-aiding technology consisted of the following steps:

1) Identification of a comprehensive set of "requirements" for the consequences of the HEDR Project. These requirements are non-negotiable items which the HEDR Project must satisfy to be acceptable; e.g., items which an auditor can check off at the end of the project. These items include fulfilling specified functions, as well as specific cost and schedule constraints. The functions, in turn, include completion of specified deliverables (e.g., project reports, historical documents, and dose estimation model) and the

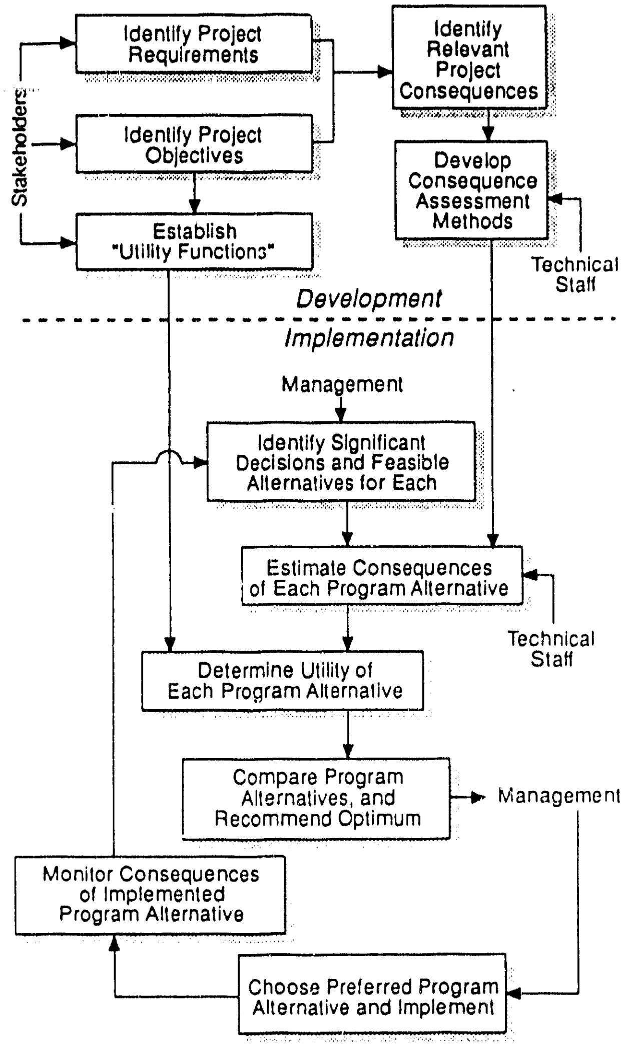

Figure 3. Decision Management Approach

provision of specified services (e.g., estimation of doses for interested individuals). A tentative list of project requirements is presented in Table 1.

The requirements should reflect the needs of the various parties affected by any decisions (e.g., DOE, CDC, and the public), i.e., the "stakeholders". They should also be comprehensive, but not unnecessarily restrictive. Such requirements have been established by polling the various stakeholders, i.e., conducting an "audience analysis", and synthesizing the results. Typically, the requirements of the various stakeholders are supplementary rather than competing, and were thus easily combined (e.g., by adopting the most restrictive).

2) Identification of a comprehensive set of "objectives" for the consequences of the HEDR Project. These objectives are preferred (but not required) items which are ultimately negotiable; e.g., items which can be traded off against others. As summarized in Table 2, these items generally include the "quality" with which the specified functions are fulfilled, as well as cost and schedule considerations; i.e.:

- maximizing the technical completeness or comprehensiveness of the deliverable or service;
- maximizing the usefulness (i.e., clarity of results, accessibility, and availability) of the deliverable or service to the various stakeholders;
- minimizing the uncertainty (or maximizing the accuracy) of the results of a deliverable;
- maximizing the acceptability of the service to the various stakeholders and the technical defensibility of the results of the deliverable; and
- minimizing the costs and schedule of the deliverable or service.

The objectives should be comprehensive, reflecting the collective preferences of the various stakeholders. Such objectives have also been established by synthesizing the results of the audience analysis. Although the objectives of various stakeholders are generally supplementary and thus easily combined, they are sometimes competing and must be negotiated in order to achieve a workable consensus.

3) Development of methods (e.g., models) for assessing the relevant consequences of the HEDR Project, vis a vis the HEDR Project requirements and objectives. Tentative "measures" which quantitatively define these consequences are also identified in Table 2. In many cases (e.g., regarding completeness, usefulness, and acceptability), these measures are expressed in terms of an assessed percentage of the maximum possible. In other cases (e.g., regarding schedule and costs), these measures are expressed in terms of an assessed percentage of some value (either the "worst" case or a multiple of a "target" value).

The consequence assessment methods need to recognize that the actual consequences will be uncertain beforehand, and thus must be able to assess such uncertainties. Such methods range from (a) simple, subjective assessments of consequences by knowledgeable staff, to (b) complex, stochastic numerical models implemented with various parameter probability distributions explicitly derived from available data. Tradeoffs must be made between the effort and reliability associated with each method, based on the "significance" of the specific decision being evaluated, where significance can be measured in terms of the range in potential consequences of that decision.

Such methods have been developed by the technical staff and, in order to maintain credibility of the results, did not involve stakeholders who might have injected their biases into the process.

4) Establishment of "utility functions" which quantify the HEDR Project objectives of Step 2 and express relative

TABLE 1 TENTATIVE HEDR PROJECT REQUIREMENTS

DELIVERABLES	SERVICES	CONSTRAINTS
Dose Estimates - selected individuals (support CDC thyroid study) - population - subpopulations Native Americans military construction migrant Individual Dose Model Declassified Documents Hanford History - releases - processes (re/ releases) - release monitoring - environmental monitoring - dose monitoring Native American Demographics Annotated Bibliography	Provide Public Reading Room - HEDR project record - documents of interest - TSP documents Provide Forum for Public/Native American Involvement - TSP meetings - workshops - public information Provide Dose Estimates (on call)	Schedule - project completion - minimum acceptable rate of document declassification - minimum acceptable frequency of TSP meetings - CDC thyroid study dose estimates - monthly reports (public information) Cost - annual budgets

preferences among the possible consequences of the HEDR Project. Such utility functions are essentially "scoring rules" which translate consequences into measures of the degree to which the objectives are satisfied and thus the level of preference; e.g., a higher score indicates a higher degree of satisfying an objective or set of objectives and thus a higher level of preference. For example, with respect to project cost, a score of zero (indicating that the objective of minimizing costs is not met to any significant degree) might be assigned for project costs in excess of some large maximum amount, a score of 100 (indicating that the objective of minimizing costs is met to the ideal degree) might be assigned for project costs less than some small minimum amount, and a linear relationship between scores and costs assigned in between. The collective score or utility, considering all objectives, is a logical and non-controversial basis for comparing decision alternatives, as discussed below.

The utility functions, as well as the HEDR Project requirements and objectives, should represent the collective preferences of the various stakeholders. Such utility functions can also be established by synthesizing the results of the audience analysis. The utility functions of various stakeholders are generally competing and must be negotiated in order to achieve a workable consensus.

Implementation

Implementation of the decision-aiding methodology, once developed as discussed above, is ongoing and consists of the following steps:

5) Identification of significant decisions which would benefit from application of the decision-aiding methodology and feasible alternatives for each decision. Such decision alternatives are identified by management, with input solicited from both stakeholders and technical staff. Those alternatives which clearly do not meet all of the HEDR Project requirements are quickly screened out, and feasible combinations of decision alternatives (i.e., alternative "programs") are identified. Alternative programs, rather than individual decision alternatives, must be evaluated because the entire program determines the consequences; i.e., decisions on one aspect of an integrated program cannot be made in isolation of decisions on the other aspects. Although the preliminary screening of decision alternatives with respect to the project requirements is a relatively mechanical evaluation, some judgement may be required in identifying a reasonable set of alternative programs (i.e., combinations of those decision alternatives).

6) Estimation of the relevant HEDR Project consequences of each program alternative by implementing the established methods from Step 3. This includes the assessment of the uncertainty in each program alternative's consequences, and correlations among those consequences and alternatives. However, only those consequences which vary among the program alternatives need be assessed. Such assessments are conducted by technical staff, and do not involve stakeholders who might inject their biases.

7) Determination of the "utility" of each program alternative by applying the established utility functions from Step 4 to that alternative's estimated consequences from Step

TABLE 2 TENTATIVE HEDR PROJECT OBJECTIVES

FUNCTIONS (see Table 1)	OBJECTIVES					
	Maximize Completeness (%)	Maximize Usefulness (% ideal)	Minimize Uncertainty (% worst)	Maximize Acceptability (% acceptable)	Minimize Cost (% 1.5 target)	Minimize Schedule (% 1.5 target)
Dose Estimates	X[a]	X[b]	X	X[c]	X	X
Individual Dose Model	X[a]	X[b]	X	X[c]	X	X
Declassified Documents	X	X[d]		X[e]	X	X[f]
Hanford History	X[g]	X[h]	X[i]		X	X
Native American Demographics	X	X	X[i]	X[j]	X	X
Annotated Bibliography	X	X	X[i]		X	X
Provide Public Reading Room	X	X[k]			X	
Provide Forum for Public/Native American Involvement		X[l]		X	X	
Provide Dose Estimates (on call)		X[m]		X	X[n]	

NOTES:

[a] i.e., regarding pathways, geographic areas, time periods, radionuclides, sources, populations, and dose types.
[b] e.g., regarding communication of results.
[c] i.e., regarding defensibility, in terms of % of ideally defensible.
[d] i.e., prioritize documents.
[e] i.e., maximize security, in terms of % worst possible.
[f] i.e., maximize rate of declassification, in terms of % ideal.
[g] e.g., regarding representativeness.
[h] e.g., regarding redundancy.
[i] i.e., maximize accuracy, precision, and comparability, in terms of % accurate.
[j] e.g., by tribal leaders.
[k] e.g., maximize accessibility.
[l] i.e., regarding accessibility and involvement (e.g., frequency and location of meetings).
[m] i.e., regarding accessibility, availability, and ease of use.
[n] e.g., minimize use of scarce resources.

6. This includes the determination of the uncertainty in each program alternative's utility and correlations among the alternatives, as a function of the uncertainties and correlations in that alternative's consequences. This is a relatively mechanical evaluation, and does not involve other input or judgement.

8) <u>Comparison of program alternatives in terms of their computed utilities, which indicates the stakeholders' degree of preference with respect to HEDR Project consequences.</u> This includes consideration of the assessed uncertainty in each program alternative's utility, as well as the correlation in those utilities among alternatives. The program alternatives are ranked in terms of their mean or "expected" utilities, as well as in terms of the probability that they have a higher utility than all other alternatives. The sensitivity of these rankings to reasonable changes in the utility functions and/or in subjective assessments, either of which may be somewhat controversial, is evaluated to determine the "robustness" of subsequent decisions. Again, this is a relatively mechanical exercise, and does not involve other input or judgement.

9) <u>Selection of the preferred program alternative by management, based primarily (but not necessarily solely) on the above rankings and their robustness.</u> Such decisions, which are consistent with the stakeholders' objectives and are otherwise based on relatively mechanical technical evaluations of consequences, should not be controversial (at least from a logical standpoint), reflecting mutually acceptable albeit implicit compromises among the various stakeholders.

Once implemented, the performance of the selected program alternative will be monitored, which does not involve significant other input or judgement. Based on observed performance, additional decisions may have to be made, i.e., implementation of the methodology (Steps 5-9) may have to be reinitiated.

FORMULATION

The decision-aiding methodology described above had to be adequately formulated for application. This involved mathematical representations of the evaluations, which were then developed into an appropriate software package for convenient PC-computer implementation.

Mathematics

The evaluations contained within the proposed decision-aiding methodology are quantitative, and can be described mathematically. The overall utility of any Alternative A can be expressed as follows[3]:

$$\begin{aligned} U(A) &= f\{\underline{M_x(A)}\}_{all\ x} \\ &= \sum_x W_x\ U_x\{M_x(A)\} \quad \textit{for independent } U_x\{M_x\} \end{aligned} \tag{1}$$

where

$M_x(A)$ is the "measure" vis a vis Objective x for Alternative A

$U_x\{M_x\}$ is the utility function for Objective x

W_x is the relative importance of Objective x.

The uncertainty in the overall utility of any Alternative A can be expressed in terms of a probability distribution (pdf), e.g., determined from Equation 1 by Monte Carlo simulation, as follows:

$$p[U(A)] = f\{p[\underline{M_x(A)}]_{all\ x},\ W_x,\ U_x\{M_x\}\} \tag{2}$$

where

$p[\underline{M_x(A)}]_{all\ x}$ is the "joint" pdf for all measures M_x for Alternative A (considering possible correlations among M_x)

The probability that Alternative A may have a higher utility than (and thus be preferred to) Alternative B can be expressed as follows:

$$\begin{aligned} P[U(A)>U(B)] &= P[\{U(A)-U(B)\}>0] \quad \textit{for any } A,B \\ &= f\{p[\underline{U(A)}]_{all\ A}\} \end{aligned} \tag{3}$$

where

$p[\underline{U(A)}]_{all\ A}$ is the joint pdf for overall utilities for all alternatives

$$= f\{p[\underline{M_x(A)}]_{all\ x,A},\ W_x,\ U_x\{M_x\}\} \tag{4}$$

Utility Functions

The utility functions express the relative preference among the various possible values of each consequence measure, ranging from least preferred (0) to most preferred (100) using a linear scale. Such utility functions can be linear or non-linear, positively or inversely proportional to the consequence measures, as well as independent or dependent on each other (depending on relationships among the objectives). For example, a highly non-linear, positive utility function might be assumed for many of the objectives regarding completeness, usefulness, and acceptability, which expresses the disproportionate value of very high percentages. Such a utility function for a measure which varies between 0 and 100 might be reasonably represented by the following analytical form:

$$U_x\{M_x\} = (101^{M_x/100})-1 \tag{5}$$

Appropriate analytical forms can typically be derived for any utility function.

For example, one of the most significant HEDR Project objectives relates to the accuracy to which dose estimates will be made. The utility function for this objective was quantified based on "value of information" concepts:

- The importance of knowing the true dose (if possible) for any individual was expressed as a numerical function of dose. Clearly, knowing higher doses should be more important than knowing lower doses, although this is not necessarily a linear relationship.
- The benefit of accurately estimating the true (albeit unknown) dose for any individual was expressed as a numerical function of dose. Clearly, the greatest benefit is achieved with highly accurate estimates and the least benefit is achieved with very inaccurate estimates.
- The current and minimum possible uncertainties in individual dose estimates were subjectively assessed. Clearly, the uncertainty in dose estimates which will result from any program alternative is bounded by these two extremes.
- The size of the population potentially exposed was estimated. Clearly, the larger the exposed population, the more important it is to know the true individual doses and the more benefit there is to accurately estimate them.

Hence, the utility function (or value of information) related to the objective of maximizing the accuracy (or minimizing the uncertainty) in dose estimates has been derived as a numerical function of: (a) the means and variances of the current probability distributions for the individual dose estimates; (b) the projected reduced variance of the probability distributions for the individual dose estimates if the program alternative is implemented; and (c) the size of the exposed population.

If the objectives (and thus the utility functions) can be assumed to be independent and if the utilities are defined on a linear scale, tradeoffs among the objectives can be expressed simply by "relative weights" (see Equation 1). Such relative weights express the factor by which the utility regarding one objective must be divided to be equally preferred to the same utility regarding another objective. Hence, for example, achieving a utility of 95 with respect to maximizing completeness of the dose estimates (i.e., U_{1a}=95) might be equally preferred to achieving a utility of 80 with respect to maximizing the usefulness of the dose estimates (i.e., U_{1b}=80), so that the relative weights for the two objectives would be determined as follows:

$$\frac{(U_{1a}=95)}{W_{1a}} = \frac{(U_{1b}=80)}{W_{1b}}$$
$$W_{1b} = W_{1a}\frac{(U_{1b}=80)}{(U_{1a}=95)} \quad (6)$$

Pair-wise comparisons of each of the objectives can thus be used to develop the relative weights.

Computer Model

The proposed decision-aiding methodology described above (including the tentative list of objectives) has been implemented in the form of a LOTUS 1-2-3 spreadsheet. In this spreadsheet, the utility functions (currently up to 10 different forms) and relative weights are specified for each objective. Various program alternatives (currently up to 10 in conjunction with a base case) can be evaluated simultaneously, with respect to the base case as well as with respect to each other. This is done by first estimating the consequence measure for each objective for the base case, including uncertainties and correlations in those measures if desired. The difference in the consequence measure for each objective is then estimated for each program alternative, again including uncertainties and correlations in those differences if desired. The uncertainties in consequence measures and differences in consequence measures can be expressed in terms of a variety of probability distribution types, as allowed by @RISK (a LOTUS add-on). The differences in consequence measures are subsequently used to determine the consequence measures for each program alternative while maintaining correlations among alternatives; i.e., the analysis is essentially normalized with respect to the base case, thus mitigating the effects of potential errors in the base case assessments.

Utilities are computed for each objective for each program alternative by implementing the specified utility function with the estimated consequence measure for that objective/alternative. The overall utility for that program alternative is then determined using Equation 1, assuming independent objectives.

Differences in the total utilities are then determined between each pair of program alternatives. However, because of the uncertainties and correlations in the consequence measures for each objective/alternative, there will be uncertainties and correlations in the overall utilities for each program alternative and thus uncertainties in the difference in utilities between any pair of alternatives. The probability that one alternative has a higher utility than (i.e., is preferred to) any other is also a function of these uncertainties. In the spreadsheet, these uncertainties, as well as the probability of one alternative having a higher utility than another, are determined by Monte Carlo simulation, using @RISK.

EXAMPLE

A simple example has been developed to illustrate the application of the proposed decision-aiding methodology. This example consists of comparing three program alternatives to a hypothetical base case, which is defined by a specific set of consequence assessments. The three program alternatives include:

1) Increasing the "depth" of the study to a specific degree, which will decrease the uncertainty in dose estimates and in the individual dose model, at increased cost and schedule.

2) Increasing the "domain" of the study in a specific way, which will increase the completeness of dose estimates and of the individual dose model, at increased cost and schedule.

3) Increasing the frequency of public meetings to a specific level, which will increase the usefulness and acceptability of the project, at increased cost.

The hypothetical assessment of the potential consequences (in terms of changes from the base case) for each of the program alternatives were input to the computer model, in conjunction with the hypothetical base case consequence assessments, and utility functions and relative weights for each objective. The program alternatives were then evaluated in parallel to determine the following, as summarized in Table 3: (1) a pdf for the overall utility for each of the program alternatives; (2) a pdf for the difference in overall utilities between each pair of alternatives, considering the correlation in utilities among the alternatives; and (3) the probability that one alternative will have a higher utility (i.e., be preferred) over each of the other alternatives.

From the above results, the degree of preference among the program alternatives can be determined. Based on expected utilities, the alternatives would be ranked as follows: 1. base case (4470), 2. PA3 (4440), 3. PA2 (3950), and 4. PA1 (3870). Based on probable differences in utilities, the alternatives would be ranked as follows: 1. base case (0.50), 2. PA3 (0.39), 3. PA2 (0.01), and 4. PA1 (0.00). In this case the rankings are the same, although the degree of preference is not, and a logical decision could be made. Clearly, however, the results are a function of the consequence assessments, utility functions and relative weights used. The sensitivity of the rankings to reasonable changes in these inputs should be assessed, especially whenever the degree of preference is small.

TABLE 3 EXAMPLE APPLICATION OF DECISION-AIDING METHODOLOGY

PROGRAM ALTERNATIVES	UTILITY[a]		DIFFERENCE IN UTILITIES[b]								
			U{PA1}-U{x}			U{PA2}-U{x}			U{PA3}-U{x}		
Base Case (BC)	m= 4470	s= 604	m= -606	s= 150	P= 0.00	m= -525	s= 211	P= 0.01	m= -30	s= 204	P= 0.39
Program Alternative 1 (PA1)	3870	579	0	0	NA	81	199	0.62	576	230	1.00
Program Alternative 2 (PA2)	3950	569	-81	199	0.38	0	0	NA	495	227	0.99
Program Alternative 3 (PA3)	4440	620	-576	230	0.00	-495	227	0.01	0	0	NA

NOTES:

a m,s are, respectively, mean and standard deviation of utility for program alternative.

b m,s,P are, respectively, mean and standard deviation of difference in utilities for pair of program alternatives, and probability that the difference is greater than zero.

It must be noted that the above example is strictly hypothetical and does not represent actual conditions; it is for illustrative purposes only. Hypothetical consequence assessments, utility functions and relative weights were used as input. Also, many additional alternative programs exist that may be preferable to the above.

CONCLUSIONS

The proposed decision-aiding methodology presented herein provides a formal, rational, comprehensive, explicit and quantitative basis for making and documenting recommendations on significant decisions within the HEDR Project. Agreement on the methodology, and subsequently consensus on the project requirements/objectives and utility functions/relative weights, must be achieved among the various stakeholders in order arrive at mutually acceptable decisions, which reflect appropriate compromises. Such agreement/consensus might be best achieved through workshops involving all of the stakeholders.

The major variables in applying the proposed decision-aiding methodology relate to the number of objectives (i.e., possibly lumping some) and the complexity of the methods used to assess the relevant consequences of any program alternative. These variables in turn will impact the resolution of the results as well as the cost and effort involved in the implementation of the methodology. Criteria should thus be developed to determine these variables for various types of decisions.

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