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Potential Enhancements to Addressing Programmatic Risk in the Tank Waste Remediation System (TWRS) Program

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April 1996

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Pacific Northwest Laboratory
Richland, Washington 99352

Summary

Pacific Northwest National Laboratory (PNNL)[a] conducted a Tank Waste Remediation System (TWRS) Risk Management methodology development task. The objective of this task was to develop risk management methodology focused on 1) the use of programmatic risk information in making TWRS architecture selection decisions and 2) the identification/evaluation/selection of TWRS risk-handling actions. Methods for incorporating programmatic risk/uncertainty estimates into trade studies are provided for engineers/analysts. Methods for identifying, evaluating, and selecting risk-handling actions are provided for managers. The guidance provided in this report is designed to help decision-makers make difficult judgments.

Current approaches to architecture selection decisions and identification/evaluation/selection of risk-handling actions are summarized. Three categories of sources of programmatic risk (parametric, external, and organizational) are examined. Multiple analytical approaches are presented to enhance the current alternative generation and analysis (AGA) and risk-handling procedures. Appendix A describes some commercially available risk management software tools and Appendix B provides a brief introduction to quantification of risk attitudes.

The report provides three levels of analysis for enhancing the AGA Procedure: 1) qualitative discussion coupled with estimated uncertainty ranges for scores in the alternatives-by-criteria matrix; 2) formal elicitation of probability distributions for the alternative scores; and 3) a formal, more structured, comprehensive risk analysis. A framework is also presented for using the AGA programmatic risk analysis results in making better decisions.

The report also presents two levels of analysis for evaluation and selection of risk-handling actions: 1) qualitative analysis and judgmental rankings of alternative actions, and 2) Simple Multi-Attribute Rating Technique (SMART). Suggestions are offered for structuring workshops for subject matter experts to identify and evaluate alternative risk-handling actions.

(a) Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

Abbreviations and Acronyms

AGA	alternative generation and analysis
CDF	cumulative distribution function
DATA	Decision Analysis by Tree Age
DOE	U.S. Department of Energy
DPL	Decision Programming Language
HLW	high-level waste
MAU	multi-attribute utility
RML	Risk Management List
SMART	Simple Multi-Attribute Rating Technique
TRU	transuranic
TWRS	Tank Waste Remediation System
WHC	Westinghouse Hanford Company
WIPP	Waste Isolation Pilot Plant

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1.0 Introduction

This section describes the purpose and scope of the Tank Waste Remediation System (TWRS) risk management methodology development task. There are two general areas of application and users for the methodologies developed. First, methods for incorporating programmatic risk/uncertainty estimates into trade studies are provided for engineers/analysts. Second, methods for identifying, evaluating, and selecting risk-handling actions are provided for managers.

1.1 Purpose

The purpose of this task is to develop risk management methodology focused on two areas:

1. Use of programmatic risk information in making TWRS architecture selection decisions.

2. Identification/evaluation/selection of TWRS risk-handling actions.

This methodology can be used to enhance or supplement the existing TWRS Systems Engineering procedures for alternative generation and analysis, decision management, and risk management. Regardless of what methodology is used, the reason for doing any analysis whatsoever is to help the decision-maker(s) make good decisions. This report provides a framework to help focus attention on the key aspects of decision-making in the two areas mentioned above, the kinds of information required to support decision analysis in these areas, and how to use the results of the analysis in actually making the decision.

Estimating key programmatic risks and incorporating this information into TWRS decision-making is the focus of the task. The term "programmatic risk" encompasses all risks to project cost, schedule, and technical performance that are associated with the implementation of a given alternative.

1.2 Scope

The scope of the effort includes both TWRS architecture selection decisions and TWRS risk-handling actions, as described below.

1.2.1 Architecture Selection Decisions

Trade studies are currently done by TWRS to compare alternative architectures, which are evaluated against a set of decision criteria. This activity, referred to as alternative generation and analysis (AGA), is supposed to incorporate risk/uncertainty into the evaluation of alternative architectures. Section 2.1.1 below (abstracted from the AGA Procedure) directs the engineers to perform a risk analysis that considers uncertainties in the expected performance of alternatives.

This report provides several methods for incorporating risk/uncertainty into TWRS trade studies. A range of approaches is possible, from a simple checklist to a more complex, systematic methodology, as outlined by the three levels of analysis described below. The results of this programmatic risk assessment methodology will enhance or supplement the TWRS Decision Management Procedure for selection of the preferred architecture. The analysis level chosen for a particular decision would depend on the importance of the decision being made and the perceived magnitude of the risks involved.

Level 1	Qualitative discussion of potential risks and likely impacts, coupled with estimated uncertainty ranges for the scores in the alternatives-by-criteria matrix.
Level 2	Formal elicitation of probability distributions for performance of the alternatives on the decision criteria.
Level 3	A formal, more structured, comprehensive risk analysis considering potential scenarios, probabilities, and impacts which would result in probability distributions for performance on decision criteria. This could consist of some combinations of direct risk assessment, parametric analysis, and scenario analysis.

1.2.2 Risk-Handling Actions

The TWRS Program needs to actively manage the programmatic risks of developing its preferred architectures using the Risk Management List (RML) as a tool. The enhanced risk-handling methodology described later in this report addresses how appropriate risk-handling actions are identified, evaluated, and selected for implementation. It provides practical guidance to TWRS program managers for selecting the appropriate risk-handling actions and using them to more effectively manage their programs.

A range of analytical approaches for evaluation/selection of risk-handling actions is possible, from simply providing some structure to the current way TWRS managers and engineers think about risk handling to a more complex, systematic methodology. This report describes two potential methodologies for evaluation and selection of TWRS risk-handling actions. The two levels of analysis described in this report are summarized as follows:

Level A	Qualitative analysis and judgmental rankings of alternatives based on costs, ability to reduce the likelihood of occurrence, and ability to reduce the consequences of occurrence.
Level B	A more complex, systematic methodology to evaluate alternative risk-handling actions, specifically Simple Multi-Attribute Rating Technique (SMART).

2.0 Background

This section describes the current approach as documented in the TWRS Systems Engineering AGA Procedure, the TWRS Systems Engineering Decision Management Procedure, and the TWRS Systems Engineering Risk Management Procedure. It also covers how the current approach is implemented, the need for improvement or enhancement of the current approach, and how to use the enhanced methodology.

2.1 The Current Approach

Section 2.1.1 describes the current approach for TWRS architecture selection decisions. Section 2.1.2 describes the current approach for selecting TWRS risk-handling actions.

2.1.1 Architecture Selection Decisions

The matrix created as the product of the AGA Procedure provides quantitative scores for how alternatives perform relative to a given set of decision criteria. These scores are "best estimates" based on a certain set of assumptions and estimation techniques (i.e., the exact cost, or completion date, or waste volume cannot be known precisely). The uncertainties in the estimates reflect programmatic risk, which should be analyzed for each alternative. Thus, each matrix score should have a corresponding uncertainty/risk associated with it.

A graded approach is taken to the level of detail needed for programmatic risk analysis. The least detailed approach is to define the possible range of scores for each matrix entry (i.e., identify highest and lowest possible, as well as the "best estimate"). The most detailed approach produces a probability distribution over the range of possibilities. An intermediate approach is to define a few, say three, points in the range and assign probabilities (summing to 1.0) to each point. The level of detail to which risk is analyzed should be determined by what information the decision-maker(s) want, the ability/cost to produce the information, and the degree of risk for the specific criterion relative to other risks. The level of detail to be used in analyzing risk should be specified in either the decision plan (provided by the decision-maker) or the work plan for the decision.

In addition to analyzing/estimating the risk, the sources of, and contributors to, risk should be identified. The following are possible sources of programmatic risk:

- validity of assumptions used in estimating performance
- higher-level alternative decisions and policy issues not yet resolved
- uncertainty in the performance of technology
- uncertainty in parametric estimates of costs (e.g., scaling factors, staffing levels) and schedules.

The extent that the various sources of programmatic risk contribute to the total risk for each alternative should be specified and documented.

The TWRS Systems Engineering Decision Management Procedure (WHC 1995a) provides guidance for planning, managing, and making decisions. It is closely tied to the AGA Procedure described above. Once information is developed by the AGA activities, it is structured into a matrix of alternative scores versus decision criteria as described above. This matrix is presented to the decision-maker(s) for review and selection of the preferred alternative.

The selection of a preferred alternative from among a set of competing alternatives is the essence of decision-making. Given the information developed by the AGA, the selection of a preferred alternative should be a straightforward process of examining the data and designating one of the alternatives as clearly preferred. A clearly preferred alternative exceeds all other alternatives across each of the decision criteria (i.e., it is the dominant alternative). Complications can arise when no single alternative emerges as a clearly preferred alternative. In these cases, one approach is for the decision-maker(s) to develop weights for each of the criteria and to combine all the criteria into a composite score (sum of the individual weighted scores on all criteria) for each alternative. The alternative with the highest composite score is the preferred alternative. However, the programmatic risks (i.e., the uncertainties associated with the scores of the alternatives) must also be taken into account, and this could potentially change the decision regarding which alternative is preferred.

2.1.2 Risk-Handling Actions

The TWRS Systems Engineering Risk Management Procedure states that "risk handling is the set of steps taken to reduce risk to an acceptable level" (WHC 1995b). Risk-handling actions are selected from the following general categories: avoidance, transfer, sharing, control, and assumption.

2.2 How the Current Approach Is Implemented

Section 2.2.1 describes how the current approach to TWRS architecture selection decisions is implemented. Section 2.2.2 describes how the current approach to TWRS risk-handling actions is implemented.

2.2.1 Architecture Selection Decisions

As noted above, the AGA Procedure states that "In addition to the scores, programmatic risk must also be analyzed for each alternative. Thus, each matrix entry shall have a corresponding description of uncertainty/risk" (WHC 1995c). In actual practice, the engineers doing trade studies attempt to capture uncertainties related to their cost estimates in a quantitative manner. However, any other risks or uncertainties that are mentioned in the trade studies are merely discussed in a qualitative manner. The intent is to flag concerns that the engineers have regarding programmatic risks that might impact one or more of the alternatives under consideration. In many cases, no attempt is made to quantify these risks.

2.2.2 Risk-Handling Actions

The current approach to identifying risk-handling actions for risk events within the TWRS Program is to conduct brainstorming sessions with technical and managerial staff. During these sessions, the potential options to avoid, control, transfer, share, and/or assume the risk are evaluated and a list of actions is generated. These actions are prioritized based upon group consensus, and compared with the current Multi-Year Program Plan to determine if the activities are currently funded. If the actions are high-priority and not funded, a change request may be required.

2.3 Need for Improvement/Enhancement

The need to improve/enhance/supplement the procedure for TWRS architecture selection decisions is discussed in Section 2.3.1. A similar need for selecting TWRS risk-handling actions is discussed in Section 2.3.2.

2.3.1 Architecture Selection Decisions

As described earlier, the existing AGA Procedure requires the development of an alternatives-by-criteria matrix (i.e., the scores matrix) with point estimates to indicate how each of the alternative architectures performs relative to the decision criteria. It also mentions the need to develop estimates of the programmatic risk for each matrix entry. The procedure can be improved by providing more explicit guidance on how to develop programmatic risk estimates and how to use this information in making decisions. Currently, programmatic risk management is seen as an additional burden on the engineers. This report describes multiple methodologies to help the TWRS Program identify and manage programmatic risks that could otherwise result in negative impacts on program costs, schedules, and technical performance.

2.3.2 Risk-Handling Actions

The current Risk Management Procedure states that several potential risk-handling actions should be identified for each risk, then a cost-benefit analysis should be performed for each of the risk-handling actions in order to prioritize them. Guidance on how to identify or evaluate the alternatives would be helpful. A simple methodology that walks the TWRS staff through the process of identifying and evaluating alternative risk-handling actions is needed.

2.4 How to Use the Methodology

The level 1 and level 2 analysis methodologies that we developed to supplement the AGA Procedure are fairly straightforward. Level 1 analysis can easily be used by TWRS engineers. Level 2 analysis may require a trained decision analyst to elicit the probability distributions. A trained analyst is probably also required to assist the implementation of the level 3 AGA methodology.

The risk-handling methodology described in this report was designed for ease of implementation by TWRS staff. Level A analysis should not pose major difficulty for TWRS staff who try to use it. However, a trained decision analyst is probably required to assist with implementation of the level B risk-handling methodology.

3.0 Sources of Programmatic Risk

Uncertainties that result in programmatic risks originate from parametric, external, and organizational sources. Parametric sources of programmatic risk are derived from uncertainties associated with measured parameters that are used to calculate technical performance. For example, uncertainties in the volume of waste, the concentration of plutonium in the waste, the concentration of aluminum in the waste, and the loading factors for the glass product may all introduce risk into the calculations of technical performance for a waste vitrification alternative. External sources of programmatic risk are derived from uncertainties associated with conditions or events that occur outside the control of the project or program. For example, the possibility of a change in a regulatory standard will introduce programmatic risk if the selected alternative cannot meet the new standard. Finally, organizational sources of programmatic risk are derived from uncertainties associated with the internal operations, such as corporate philosophy, internal conduct of operations procedures, and employee incentive structures.

3.1 Parametric Sources of Programmatic Risk

Parametric sources of programmatic risk may result from uncertainties associated with the input data for a technology or project. They may also result from uncertainties associated with the operability, maintainability, and technical performance of the technology or project.

Various types of input data may be needed to characterize the spatial extent, magnitude, and temporal duration of the problem for which a decision is needed. For example, to select a processing technology for a given waste form, data may be needed on the physical form, chemical composition, homogeneity, and spontaneous rate of change of that waste form. Each data point has an associated uncertainty that can result in programmatic risk. Estimates of uranium content, for example, may have a large degree of associated uncertainty if few samples were taken and the distribution of uranium in the waste form is not uniform. Without a better estimate of uranium content, it may not be possible to determine conclusively whether a given technology will process the waste so as to comply with regulatory standards.

The operability of the technology or project may also introduce programmatic risk. The ability to effectively and efficiently start up and shut down the technology or project, the internal process control mechanisms (e.g., the number and type of process control points), and the ability to respond and troubleshoot off-normal events may all impact cost, schedule, and technical performance. In addition, the characteristics of the operator interface, including the level of training required to operate the system or project, and the degree, type, and frequency of operator interaction with the system may impact cost, schedule, and technical performance. In general, simpler systems that use mature technologies and standard components, and that require minimal operator training and interaction with the system will be more predictable in their performance, and will therefore have lower levels of associated programmatic risk.

The maintainability of a technology or project is influenced by its complexity, reliability, repairability of associated system equipment and components, and flexibility of program sub-elements. As complexity increases (e.g., the level of training required to perform maintenance increases, the need for special or unique tools or procedures increases, the design qualities make repairs more difficult, standardized parts are replaced by customized parts, ease of troubleshooting is reduced), the ability to easily maintain the system or project decreases. Similarly, the ability to estimate the impacts of off-normal events also decreases. Reliability of the system or project is also important as increased failure rates; shorter mean times between failures; and increased frequency of test, calibration, and preventative maintenance procedures result in reduced technical performance, increased cost, and slipped schedules. Finally, the repairability of the system or project (e.g., as determined by work space factors, location of equipment, means of repair or replacement, number and type of repair and maintenance personnel, and pre-maintenance preparation requirements) also introduces uncertainty into technical performance and, hence, cost and schedule.

Uncertainty may also be associated with the estimates of the performance of a technology or project. Each assumption upon which estimates of technology or project performance are based has an associated level of uncertainty. Uncertainty may also be associated with estimates of the degree of flexibility inherent in the technology or project, and the ability to customize the technology or project. Finally, technologies at different levels of technical maturity typically have different levels of uncertainty associated with estimates of their technical performance. Uncertainty usually decreases as technologies and projects evolve from conceptual studies, to bench-scale demonstrations, to pilot-scale demonstrations, and finally to production-scale applications.

3.2 External Sources of Programmatic Risk

External sources of programmatic risk are numerous and often difficult to identify. (Lawsuits, for example, may come as a total surprise.) Moreover, the ability to manage or control them is limited. However, their ability to impact cost, schedule, and technical performance can be great.

The diversity of external sources of programmatic risk and the widely different modes of action through which they may operate make it difficult to generalize about their origins or modes of risk generation. Similarly, it is difficult to generalize about strategies for risk reduction, mitigation, or avoidance. Hence, no attempt will be made herein to do so. The following non-inclusive list is provided only to illustrate the diversity of the external sources of programmatic risk that are relevant to the TWRS Program:

- lack of agreement on Hanford end-state land uses
- unresolved, high-level decisions and policy issues that affect the ability to meet statutory intent and regulatory requirements
- the potential for regulatory change
- present and future stakeholder acceptability
- lawsuits brought by outside parties
- imperfectly understood site characteristics
- availability, adequacy, and reliability of supporting infrastructure

- externally driven schedules that affect technologies or project activities (e.g., U.S. Department of Energy [DOE] schedules, Tri-Party Agreement[a] milestones and changes therein, stakeholder schedules)
- externally shaped resource profiles (e.g., quantity and timing of funding)
- cost, availability, and adequacy of critical subcontract support (e.g., analytical laboratory support, specialty engineering support services).

3.3 Organizational Sources of Programmatic Risk

Organizational sources of programmatic risk may also be numerous and difficult to identify. But in contrast to external sources of programmatic risk, it may be possible to manage or control them to a considerable degree.

As with external sources of programmatic risk, organizational sources and their modes of action are diverse, making it difficult to generalize about their origins or modes of risk generation. Similarly, it is difficult to generalize about risk-handling strategies. The following non-comprehensive list is provided only to illustrate the diversity of the organizational sources of programmatic risk that are relevant to the TWRS Program:

- ability or inability of management to make timely decisions (e.g., management affliction with "analysis paralysis," conflicts among decision-makers for related program elements)
- availability, reliability, and technical skill base of project staff
- degree of flexibility in the scheduling of staff; ability of scheduling functions to adjust to off-normal conditions
- staff morale
- degree to which stove-piping of related and/or duplicative efforts occurs within the organization
- degree to which incentives for management and staff are connected with (or disconnected from) program mission and objectives (e.g., degree to which incentives exist to build bureaucracies rather than solve problems).

(a) Hanford Federal Facility Agreement and Consent Order, Washington State Department of Ecology, Environmental Protection Agency, U.S. Department of Energy, 1989, as amended.

4.0 Risk Management in Alternative Generation and Analysis (AGA)

This section describes potential methodologies for improving the consideration of programmatic risk in the current AGA Procedure and the current Decision Management Procedure. In Section 4.1, three levels of analysis are provided to enhance the AGA Procedure. In Section 4.2, a framework is presented for using the AGA programmatic risk analysis results in making decisions.

4.1 Potential AGA Methodology

Interviews were held in January 1996 with Westinghouse Hanford Company (WHC) engineers responsible for doing TWRS trade studies. They told us that implementation of the current AGA methodology often results in a matrix of simple point scores for each of the alternatives on each of the decision criteria. The only exception is that a range of costs is generally estimated. Thus, the only uncertainty that is incorporated into many TWRS trade studies in actual practice is the uncertainty related to the cost estimates.

Three levels of analysis are described below for the potential enhancement to the AGA methodology. The decision-maker(s) and responsible engineers will determine which level is appropriate for their study. In fact, it is not necessary to select one level of analysis before undertaking a study; a mix of levels might make sense in some cases. Also, the appropriate level of analysis may not become clear until the engineers are immersed in the details of the initial analysis. Selection of the appropriate level of analysis and carrying out the analysis should be considered an iterative process.

Level 1 analysis consists of a qualitative discussion of the greatest potential risks and likely impacts, coupled with estimated ranges for the scores in the alternatives-by-criteria matrix. Level 2 analysis is a systematic process for elicitation of probability distributions that will result in a more thorough representation of the key sources of programmatic risk/uncertainty. Level 3 analysis is a formal, more structured, comprehensive risk analysis considering potential scenarios, probabilities, and impacts which would result in probability distributions for performance on decision criteria.

The potential methodology will help the engineers doing the trade studies to quantify, for each alternative architecture, the uncertainty associated with the scores for the decision criteria. For each alternative, they should determine either ranges or probability distributions for the key criteria. These ranges or distributions measure the magnitudes of the programmatic risks. However, ranges or distributions may not be necessary for all the cells in the alternatives-by-criteria matrix; they may not make sense or they may be unimportant for some cells.

4.1.1 Level 1 Analysis

Level 1 analysis provides a qualitative discussion of identified programmatic risks, their magnitudes, their likelihoods, and their possible consequences. Programmatic risks are encompassed by the uncertainties associated with the scores the alternatives receive on each of the decision criteria used in the AGA Procedure. There is an existing set of general decision criteria that should serve as a starting point for the

AGA process (Keeney and von Winterfeldt 1996). These criteria can be adapted by TWRS management and technical staff for a particular trade study to ensure that all relevant criteria and programmatic risks are considered in the analysis. The decision plan should document the agreed-upon criteria.

A workshop format can be used by the engineers doing the trade study to develop estimates of programmatic risk (or it can be done offline). For each of the decision criteria, the engineers should discuss their perceptions of the amount of programmatic risk and the factors that influence it. They should document the key factors, then spend the majority of the time trying to quantify the greatest perceived risks (uncertainties) for each alternative.

Engineering analysis, models, and expert judgment can be used to estimate ranges for the scores each alternative architecture receives on the decision criteria used in the AGA (i.e., best estimates as well as confidence intervals should be estimated). For a level 1 analysis, all that is necessary is an estimate of the expected value and the highest and lowest possible scores for each alternative on each criterion. These simple range estimates are substitutes for the development of more detailed probability distributions as described below for level 2 and level 3 analyses. A matrix of programmatic risks for each alternative on each criterion should be created, analogous to the AGA matrix of scores, as shown in Table 4.1. For most (if not all) of the scores, range estimates of the uncertainties should be developed.

One approach to determining uncertainty ranges is to explore the sources of programmatic risk and elicit a worst-case, best-case, and most-likely estimate for each decision criterion. For each of the alternative TWRS architectures, the steps associated with this approach are as follows:

1. Identify and select experts to participate in the process.

2. Identify the factors contributing to the sources of programmatic risk. Sources of programmatic risk include parametric, external, and organizational sources as described in Section 3.0.

Table 4.1. Sample Alternatives-by-Criteria Matrix with Corresponding Uncertainties (Range Estimates)

	Criterion 1	**Criterion 2**	**Criterion 3**	**Criterion n**
Alternative 1	Score_{11} Uncertainty_{11}	Score_{12} Uncertainty_{12}	Score_{13} Uncertainty_{13}	Score_{1n} Uncertainty_{1n}
Alternative 2	Score_{21} Uncertainty_{21}	Score_{22} Uncertainty_{22}	Score_{23} Uncertainty_{23}	Score_{2n} Uncertainty_{2n}
Alternative 3	Score_{31} Uncertainty_{31}	Score_{32} Uncertainty_{32}	Score_{33} Uncertainty_{33}	Score_{3n} Uncertainty_{3n}
Alternative n	Score_{n1} Uncertainty_{n1}	Score_{n2} Uncertainty_{n2}	Score_{n3} Uncertainty_{n3}	Score_{nn} Uncertainty_{nn}

Note: The scores in Table 4.1 are the most-likely point estimates, while the uncertainties are ranges between the worst-case values and the best-case values identified.

A potential approach for each of these steps is explained below. The process would probably require a workshop session, although some elements might be completed as individual "homework" assignments. The product of the workshop would be a set of matrices showing sources of programmatic risk versus decision criteria for each alternative architecture.

Step 1 Identify and select experts.

Identify experts who are familiar with the technical issues associated with each alternative to address parametric uncertainties. In addition, experts who are familiar with external and organizational risks should be included in the analysis team.

Step 2 Identify the factors contributing to the sources of programmatic risk.

Provide the group with definitions of the three categories of sources of programmatic risk (parametric, external, and organizational) and give examples of each. For each category, brainstorm factors (or issues or assumptions) that contribute to uncertainty associated with the point estimates for the decision criteria, independent of the specific alternatives. Place each item on a separate card, then organize the cards to relate the factors to each of the three categories. Next, identify any additional factors that contribute to uncertainty but relate only to a specific alternative.

Step 3 Evaluate the relative importance of these factors to each alternative.

Precision is not critical in this step. Rather, the activities described herein are intended to help TWRS staff think broadly about the factors creating risks to their program, and how these factors may affect the alternatives under consideration.

Evaluate each alternative separately in this step. Ask each participant to rate the relative impact of each factor on the scores for each of the decision criteria for an alternative (i.e., no impact, some impact, large impact) and give a short rationale for their answer. It may be useful to have participants write down their answers prior to the meeting or use meeting facilitation software to efficiently capture this information in a group session. Compare participants' ratings and rationales and try to derive a consensus estimate of the relative impact of each factor on the scores for each decision criterion for each alternative, as shown in Table 4.2.

Step 4 Estimate the most-likely value and the range for the scores for each decision criterion.

For each alternative, ask each participant to separately review a matrix showing the group rating of the factors impacting the scores on each decision criterion and their rationales. Each participant should use this to estimate their best-case, worst-case, and most-likely estimate for each criterion. The most-likely estimate is the score, and the best- and worst-case estimates are the bounds on the range of uncertainty. For each alternative, review the results and try to achieve a group consensus on these three estimates. After estimating and reviewing the results for each alternative, compare the results across all the alternatives to check if there are any inconsistencies that appear to need adjustment.

Table 4.2. Impacts of Programmatic Risk Factors on Scores for a Particular Alternative

Source of Risk	Factor	Criterion 1	Criterion 2	Criterion n
Parametric Source 1	F1	None	Some	Large
Parametric Source 2	F2	Large	Some	None
Parametric Source 3	F3	Some	Some	None
External Source 1	F4	Some	None	None
External Source 2	F5	Large	Some	Some
Organizational Source 1	F6	Some	Some	Some
Organizational Source 2	F7	None	None	Some

4.1.2 Level 2 Analysis

Level 2 analysis provides a more thorough representation of the key uncertainties than level 1 analysis does through the development of probability distributions rather than simple range estimates. There are multiple options for obtaining the distributions (e.g., written documentation of prior studies, formal elicitation of probabilities, detailed analytical modeling). This section describes a formal process to elicit probability distributions from experts as one option.

Level 2 analysis methodology can benefit from significant interactions between a trained decision analyst and the subject matter experts. The subject matter experts can try to assign probability distributions on their own, without the help of a trained analyst. However, they will likely do a better job of this if a trained analyst is there to help. The main reason for this suggestion is that biases may enter the results without an analyst present to explore the experts' responses. Several workshop sessions will likely be needed.

The level 2 analysis methodology includes the following steps:

Step 1 Identification and selection of the experts (both subject matter experts and decision analysts) - Experts should be identified who are familiar with the technical issues associated with each alternative to address parametric uncertainties. In addition, experts who are familiar with external and organizational sources of programmatic risks should be included in the analysis team.

Step 2 Motivation - The purpose of this step is to train the subject matter experts to prepare for the elicitation process, including the following steps:

- Familiarize them with probability as a quantification of the current state of knowledge.

- Describe the importance of expert judgment.
- Make them comfortable with the techniques to be used to assess probabilities.
- Inform them about potential rules of thumb and biases.

Step 3 Structuring - The purpose of this step is to provide clear definitions of all terms used in the analysis, especially events whose probability distributions will be elicited.

Step 4 Conditioning - The purpose of this step is to provide clear definitions of all assumptions and key variables used in the analysis, and to identify the factors that influence the variables being elicited.

Step 5 Elicitation of probability distributions (through decomposition as necessary) - The analyst should begin by asking for the extreme values for the uncertain variable. Then the analyst should ask for scenarios that might lead to outcomes beyond the extremes, as well as the probabilities of outcomes beyond the extremes. The analyst should then elicit probabilities for the median and the quartiles. All the outcomes and probabilities should be plotted on a cumulative distribution function (CDF) to graphically represent the results of the elicitation process to the subject matter experts.

Step 6 Verifying - The purpose of this step is to analyze and cross-check the results, resolve differences as needed, and aggregate the results (by either mathematical averaging or group consensus). The objective is to test the expert judgments to make sure the participants really believe them. If necessary, some of the above steps may be repeated.

4.1.3 Level 3 Analysis

Keeney and von Winterfeldt (1989) state that "When a technical problem is complex, it is extremely difficult to informally process all of the information in one's head. This is one reason why engineers and scientists build models to aid their thinking in complex situations." Level 3 analysis (i.e., a quantitative risk analysis) is effective for such complex technical problems. Some more specific situations where it is desirable to do a level 3 analysis are

- if you already have a deterministic model and sensitivity analysis shows a significant impact on criteria scores depending on the values assumed for some variables
- if significant uncertainty in criteria scores has been identified and the decision-maker wants to better understand the sources of uncertainty
- if you suspect there is a lot of uncertainty associated with some criteria scores, but are unable to quantify the uncertainty directly (it would then be necessary to identify the key variables that can impact the criteria scores and, in effect, build a model to estimate the uncertainty)

- if you want to do a value-of-information analysis to identify what information would be valuable to improve the expected outcome of decision-making

- if it is recognized that the decision is being fundamentally driven by uncertainty (i.e., uncertainty is seen as having a significant impact as compared with an analysis based purely on value tradeoffs).

This section describes how to perform a level 3 analysis, including how to use parametric analysis or scenario analysis and how to integrate them in an overall evaluation as appropriate. The product is a CDF for any decision criterion for which the level of analysis is considered valuable. McConville et al. (1995) describes a model that can be used for this type of analysis for a few specific waste treatment strategies.

TWRS trade studies are concerned with measuring and comparing expected outcomes of alternatives. In particular, they attempt to measure the expected performance of alternatives on criteria that capture what is important in the decision outcome. In level 1 and level 2 analysis, these measurements are based upon direct judgments. However, sometimes the complexity of the process being evaluated leads to the construction of models to measure expected outcomes (i.e., level 3 analysis). An initial decision analysis is often based upon a deterministic model and the result is point estimates of performance on criteria. This initial analysis is often followed up by a sensitivity analysis which is designed to identify those estimated parametric values that, when varied through their range of uncertainty, result in the greatest change in the estimated performance.

A risk assessment can uncover both parametric uncertainties and external event uncertainties. Parametric uncertainties refer to the uncertainties in intermediate parameters that enter into the calculation of alternative performance. An example of a parametric uncertainty is the amount of aluminum in the high-level waste (HLW) stream and the consequent loading factors for the glass. This impacts the amount of HLW that will ultimately be produced and sent to the national repository.

External event uncertainties are concerned with events that are outside the control of the decision-maker. The outcome of the decision depends on which state these events end up in, as well as the chosen alternative. Consider for example, the decision of whether to carry an umbrella. The outcome of this decision depends on the weather as well as the alternative chosen. To use another example from TWRS, the outcome of the decision of whether to send transuranic (TRU) tank waste to the Waste Isolation Pilot Plant (WIPP) depends on whether WIPP will accept Hanford tank waste, which in turn may depend on WIPP's capacity and how much they receive from other sources.

The possibility that Hanford TRU waste would not be accepted by WIPP might be ignored in an analysis of alternatives because it is thought to be outside the control of the TWRS Program. It is more comfortable to treat acceptance by WIPP as an assumption. However, this is a risky assumption, and it is possible to explicitly consider the uncertainty in an analysis of alternatives.

Because of the tendency for external event uncertainties to go unnoticed, a systematic approach must be taken to identify them. Systematic risk assessment is an ideal forum for the identification of external event uncertainties. Especially suited are structured interviews that can easily lead the informant to a broad-based consideration of what can go wrong.

Efforts should be made to encourage the identification of scenarios other than those that are expected or desirable. Brainstorming sessions should be used to encourage creativity, openness, and non-judgmental expression of ideas. Once all ideas are on the table, there should be an initial screening, and those ideas that have merit can be explored in more detail as part of a formal risk analysis.

A risk analysis can often benefit from a formal modeling process. A model can sometimes be quite simple and consist of only of a single decision, one or more uncertainties, and a single outcome parameter. In other cases, it may benefit from highly complex modeling consisting of a collection of submodels for each of the parameters of interest, many uncertainties, and a complex decision structure in which many combinations of outcomes are evaluated. In either case, the model may focus on parametric uncertainties, or external event uncertainties, or both.

The process for a parametric risk analysis is as follows:

1. Create a deterministic model.

2. Perform a sensitivity analysis.

3. Reanalyze with the key uncertainties treated probabilistically.

4. Examine the output (a CDF for the outcome(s) of interest for each alternative).

The deterministic model may consist of a simple or complex spreadsheet that relates alternatives to outcome objectives. The sensitivity analysis may take the form of a "tornado diagram," which shows the range of outcome changes as a function of varying input parameters over some common range of uncertainty (e.g., a 90% confidence interval). If these results are presented graphically in horizonal bar charts, and arranged top to bottom in order of magnitude of variation in outputs, the resulting graph will look like a tornado. Those uncertainties that have significant impacts on outcomes can then be treated probabilistically by estimating their distributions. The resulting analysis will show probability distributions of outcome variables rather than just point estimates. This allows the decision-maker to see clearly the range of potential outcomes and their probabilities, and to decide if the probabilities of unacceptable outcomes are too great to be acceptable. Figures 4.1 and 4.2 show sample tornado diagrams and CDFs taken from McConville et al. (1995) to illustrate the techniques.

The process for an external event risk analysis is as follows:

1. Identify critical events and possible states.

2. Determine probability of states.

3. Determine impacts to alternative outcomes conditioned on states.

4. Examine the output (a CDF for the outcome(s) of interest for each alternative).

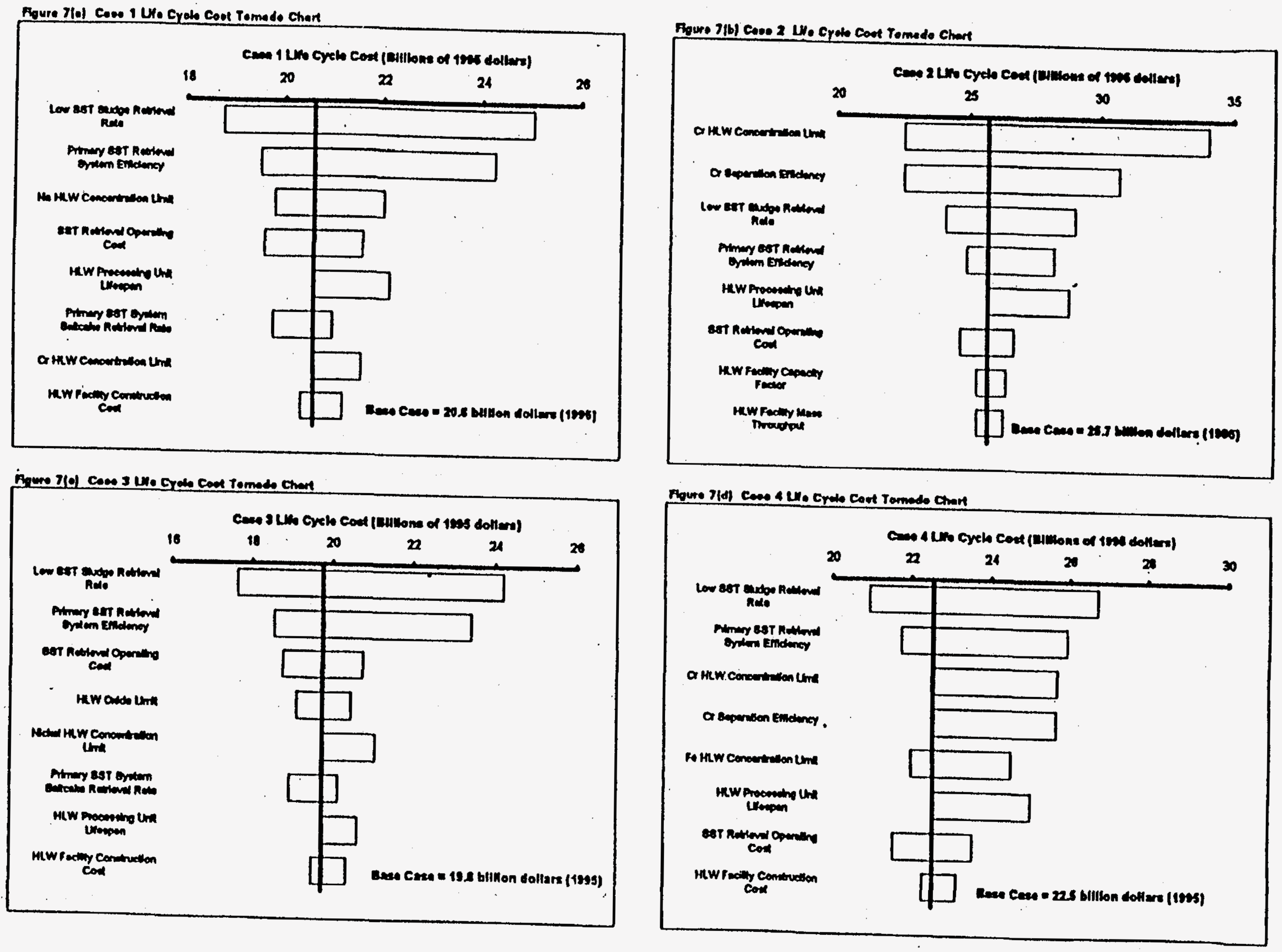
Figure 7(a) Case 1 Life Cycle Cost Tornado Chart

Figure 7(b) Case 2 Life Cycle Cost Tornado Chart

Figure 7(c) Case 3 Life Cycle Cost Tornado Chart

Figure 7(d) Case 4 Life Cycle Cost Tornado Chart

Figure 4.1. Sample Tornado Diagrams

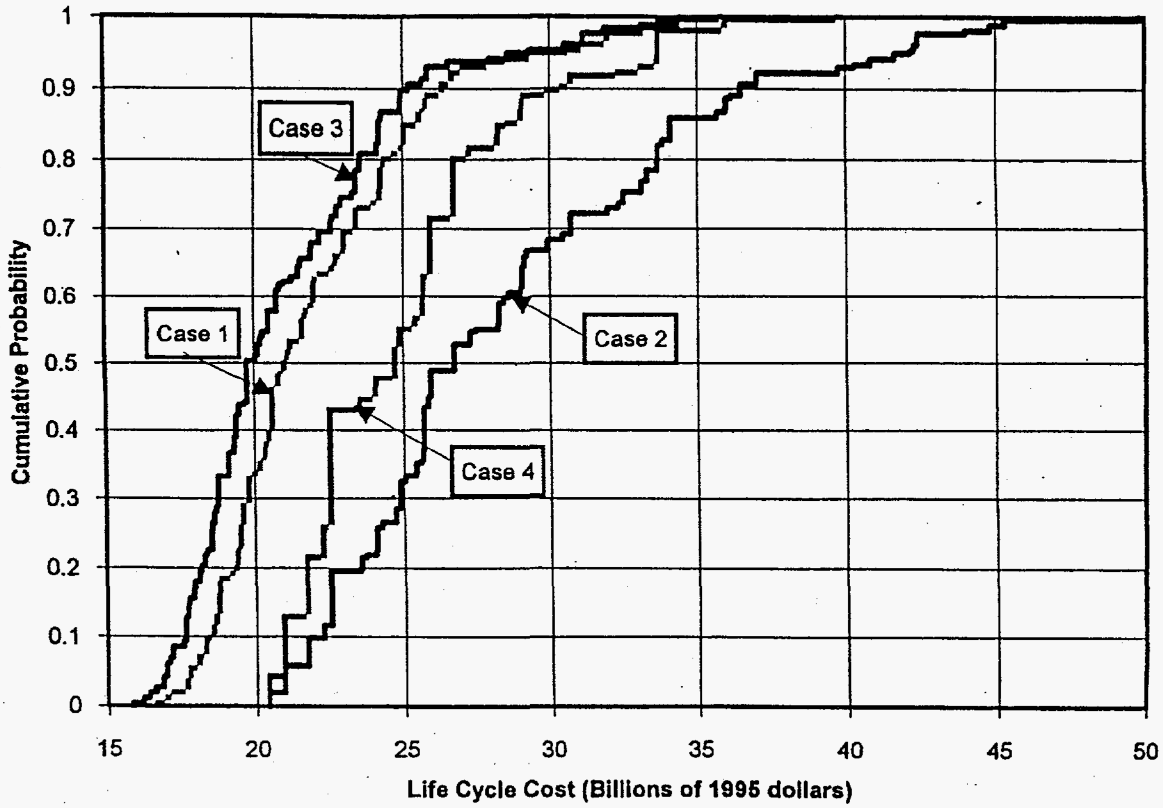

Figure 4.2. Sample Cumulative Distribution Functions

The relationships between alternatives, events, and outcomes can be represented as a decision tree or an influence diagram. There are various software packages that facilitate the calculation of the expected values of alternatives and output the CDFs (see Appendix A).

In practice, both types of risk analysis will be carried out in parallel in a single model. In fact, once the parametric uncertainties are identified, they will be represented as a decision tree and/or an influence diagram. The risk analysis will consist of the simultaneous consideration of both parametric and external event uncertainties.

4.2 Use of Programmatic Risk Information in Making Decisions

This section describes a methodology for using the programmatic risk analysis results developed in the AGA process in selecting the preferred alternative.

4.2.1 Introduction

Traditionally, trade studies have resulted in an alternatives-by-criteria matrix in which point estimates have been the extent of the formal data collection, and uncertainties on these point estimates were not provided (with the exception of cost). Risk information provides additional valuable information to the decision-maker; however, it can also lead to additional demands on the decision-maker to process this information in a meaningful way in order to make a decision. The extent of additional analysis necessary to aid the decision-maker depends on two factors, which need to be considered in combination. One factor is the degree to which performance information needs to be aggregated beyond the level of individual criteria to assist the decision-maker in understanding value tradeoffs. The other is the extent to which the decision-maker is able to make intuitive judgments about risks and their acceptability based upon a direct consideration of the uncertainty information. This results in the analysis possibilities shown in Table 4.3. Section 4.2.2 provides a guide to determining where in this table a particular analysis should be. Section 4.2.3 describes in detail approaches for each of the cells in Table 4.3.

Aggregation of decision criteria is addressed with value tradeoffs and weighting of criteria, which is a common practice in trade studies. Evaluation of risks can be based upon a direct consideration of possibilities, or utility theory can be invoked as an aid to the decision-maker in understanding his/her risk tolerance. Which of the four possibilities should guide the analysis depends on the decision-maker, the need to document and justify the decision rationale, the resources available, and the results of the data collection.

This section addresses the type of analysis necessary to support each of these four possibilities. Where the risks are few and can be considered independently of the performance analysis, it provides guidelines or heuristics for considering the risks. For cases with complexities that are beyond intuitive analysis or where a more formal justification and documentation of the decision rationale is desirable, processes for carrying out such an analysis are provided.

Table 4.3. Alternatives-by-Criteria Matrix Analysis Possibilities

	Direct Risk Judgments	**Utility-Based Risk Judgments**
No Aggregation of Criteria	**Analysis Method 1.** Intuitive value trade-offs. Direct judgments of risks from cumulative distribution functions (CDFs) or confidence intervals.	**Analysis Method 3.** Intuitive value trade-offs. Point estimates based on utility theory that incorporates risk attitude.
Aggregated Criteria	**Analysis Method 2.** Rolled-up performance based on weights. Risk considered by: 1. Individual CDFs 2. Uncertainty displayed graphically 3. Aggregated CDFs	**Analysis Method 4.** Overall utility for alternatives which aggregates value trade-offs and includes risk attitude.

The emphasis in this section is on the "Direct Risk Judgments" column of Table 4.3. Various methods are presented for representing uncertainties to help the decision-maker judge the acceptability or desirability of alternatives with uncertain levels of performance. The objective is to represent the uncertainties so that they are more easily grasped by the decision-maker. The decision-maker may or may not choose to provide value tradeoffs that make possible an aggregation of the scores on individual criteria to higher-level scores or to an overall score. If tradeoffs are provided in the form of weights, then it will be possible to aggregate the uncertainty information to a higher level as well.

The "Utility-Based Risk Judgments" column of Table 4.3 concerns situations in which the decision-maker has difficulty making direct judgments about the desirability of alternatives with uncertain outcomes. In this case, a decision analyst can facilitate the decision-maker's understanding of his/her risk tolerance, and this information can then be used in formulating a decision rule to guide the selection of an alternative.

4.2.2 Guide to Choice of Analysis and Decision-Making Approach

Table 4.3 provides a succinct description of the possibilities for decision aiding and analysis, but it does not address what level of analysis would be appropriate in a given decision situation. Figure 4.3 provides a guide to choosing the necessary level of decision aids and analytic methods. This figure should not be viewed as a roadmap to be navigated from start to finish for each decision. For a particular decision, one can start at whatever level seems appropriate. Moving from top to bottom, the guide takes a decision-maker to successively more complex levels of analysis, as necessary, to make a decision.

The type of decision aiding and analysis will depend on a variety of factors in the data, as well as the decision-maker's ability and desire to directly synthesize the information. Factors to consider are the number of criteria for which there are significant risks, the extent of interactions between various criteria, and the extent of interactions between performance and risk. Of fundamental importance is the ability of the decision-maker to select a preferred alternative based upon direct consideration of the uncertainties in addition to the point estimates.

Once data that include uncertainty information are collected in an alternatives-by-criteria matrix, there are several issues that must be addressed. One issue concerns the acceptability of risk for a single alternative on a particular criterion. Another issue concerns tradeoffs between risk and performance. The most difficult issue is how to consider risk and select the best alternative when faced with an alternatives-by-criteria matrix that includes uncertainties and performance tradeoffs across several criteria. If a decision based on individual analyses of risks is not obtained, then an integrated analysis may be necessary. This analysis can focus on the integration of uncertainties only, or it can also address the integration of risk attitudes. In the latter case, a multi-attribute utility (MAU) analysis is required. A brief overview of MAU analysis is provided; it is recommended that such an analysis be facilitated by a professional decision analyst.

The assumption in Figure 4.3 is that the decision-maker uses the point estimates to evaluate the alternatives, and then considers the risks somewhat independently of the performance analysis. If this is possible, then the usual procedures for analysis of the alternatives-by-criteria matrix apply, and one would

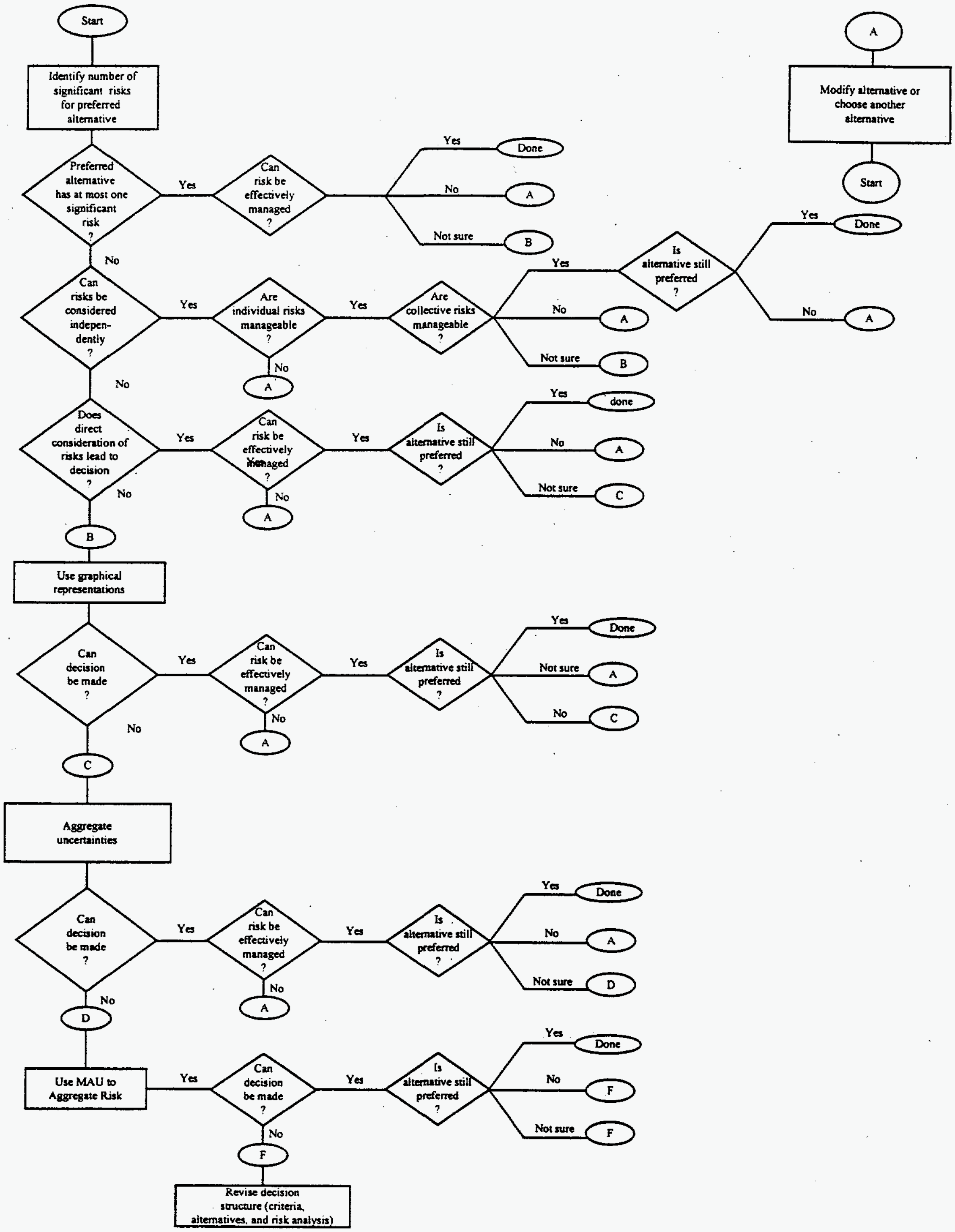

Figure 4.3. Guide to Choosing Decision Aids and Analytical Methods

append an analysis of risks. The other possibility is that the risks are so intertwined with performance that an integrated analysis is necessary in order for the decision-maker to reach a decision.

If the risks are to be considered somewhat independently then, as shown in Figure 4.3, it is suggested that the number of criteria having scores with significant risks should be initially identified. Of particular interest is the alternative that would be preferred based on point estimates alone. If there is at most one criterion with significant risk, then a judgment can be made as to whether the risk can be managed. If the risk management is acceptable and the alternative is still preferred when the risk is considered, then the decision-maker can select that alternative. On the other hand, if the risk cannot be managed effectively, then the alternative must be modified to make it manageable, or another alternative must be chosen. The process is repeated until an alternative is identified with both acceptable performance and manageable risk.

If there is more than one significant risk for the initially preferred alternative (the preferred alternative without consideration of risk), then one issue is whether these risks can be thought of independently. For example, there may be risks associated with both cost and schedule. The decision-maker may be able to consider these independently (i.e., determine that each risk can be effectively managed). On the other hand, the risk of a cost overrun (by itself manageable) combined with a schedule delay (also by itself manageable) may not be manageable if they were to occur simultaneously. In other words, one could conceivably spend more to meet the schedule or justify schedule delays to save money, but the risk of being both over budget and behind schedule would not be manageable. If this is the case, then the risks must be considered jointly.

If the criteria can be considered independently, then judgments must be made as to whether the risks are manageable for each criterion considered independently. If some criteria have unmanageable risks, then the preferred alternative may need to be modified or another alternative may be selected, as indicated in Figure 4.3. If all the risks are manageable when considered individually, then the issue is whether the collective risk is manageable from a purely additive point of view. In other words, is the overall risk still manageable given that there are multiple criteria that are uncertain? If the answer is yes, then one might reexamine whether the initially selected alternative is still the preferred alternative when risk considerations are factored in. If so, then the decision-maker is advised to select that alternative. If not, then the alternative should be modified or a new alternative selected and the process should start over. The decision-maker is similarly advised in the event that the collective risk is not manageable. A third possibility is that the decision-maker has difficulty sorting out the various risks. Displaying the results of the uncertainty analysis in a graphical form may provide the additional clarity that is needed to make a decision.

If the risks cannot be considered independently, then it is still possible to achieve clarity and make a decision by direct consideration of the potential risks. For example, for cost and schedule, it may be possible to make a direct judgment concerning the manageability of the combined risk. If this risk is manageable, and the initially chosen alternative is still preferred, then it should be selected. If the combined risk is not manageable or the alternative is no longer preferred, then the alternative may be modified or another alternative may be chosen. If the decision-maker has difficulty sorting out the manageability of the combined risk, then it will probably be necessary to aggregate the uncertainties.

Graphical methods can aid in visualizing the magnitude of the risks. For a single criterion, showing error bars in addition to the expected magnitude of performance can aid the decision-maker in judging the relative risks. For two criteria, regions of expected performance can be plotted. These methods may help the decision-maker make the decision without actually integrating the uncertainty across criteria or using more formal methods.

If the risks are to be integrated, there are two possibilities. In the first, the integration is over the uncertainties. If the decision-maker is able to make direct judgments about the manageability of risk as well as tradeoffs between risk and performance (if any), then this type of integration is sufficient. If the decision-maker is unable to make such judgments, then a more formal analysis of risk preferences is needed, specifically MAU analysis. To carry out a utility analysis, it is necessary to modify the usual procedures for assessing value functions and weights.

To recap, the simplest cases are those with significant risk for only one criterion (e.g., cost). The issue is whether or not this risk is manageable. If not, then the alternative may be modified to make the risk manageable, or another alternative may be selected which may have lower expected performance, but also less risk. If the decision-maker can decide whether the risk is manageable based upon the risk information provided, then no additional analysis is needed. However, if there are many uncertainties such that the risks are better on some dimensions and worse on others (depending on the alternative), or there are tradeoffs between performance and risk that the decision-maker is uncomfortable with, then additional analysis is needed. The situation is analogous to tradeoffs in the alternatives-by-criteria matrix. If the choice is clear without assigning weights or can be made clear by a graphical Pareto analysis (a process of identification and elimination of dominated alternatives), then there is no point in doing additional analysis. However, if it is not clear, then additional analysis can aid the decision-maker. What follows is a more detailed consideration of the above situations.

4.2.3 Analysis and Decision-Making Methods

Direct judgments of risks are made based upon direct consideration of possible outcomes and their likelihoods. This can be done for individual criteria, or the combined uncertainty for several criteria aggregated to a higher-level objective, or even an overall measure of performance based upon a weighted average of performance over all criteria. These judgments may be facilitated by various decision aids consisting of graphical displays or Monte Carlo simulation.

Analysis Method 1 - Risk Judgments for a Single Criterion

First, consider the simplest situation in which there is significant risk on only one variable (e.g., cost). If a level 2 or 3 analysis (as described in Sections 4.1.2 and 4.1.3) was done, then a CDF is available to aid the decision-maker. An example CDF for cost is shown in Figure 4.4. The CDF has cost on the horizonal axis and the probability that cost will be that much or less on the vertical axis. For the example shown in Figure 4.4, the best estimate for total cost is \$12 million (i.e., there is a 50% chance that it will be lower than \$12 million, and a 50% chance that it will be higher than \$12 million). In the unlikely event that all the component cost estimates included in this total are at their most optimistic values, it could be as little as \$8 million. On the other hand, there is a 20% chance that the cost could exceed \$18 million, and there is a

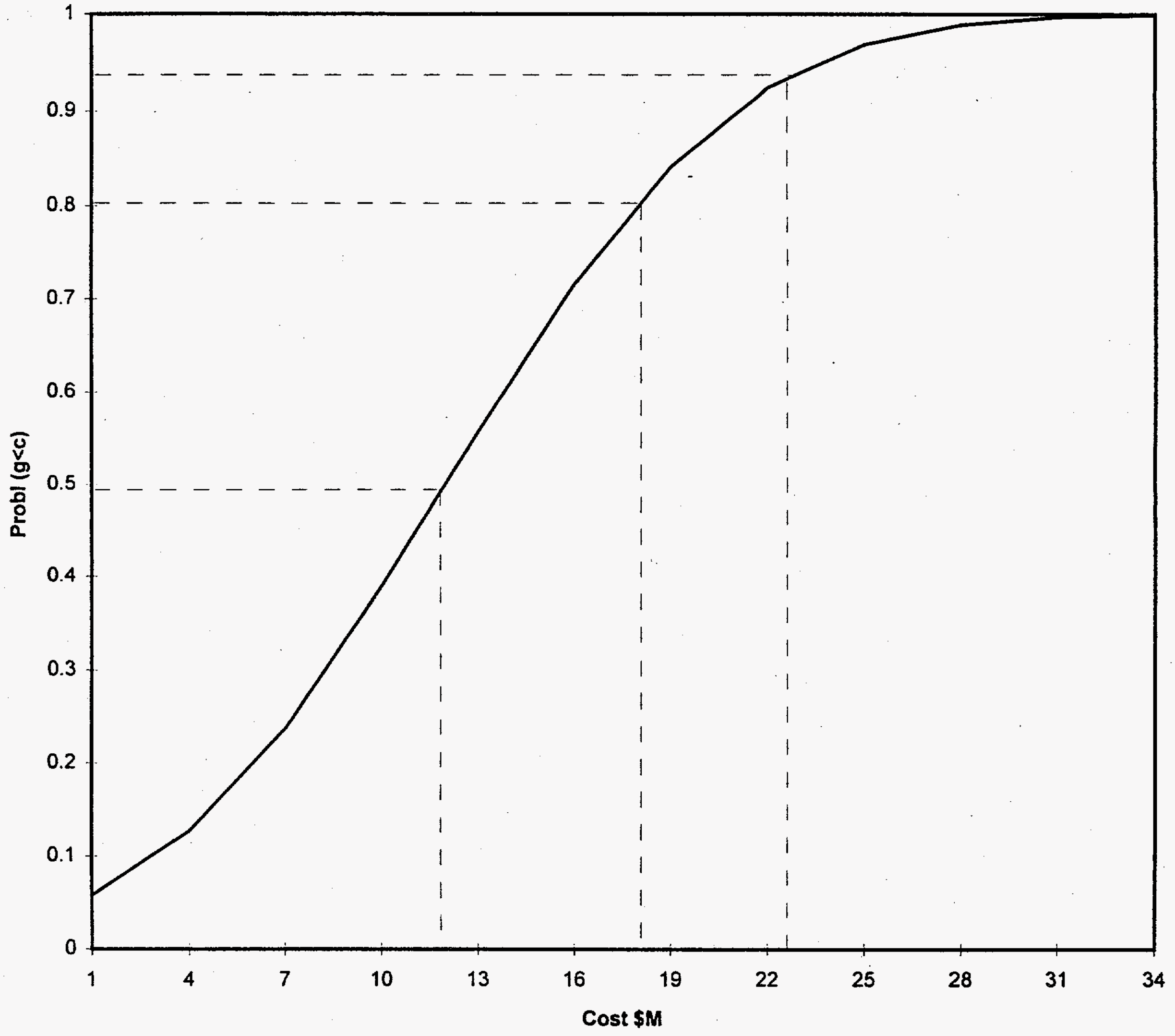

Figure 4.4. Example CDF for Cost

5% chance that it could exceed $24 million (i.e., the cost could be twice the best estimate). The decision-maker must decide whether this risk can be effectively managed. If so, then the analysis is done. The decision-maker would select the alternative that performed best based on a consideration of point estimates alone and which is judged to have manageable risk.

It is possible that the analysis does not support the creation of a CDF and only uncertainty ranges are available (rather than CDFs). This information can still be displayed graphically, as shown in Figure 4.5. This figure shows the point estimates of the cost of several alternatives as well as 90% confidence intervals. These are intervals such that there is only a 5% chance that the cost will exceed the interval and a 5% chance that the cost will be less than the interval. In the example shown, alternative 2 has the lowest

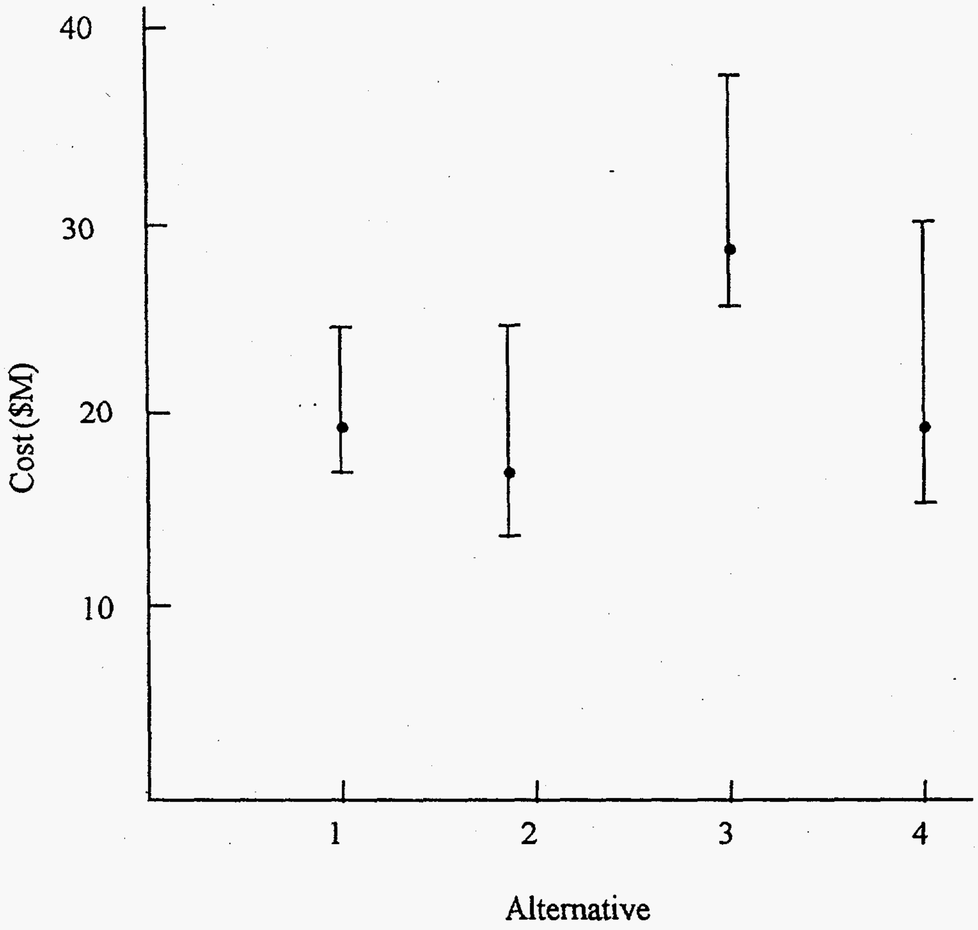

Figure 4.5. Example Uncertainty Ranges for Cost

expected cost and its cost is not expected to exceed that of the next most costly alternative. Thus, alternative 2 would probably be chosen if it performed as well as the other alternatives. The information from the CDFs may be displayed in this manner as well, and may prove more useful for the decision-maker.

In addition to judgments about risk for individual criteria with respect to a single alternative, it may be necessary to address tradeoffs among alternatives for performance and risk, still considering a single criterion. This situation is depicted in Figure 4.6, and is possibly a more difficult judgment to make directly. Figure 4.6 shows the CDFs for two alternatives that performed similarly on all criteria except cost. Alternative 1 has an expected cost of $12 million and alternative 2 has an expected cost of $14 million. However, while alternative 1 is expected to cost less, it has a greater risk. There is a 15% chance that alternative 1 could cost more than $20 million. There is less than a 1% chance that alternative 2 could cost over $20 million. The decision-maker may or may not have a clear preference in this situation. If not, then a utility function for cost can be assessed, and the expected utility for cost should be used in the decision analysis. Assessment of single utility functions is addressed in Appendix B.

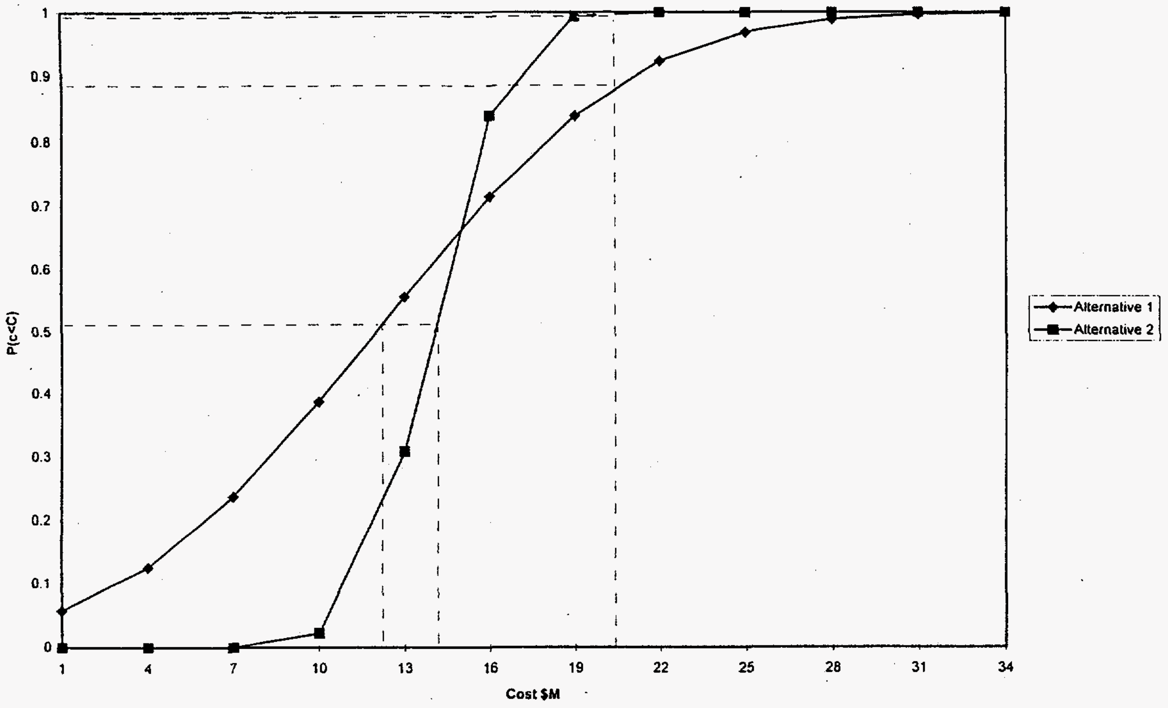

Figure 4.6. Example CDFs for Cost for Two Alternatives

Analysis Method 2 - Risk Judgments for Several Criteria

The situation gets more complex when there are significant risks for multiple criteria, the risks for one alternative may be less for some criteria and more for others, and there is a need for tradeoffs across the criteria. There are two possibilities when considering risks for several criteria: 1) they can be judged independently, or 2) they must be considered jointly. If they can be considered independently, then analysis method 1 can be applied. If this is the case, one can consider the risks for the preferred alternative individually. If the individual risks are all manageable, then the decision-maker may choose that alternative. It is also possible that the decision-maker may judge each of the risks to be manageable in themselves, but taken collectively, the overall risk may be too high. If this is the case, the alternative that was ranked second (without considering risk) should be revisited. If the risks for this alternative are considerably less, then the decision-maker may decide to select this alternative. However, it may be that the decision-maker is unable to make this determination when considering the risks independently. In that case, a more integrated approach to risk judgments can be undertaken.

One possibility is to display graphically the uncertainties on two criteria simultaneously. (This is just a two-dimensional extension of confidence intervals shown in Figure 4.5.) For two attributes, confidence regions can be plotted as shown in Figure 4.7. This figure shows uncertainty regions for cost and available tank space. Care must be taken in interpreting the likelihood that the alternative will fall within the plotted region. The plot shown is based on two 90% confidence intervals. If uncertainties in cost and tank space

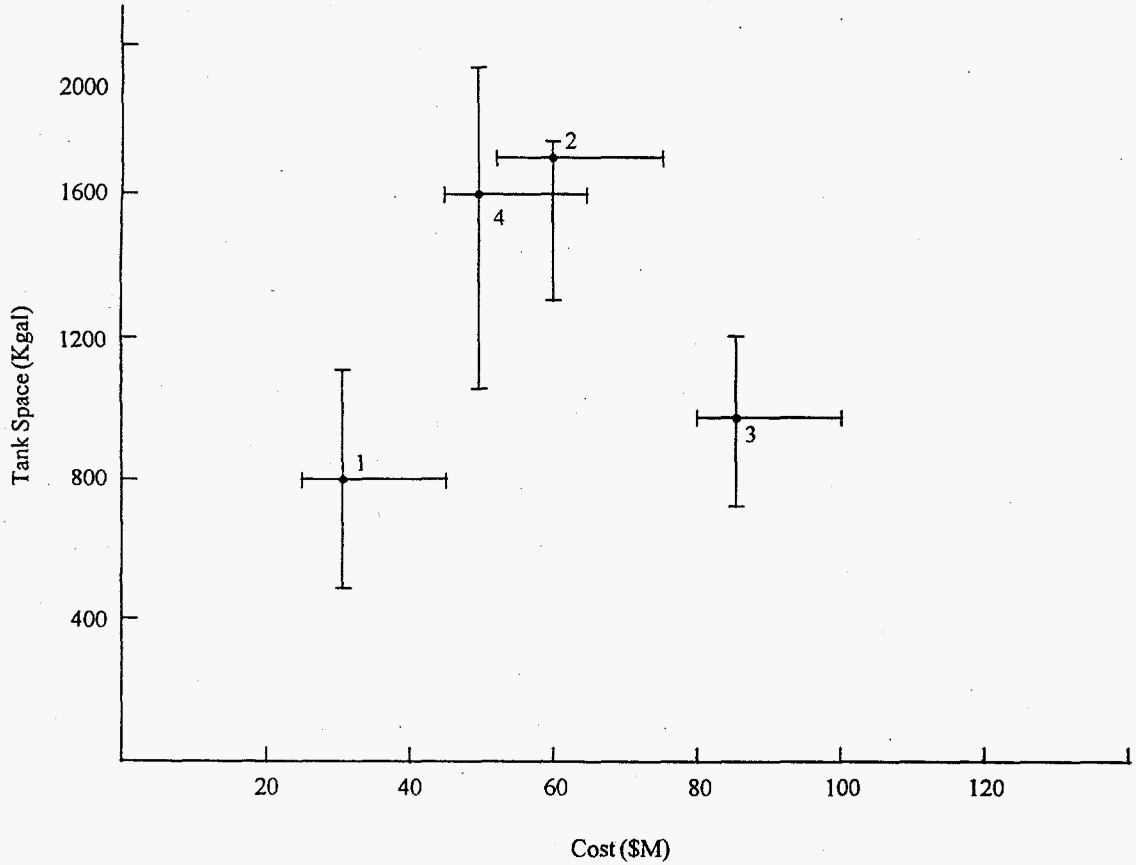

Figure 4.7. Uncertainty Regions for Cost and Available Tank Space

are independent, then there is only an 81% chance that the alternative would perform in the plotted region. If the two variables are not independent (e.g., complements or substitutes), the actual probability could be more or less.

The information shown in Figure 4.7 is a generalization of Pareto analysis that is often used as part of a deterministic analysis of performance. Alternatives 1, 4, and 2 are on the Pareto frontier in that they provide successively more performance per dollar. Alternative 3, on the other hand, is dominated by alternatives 4 and 2 since it provides less space for more cost. Choosing between alternatives 2 and 4 is more difficult since 2 costs more and is expected to perform better; however, alternative 4, which costs less, may outperform 2. This provides an extension of a Pareto plot in a way that graphs the uncertainties on both dimensions. One can also plot cost versus the uncertainty of several criteria that have been rolled up into a higher overall criterion, or even cost versus the overall value excluding cost. This requires the integration of uncertainties across several criteria or all of the criteria, which is discussed in the next section.

Pareto analysis on two dimensions provides insight into value tradeoffs. When uncertainty regions are considered, it shows the extent to which performance may overlap. When the regions of uncertainty do not overlap, then a case can be made to go with the tradeoffs based purely on the point estimates. If there is considerable overlap, then the conclusions are less definitive, and additional analysis may be warranted.

Analysis Method 3 - Integrated Uncertainty Analysis

This section describes an integrated approach to considering the uncertainty across multiple criteria. The process quantifies the uncertainty for rolled-up criteria, and even the overall criterion; however, it does not integrate risk attitude on individual criteria into an overall risk attitude. Direct judgment regarding the manageability of risk by the decision-maker is still necessary. The output of this analysis will be similar to that shown in Figure 4.6 for the cost of two alternatives. However, the CDFs would be for a higher-level criterion or even the overall criterion. This allows the overall risks of several alternatives to be compared. It may still require similar tradeoffs concerning performance and risk. If these judgments could not be made directly, then the decision-maker would need to use MAU analysis.

The process for rolling up uncertainties into an overall function is most easily done by Monte Carlo simulation. The process assumes the existence of weights, so this is only possible if weights have been assessed to address the relative importance of criteria to the level for which they are to be rolled up. The simulation consists of sampling from the probability distributions for the individual criteria, aggregating them according to the weighting rule, and repeating the process a number of times to get a distribution of the aggregated values. If the probability distributions were not assessed for some or all of the individual criteria, it may still be possible to carry out the simulation by assuming that the ranges represent uniform distributions.

The actual simulation can be carried out using a spreadsheet in conjunction with simulation software such as @ Risk or Crystal Ball. Alternatively, commercially available decision analysis software (such as Logical Decisions) also has this capability. Appendix A contains brief descriptions of these and other risk analysis software tools.

Analysis Method 4 - Integrated Risk Analysis - Quantification of Risk Attitudes

If the decision-maker is unable to clearly evaluate the risks based on a direct consideration of the uncertainties with the aid of graphical methods or by an integrated uncertainty analysis that rolls risks up to higher levels, then a more formal integrated analysis that captures risk information may be warranted. This analysis would require the full power of MAU theory and the assistance of an experienced decision analyst. An overview of this process is presented in Appendix B. It is not intended to describe the MAU process in detail, but to outline what is involved. Complete descriptions are available in the literature. The classic text is Keeney and Raiffa's *Decisions with Multiple Objectives*, published in 1976. More accessible descriptions are available in Clemen (1991), von Winterfeldt and Edwards (1986), and Keeney (1992).

Quantification of risk attitude employs the general philosophy of decision analysis (i.e., the approach to complex decisions is to divide and conquer). This approach separates the decision into its component parts, obtains judgments on the individual parts, and resynthesizes them in order to arrive at an overall evaluation. An integrated risk analysis is carried out in a similar manner. It is assumed that scales have been identified for all the criteria. It may be the case that value functions have been identified to capture the relative importance of different levels of performance on single criteria, and weights may have been assessed to determine the relative importance of the various criteria. This would have been necessary to roll all the criteria up into a single number to capture the relative values of the alternatives.

Quantification for the purpose of capturing risk attitude, while similar to the quantification alluded to above, is carried out with some important differences. This is necessary so that the values arrived at not only roll up the scores in a way that provides a single number to allow comparison of overall performance, but also do so in a way that captures attitude toward risk. Consequently, there is a slightly different meaning given to individual value functions and the overall value model. This requires that these models be developed through slightly different assessment procedures that capture risk attitude. Functions and models so developed are referred to as utility functions and models, as contrasted with value functions and models. A brief overview of quantification in decision analysis is presented in Appendix B.

5.0 Potential Risk-Handling Methodology

Potential methodology for identification, evaluation, and selection of alternative risk-handling actions is described in this section.

5.1 Identification of Specific Risk-Handling Actions

Risk handling encompasses the set of management decisions to plan, execute, and report on specific risk-handling actions (prevention or mitigation strategies) to address the risks on the RML. The goal of risk handling is to reduce the risk to an acceptable level (i.e., a level that can be effectively managed). It is important to ensure that the amount of risk reduction achieved is worth the cost of implementing the risk-handling actions.

The identification of specific risk-handling actions could profitably be done by a group of subject matter experts in a workshop setting, since the identification of alternative actions requires a high level of creativity. It is often easier to harness creativity through a group brainstorming session (where participants are stimulated by the new and different ideas proposed by others) than it is for an individual to come up with creative ideas on his/her own. An important initial step in such a session is to identify which of the risks on the RML are not independent and must be considered in a holistic manner. This step will reduce the number of risks that must be addressed separately and thus shorten the time required to complete the brainstorming process. Also, the workshop participants should be sure to consider key interactions between TWRS program elements in identifying appropriate risk-handling actions.

Risk-handling actions for all the individual risks (or some combinations of them) should be identified through a structured brainstorming activity. Specific actions should be identified by systematically brainstorming alternatives within each of the categories of risk-handling actions documented in the TWRS Risk Management Procedure: risk avoidance, risk transfer, risk sharing, risk control, and risk assumption. No category is preferred over any other category. The objective is to reduce the risk to an acceptable level by whichever risk-handling action is most cost-effective and efficient for the particular risk.

For each risk being addressed, the group should employ the simple framework described in the following steps to identify candidate risk-handling actions:

Step 1 Brainstorm specific risk avoidance actions that could be taken to completely rule out the potential for a risk and its consequences. For example, choose a different course of action that does not include the risk. For practical purposes, the risk no longer exists; it has been eliminated.

Step 2 Brainstorm specific risk transfer actions that could be taken to entirely give a risk to another organization through contractual agreement (e.g., privatization), arrangement, or directive.

Step 3 Brainstorm specific risk sharing actions to allocate a portion of a risk to another organization so as to reduce risk likelihood or consequences.

Step 4 Brainstorm specific risk control actions to monitor and correct conditions so that risk likelihood and consequence severity are reduced.

Step 5 Brainstorm specific risk assumption actions where a conscious decision is made to accept the consequences if the risk occurs. This includes situations where a risk is accepted without taking any action beforehand, as well situations as where residual risk must be accepted after many actions have already been taken. "Fallback" positions should be developed for any risk assumption actions that are selected for implementation.

Step 6 Prepare a master list of candidate risk-handling actions (and which category they are in) to be evaluated as described in Section 5.2.

5.2 Evaluation/Selection of Risk-Handling Actions

A range of analytical approaches for evaluation/selection of risk-handling actions is possible, from simply providing some structure to the current way TWRS managers and engineers think about risk handling to a more complex, systematic methodology. This section describes two potential methodologies for evaluation and selection of TWRS risk-handling actions. It is not necessary to pick just one of them; a combination may be more useful in a particular situation.

The analysis level chosen should depend on the perceived magnitude of the risk(s) involved. The two levels of analysis described in this section are summarized as follows:

Level A Qualitative analysis and judgmental rankings of alternatives based on cost, ability to reduce the likelihood of occurrence, and ability to reduce the consequences of occurrence.

Level B A more complex, systematic methodology to evaluate alternative risk-handling actions, specifically SMART.

5.2.1 Qualitative Analysis and Judgmental Rankings

The purpose of this evaluation approach is to ensure that risk-handling actions are adopted based on their effectiveness. Some risk-handling actions will impact more than one risk, therefore the approach seeks to evaluate actions in an integrated way. The approach includes the following elements, which are discussed below:

- create a matrix of risks and risk-handling actions
- select an initial risk to manage

- evaluate and select risk-handling options for that risk
- select additional risks and add additional risk-handling actions as necessary
- evaluate the total set of actions selected and adjust as necessary.

A structured approach to evaluation/selection of risk-handling actions requires constructing a table to keep track of the actions and what categories they belong to (see Table 5.1). Actions 1 and 2 will enable the program to avoid the risk, actions 3 and 4 will enable the program to transfer the risk, and so on.

The steps described in this paragraph may be done offline as "homework" before assembling a workshop for the next step in the prioritization process. First, make a rough estimate of the cost associated with implementing each risk-handling action. Second, create a matrix of risks and specific risk-handling actions identified through the process described in Section 5.1. Table 5.2 shows an example of such a matrix. Third, identify the risk which has the greatest number of risk-handling actions and/or the most actions common to other risks. In the example shown in Table 5.2, risk 1 would be selected because it has three risk-handling actions (numbers 1, 3, and 5) that might be used to manage all the other risks except for risk 5.

Rank each risk-handling action for its relative effectiveness in reducing the probability of occurrence (the best option is ranked 1). Next, rank each risk-handling action for its relative effectiveness in reducing the consequences of that risk. It will probably be useful to ask participants to do this ranking individually and then compare and discuss the results to achieve a consensus. Alternatively, the group can try to

Table 5.1. Risk-Handling Structure for a Particular Risk

Risk-Handling Action	Avoid Risk	Transfer Risk	Share Risk	Control Risk	Assume Risk/Develop Fallback Position
Action 1	x				
Action 2	x				
Action 3		x			
Action 4		x			
Action 5			x		
Action 6			x		
Action 7				x	
Action 8				x	
Action 9					x

Table 5.2. Risk-Handling Action Matrix

Risk-Handling Action	Cost, $K	Description of Risk-Handling Action	Risk 1	Risk 2	Risk 3	Risk 4	Risk 5
Action 1	10		x	x	x	x	
Action 2	40			x			x
Action 3	300		x	x			
Action 4	20				x		x
Action 5	50		x			x	
Action 6	80		x				
Action 7	800			x	x		

directly achieve consensus on the relative rankings by using a group process technique to do pair-wise comparisons of the actions' effectiveness in reducing risk.

Next, multiply the rankings for effectiveness in reducing probability and effectiveness in reducing consequence. The resulting numbers provide a guide to the effectiveness of the actions, but only a guide. They are intended primarily to help staff think systematically about the effectiveness of the actions and generally identify relatively effective actions. The results of the sample analysis are shown in Table 5.3. Risk-handling action 3 appears to be the most effective, followed by action 6.

Going down the ranked list of risk-handling actions from the lowest (most effective) to the highest (least effective), the group should evaluate whether the residual risk (after selecting the most effective action to implement) is sufficient to remove the risk from the RML. If not, additional actions should be added to the list of risk-handling actions already selected, one at a time, until the residual risk would no longer be considered unacceptable. If two actions tie in their effectiveness score, evaluate adding them individually to the action(s) already selected before choosing both of them to better manage the risk. Additional actions should be added and the residual risk evaluated until it is reduced sufficiently or all the identified actions are selected. If all actions are adopted but the residual risk is still judged unacceptable, the group should repeat the process described in Section 5.1 and identify additional risk-handling actions.

After completing this analysis for a single risk, select another risk from the matrix. It is preferable to select a new risk that has several risk-handling actions in common with the previous risk analyzed. In the example shown in Table 5.2, risk 2 would be a good choice because it has two risk-handling actions in common with risk 1 (actions 1 and 3). Evaluate if the risk-handling actions already selected for the previous risk are sufficient to reduce the next risk to an acceptable level. If not, repeat the ranking process for the new actions not yet adopted and add the most effective actions until the risk is acceptable or the actions have all been selected.

Table 5.3. Analysis of Risk-Handling Actions for Risk 1

Risk-Handling Action	Cost, $K	Probability Reduction Ranking	Consequence Reduction Ranking	Product of the Two Rankings
Action 1	10	2	4	8
Action 3	300	1	2	2
Action 5	50	4	3	12
Action 6	80	3	1	3

Repeat this process until all the risks have been evaluated. Then, sum the estimated total cost required to implement all the selected risk-handling actions. If this total is too high, eliminate risk-handling actions that are least effective. Re-evaluate those risks impacted by the adjustment as necessary. Finally, look at the set of risk-handling actions selected to make sure that actions designed to reduce one risk do not also tend to increase another risk. Until this point, this evaluation process has assumed that risk-handling actions do not work at cross-purposes to simplify the analysis.

5.2.2 Simple Multi-Attribute Rating Technique (SMART)

This methodology can be used when the choice of the "best" risk-handling action is not intuitively obvious and a more formal consideration of the impacts of the various actions on TWRS Program objectives is desired. The process can be implemented in a fairly mechanical manner and is suitable for use (possibly with some initial training) without the aid of a decision analyst. It is the same basic multi-attribute decision analysis methodology used in the TWRS AGA Procedure to create the alternatives-by-criteria matrix.

SMART is a simple rating procedure for making decisions in which there are multiple, possibly conflicting, objectives. It can be used to help identify the risk-handling action with the greatest positive impact in terms of reducing programmatic risks related to cost, schedule, and/or technical performance. Each candidate risk-handling action is rated on each of the objectives, and the objectives are given weights that reflect their relative importance. The score for an action is the weighted average of the ratings.

Step 1 Identify the Alternative Risk-Handling Actions

A description of each identified risk-handling action should be recorded.

Step 2 Identify the Objectives

The selected risk-handling action(s) should maximize the TWRS programmatic objectives of minimizing cost, maximizing technical performance, and meeting or exceeding schedule requirements.

Step 3 Identify Scales and Ranges

Scales are used to measure the relative value of each alternative risk-handling action on the objectives identified above. Ranges must be defined to represent the upper and lower end-points of the scales, and they must be broad enough to encompass all the alternatives.

Step 4 Rank the Objectives

Consider two scenarios - one in which the outcome is best on all the objectives, and one in which the outcome is worst on all the objectives.

Suppose you are in the worst-case scenario. If you could change the outcome on one objective from worst to best, which one would it be? This is the objective you rank first in importance. What would you rank second in importance? Third in importance?

Step 5 Construct Hypothetical Alternatives

Weights reflect the relative importance of the objectives for the ranges that are being considered. To obtain the weights, it is first necessary to construct hypothetical alternatives based upon the rankings obtained in the previous step. For alternative 1, assign the best outcome to the objective that was ranked first. Assign all other objectives the worst outcome. For alternative 2, assign the best outcome to the objective that was ranked second, and worst outcomes to all the other objectives. For alternative 3, the third-ranked objective should be assigned the best outcome and all the others the worst outcomes.

Step 6 Score Hypothetical Alternatives

Now consider alternative 1. This alternative has the best possible outcome on the objective that was considered most important and the worst possible outcome on all the other objectives. Suppose this alternative is assigned a score of 100. With this assignment in mind, assign scores to the other alternatives that reflect their values relative to alternative 1. These scores should decrease as the alternative numbers increase; otherwise, the initial rankings of the objectives should be reconsidered.

Step 7 Calculate Normalized Weights

The scores for the alternatives are the raw weights for the objectives. Next calculate the normalized weights, whose values should sum to 1. To do this, sum the scores for the alternatives to get a total. The normalized weight for each objective is just its raw score divided by this total.

Step 8 Score the Alternative Risk-Handling Actions

Estimate the relative value for each alternative on each of the objectives by scoring them on a scale of 0 to 100.

Step 9 Calculate Alternative Values

For each alternative, multiply the normalized weight for each objective by the score for each objective and record the product. Note that the normalized weights are the same for all the alternatives. Total these products to get the overall score of each alternative.

Step 10 Choose Preferred Alternative(s)

Select the preferred risk-handling action(s). It is not necessary or recommended that only one action be selected for each risk. It may be appropriate to select multiple risk-handling actions for some critical risks. The SMART results will help identify good actions, but again, the actual numbers provide only guidance. Sound judgment is still required regarding how many actions are needed and which alternatives are the best choices.

5.2.3 Closing

Three analytical approaches to evaluation/selection of risk-handling actions are described in this section, ranging from simple structuring to more complex analysis. It is not necessary to pick just one of the approaches; some combination may be more useful in a particular situation. The complexity of the analysis that is undertaken should depend on the perceived magnitude of the risk(s) involved.

The methods described in this section can be used to supplement/enhance the existing TWRS risk-handling procedures. They do not constitute the only possible approaches to risk handling, but they do provide users with some additional guidance to help them make difficult judgments.

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7.0 Glossary

Alternative - A concept, design, hardware, software, procedure, personnel, infrastructure, or combinations of them that may be used to meet the objectives of a given mission.

Architecture - System configuration.

Consequence - The estimated magnitude of the negative effect (severity) of an undesirable event, should it occur.

Constraint - A requirement that is imposed by external organizations (e.g., U.S. Congress, DOE Orders, Washington Department of Ecology).

Cost risk - Risk to a program of exceeding the cost estimate.

Cumulative distribution function - One way to express a probability distribution; it portrays the probability that an uncertain quantity is less than or equal to a specified value for the range of values.

Decision criteria - Factors used to select a preferred alternative. Decision criteria may be quantitative or qualitative.

Decision frame - A statement of the problem.

Decision-maker - An individual who has the responsibility for making decisions.

External uncertainties - Uncertainties to the program that are beyond the program's control (e.g., disruptions caused by changes in laws and regulations).

Influence diagram - A decision analysis structuring technique that presents a graphic picture of the interactions of decision variables and random variables in a decision model without superimposing a decision tree or an event tree structure.

Likelihood - The chance, or probability, that an event will occur.

Operational scenario - Description of the operating environment and associated activities within which a mission will be accomplished including, for example, start-up dates, mission duration, interfaces with other operations, capacities, support requirements for utilities, operating staff, maintenance, storage, analytical services, specialty engineering services, etc.

Organizational uncertainties - Uncertainties to the program that are associated with the structure and functions of the organization that is responsible for conducting the program. Examples include the efficiency and effectiveness of scheduling functions, and the ability to make decisions in a timely manner.

Parametric uncertainties - Uncertainties in the values of the intermediate variables that are used in risk analysis calculations (e.g., contaminant concentration in a waste stream).

Parametric analysis - A process for risk analysis that includes creating a deterministic model and performing sensitivity analysis on all the key parameters, varying them one by one over their expected ranges while all other parameters are held constant.

Pareto analysis - A process of identification and elimination of dominated alternatives, generally done graphically.

Performance measure - A metric by which an alternative can be analyzed. It should be noted that performance measures are strongly related to decision criteria. Performance measures are parameters that are evaluated (quantitatively or comparatively) to measure the performance of an alternative on various decision criteria. Each "value" (end, means, or process) for a decision is typically translated into a performance measure so that it can be used as a decision criterion.

Probability - The chance, or likelihood, that an event will occur.

Programmatic risk - The risks to project costs, schedule, and technical performance that are associated with the implementation of a given alternative.

Residual risk - The risk that remains after all risk-handling actions have been fully implemented.

Risk - The combination of the probability of an event occurring and the significance of the consequences of that event.

Risk analysis - Quantification of the likelihood of an undesirable event occurring and the impacts such an event would have on the program should it occur.

Risk assessment - The examination of all aspects of a program to identify potentially undesirable events and to determine the detrimental impacts those events would have on the program.

Risk assumption - Strategy to accept a risk and its consequences, with no action taken beforehand.

Risk avoidance - Strategy to completely rule out the potential for a risk and its consequences.

Risk control - Strategy to monitor and correct conditions so that risk likelihood and consequence severity are reduced.

Risk handling - Strategies and actions taken to avoid, eliminate, reduce, transfer, track, and/or control risks.

Risk management - The process of identifying, evaluating, and handling risks, as well as communicating risk information about the actions to be taken and the results of those actions.

Risk mitigation - Reduction of the consequences of a risk.

Risk planning - The process of forcing organized purposeful thought to the subject of eliminating, minimizing, or containing the effects of undesirable occurrences.

Risk sharing - Strategy to allocate a portion of a risk to another organization so as to reduce risk likelihood.

Risk transfer - Strategy to entirely give a risk to another organization through contractual agreement (e.g., privatization).

Scenario analysis - A process for risk analysis of external events which includes the following steps: 1) identify critical events and possible states, 2) determine probability of states, 3) determine impacts to alternative outcomes conditioned on states, and 4) prepare a CDF for the outcome(s) of interest for each alternative.

Schedule risk - Risk to a program of not meeting the major milestones.

Sensitivity analysis - An analysis performed after a model is built to answer "what if" questions and determine if the decision is sensitive to small changes in any particular aspect of the model.

Supportability risk - Risk to the program that systems do not perform adequately during operations (e.g., that reliability requirements are not satisfied).

Technical performance risk - Risk to the program of a system not meeting the required level of technical performance.

Uncertainty - Risk; lack of predictability.

Values - What the decision-maker cares about. Values should be the driving force for decision-making (Keeney 1992).

Appendix A

Risk Tools

Appendix A

Risk Tools

A.1 Crystal Ball

Crystal Ball is a forecasting and risk management program for Macintosh computers. The user creates a spreadsheet in Microsoft Excel, Multiplan, or Works; Informix's Wingz; or Ashton-Tate's Full Impact. Through Monte Carlo simulation, Crystal Ball forecasts the entire range of possible results for a given situation. It also shows confidence levels, so the user knows the likelihood of any specific event taking place. Crystal Ball provides the user with a strong intuitive feel for the decision at hand.

A.2 @ Risk

@ Risk brings risk analysis techniques to the industry standard modeling packages, Microsoft Excel or Lotus 1-2-3. It uses Monte Carlo simulation to perform risk analysis on a project by simulating the project and then trying hundreds of thousands of "what if" scenarios. The user gets a range of possible values for the results which can be used to answer many important questions (e.g., How long could the project possibly take? What are the odds that the project will be completed under budget?)

A.3 Decision Programming Language (DPL)

DPL is a decision analysis software package that allows a decision-maker to model decisions in which uncertainty and risk are major components of the analysis. It operates on a 386 (or higher) personal computer. DPL models decisions with both decision trees and influence diagrams. Influence diagrams are graphical networks consisting of nodes and arrows that show the dependencies among the decisions, events, and values. Decision trees show the timing of decisions, events, and outcomes. The two representations taken together provide a powerful and compact way to represent and communicate a decision structure. DPL calculates the expected value of alternatives as well as cumulative probability distributions. DPL supports Bayesian revision by simply changing the order of events in the decision tree. This makes it easy to calculate the value of perfect and imperfect information. DPL also allows for a variety of sensitivity analyses that can guide the development and/or revision of a decision model.

DPL can interface with spreadsheet models. It will help identify key uncertainties in the deterministic spreadsheet model, which can then be treated probabilistically by DPL. In the resulting decision analysis, DPL will call in the spreadsheet as a subroutine.

A.4 Supertree

Supertree is a decision analysis software program to estimate values and outcomes in complex situations. A computer model is constructed to reduce a complex problem into manageable components. An influence diagram or decision tree is used to divide uncertainty into subfactors until the level is reached where intuition functions most effectively. This modeling approach is especially appropriate in business decisions, where the expertise of many individuals and groups must be combined in evaluating a decision problem.

A.5 Decision Analysis by Tree Age (DATA)

Decision Analysis by Tree Age (DATA) is a decision analysis software package that allows a decision-maker to model decisions with a decision tree representation or code. Emphasis is on modeling uncertainty and risk aspects of decision-making. DATA operates on any Macintosh computer running System 6.0 or higher.

Decision trees are easily constructed and modified. The program calculates expected values of alternatives by "rolling back" the tree. It performs a variety of sensitivity analyses, including two-way sensitivity analysis on probabilities. It will print out a variety of graphs and interface with spreadsheets and can easily do Bayesian revision.

A.6 Logical Decisions

Logical Decisions is a software package for the analysis of decisions with multiple objectives. The emphasis is on modeling the tradeoffs among the objectives, as well as the value of different levels of achievement on a specific objective. It operates on a 286 personal computer or better. Both Windows and DOS versions are available.

Logical Decisions represents decision problems as a value hierarchy, in which the highest-level objectives get further specified until criteria are identified which can be used to measure the performance of alternatives. It provides a variety of methods for assessing the weights of the objectives, including MAU analysis, the analytic hierarchy process, and SMART. It also provides for the creation of individual value functions. It calculates an overall value for alternatives based upon an objectives function that is either additive or multiplicative, depending on which preferential independence assumptions are met. The results of the analysis can be displayed in a variety of useful ways that provide insight to the decision-maker as to which objectives are driving the analysis. Logical Decisions also performs sensitivity analysis on the weights assigned to the objectives.

Appendix B

Introduction to the Quantification of Risk Attitudes

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Introduction to the Quantification of Risk Attitudes

This appendix describes value models and utility functions in a manner necessary to capture risk attitude.

B.1 Value Models

Value models are the means by which a single number is used to describe the relative value of alternatives. The validity of a value model requires that if one alternative is preferred to another, then the score assigned to that alternative should be greater than the other.

Three aspects of a value model must be considered. First is the relationship between levels of performance on a particular objective and the relative values of these levels. This relationship is captured in value or utility functions. Value and utility functions serve a similar purpose. By convention, utility is the term used when risk is explicitly considered in the model. The second aspect of a value model is how the relative importance of the individual objectives is represented. This is commonly thought of as the weight given to the objectives, which are represented as weights in the value model. However, the number of weights required depends on the interactions among the objectives, which is related to the third aspect - the appropriate functional form for the value model. This form depends on considerations of the preferences for various combinations of levels of performance on the objectives. Simple methods of evaluating alternatives are based upon simple "rate and weight" schemes that assume a linear additive value model. Such models, while often appropriate, depend on the judicious selection of a set of objectives.

There are three basic types of value models or ways of quantitatively representing preferences: additive, multiplicative, and multilinear representations. A multilinear representation is the most complex, but the most general representation. As such, it requires the fewest assumptions regarding the qualitative preferences of the decision-maker. It is the most difficult to use in that it requires the largest number of assessments having the greatest number of parameters.

A discussion of the assumptions necessary for each of these models to be valid is beyond the scope of this report. However, for the additive model to hold, the attributes must be additively independent. Generally speaking, this means that pairs of attributes are neither substitutes for each other (such as potatoes and rice) nor complements (such as bread and butter). When additive independence fails, it is usually possible to identify a hidden or underlying objective which can be brought into consideration as part of the value hierarchy. Most analysts nowadays advocate modifying the value hierarchy whenever possible, so that an additive model is appropriate. For a further discussion of these issues, see any of the previously cited references (especially Keeney 1992). In any case, additive models are generally a good approximation to non-additive models.

B.2 Value/Utility Functions

The value/utility model is the means to integrate the individual value/utility functions that put the individual attribute scores on a common basis. Value functions address the relative importance of different levels of performance on a single objective. They take as their range the various levels of performance and typically map them into the unit interval [0,1]. One reason for mapping the performance into value space is that an objective's importance may not be linear with its scale. Another reason for transforming performance measures into value space is that it provides a common metric for comparing the relative importance of different criteria. This also makes possible an overall assessment of alternatives with a single number that reflects its overall value. Value functions are called utility functions if they contain risk preference information. Thus the assessment of utility functions is somewhat different than the assessment of value functions in that it must be done in the context of risk so as to capture the risk attitude of the decision-maker.

The shape of the utility function depends on the risk attitudes of the decision-maker. Risk attitudes can be put into three categories: risk averse, risk neutral, and risk seeking. Risk attitude is typically situation-specific. The same individual may buy lottery tickets and insurance, thus exhibiting both risk seeking and risk aversion. These attitudes toward risk can be precisely defined in terms of the relationship between the certainty equivalent (CE) for a gamble and the gamble's expected value (EV). To understand this relationship, we define a simple gambling situation. A two-outcome gamble (G) is a situation in which an individual receives some amount of money (x) if some event (E) occurs, and another amount (y) if E does not occur. The EV of the gamble is given by

$$EV(G) = P(E)*x + (1-P(E))*y,$$

where P(E) is the probability that E will occur. To make this more concrete, consider the game of a coin toss in which you receive $100 if it comes up heads and nothing otherwise. If it is a fair coin, then P(H) = 0.5. Thus,

$$EV(G) = P(H)*100 + (1-P(H))*0$$

$$= 0.5*100 + 0.5*0 = 50.$$

The expected value of $50 is the amount of money that one would expect to win on average if they played this game over and over. The CE is the amount of money a person would be indifferent to having in lieu of the right to play the game. Consider for a moment, if you had the right to play the game described above; you know there is a 50-50 chance you could win $100 and that you have nothing to loose. If someone offered to purchase your right to play the game, would you sell it? Suppose they offered you $10. Most people would not sell for $10. Most people would sell for $50. In between these two numbers is some amount (possibly \$30) where they would be indifferent between selling and playing the game. This amount is the CE. It is the certain amount that a person is indifferent to having in lieu of playing the gamble. If the CE is less than the EV, then the person is risk averse. If the CE is greater than the EV, then they are risk seeking. (The expected values of commercial games of chance are always less than what they cost to play; this is how casinos get rich and state lottery funds generate revenues.)

Forms for utility functions corresponding to risk aversion, risk neutrality, and risk proneness, respectively, are as follows:

$$U(x) = a + b(-e-cx)$$

$$U(x) = a + b(cx)$$

$$U(x) = a + b(ecx)$$

where a, b ≥ 0 and c is positive for increasing utility functions and negative for decreasing utility functions. Because the utility of x for the least desirable value is 0, and the utility of x for the most desirable value is 1, only a single intermediate value needs to be assessed in order to obtain estimates of the parameters. This estimate is commonly made by obtaining the certainty equivalent for a gamble with 50-50 chance of either the most desirable level of x or the least desirable level of x. Other values of x can be assessed to assure consistency.

Value functions do not explicitly consider risk, and therefore they are not assessed from CEs for gambles. A common way to assess a value function is to obtain an intermediate value for x, denote it by x', such that $v(x') - v(xo) = v(x^*) - v(x')$, where xo is the least desirable level for x and x* is the most desirable level for x. Intermediate values can also be assessed then between x' and xo and x* and x'. A smooth curve can then be fitted to these points. It may turn out that a good fit will be exponential functions. (This will be the case if the relative distance to the midpoints is the same for each of the segments.) Even though the same functional forms may be used for either a value or utility function, there is a very different meaning attached to these two types of functions. The utility function captures an attitude toward risk. The value function is a psychophysical function that relates the magnitude of some physical scale (like miles-per-gallon) to a psychological perception of value.

It should also be pointed out that the above discussion of value functions assumes they are monotonic. Not all value functions are monotonic. For example, a value function for the amount of nitrogen in the soil would be non-monotonic because up to some amount, increased nitrogen results in healthier soil that is better for plants; however, too much nitrogen can be bad for plants. It should also be pointed out that non-monotonic value functions often imply other objectives that have not been explicitly identified. In the nitrogen example, nitrogen is really a means to a more fundamental objective that might be, for example, crop yield.

Commercial software packages such as Logical Decisions (see Appendix A) have interactive assessment tools for both utility functions and value functions. Logical Decisions will also determine the unsubscripted k for a multiplicative model based on interactive assessment.

Utility theory is a powerful methodology that captures both value tradeoffs and risk preferences and provides a decision rule consisting of the maximization of expected utility. Thus, the decision-maker would choose the alternative with the highest expected utility. When the analysis is properly carried out, this is a single number that captures both value tradeoffs and risk preferences.

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