ADA 154 976

RISK MANAGEMENT FOR WEAPON SYSTEMS ACQUISITION: A DECISION SUPPORT SYSTEM

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ADA 154 976

28 February 1985

Final Report for Period Covering 15 June 1984 - 28 February 1985
Contract No. F33615-84-M-5084

Prepared for
AIR FORCE BUSINESS RESEARCH MANAGEMENT CENTER
Wright-Patterson AFB Ohio 45433

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EXECUTIVE SUMMARY

I. Summary of Accomplishments of the Feasibility Study

Two principle aims were set forth for the completion study--(i) assess the feasibility of the development of an integrated methodology for the overall risk assessment and management of weapons system acquisition, and (ii) assess the feasibility of translating the integrated methodology into a working tool in the form of a prototype decision support system (DSS).

To provide the necessary inputs for the project, we studied and identified specific risk management issues and concerns associated with the weapons system acquisition process, focusing on:

* the institutional aspect--the decision-making structure associated with weapons system acquisition as well as the management instruments that are at the disposal of the program office.
* past decision experience--particularly the issues, concerns, criteria, and premises that were used during the project planning and selection state for certain selected weapons-system acquisition projects of the past and (based on past experience)the potential impacts that changes in the basic premises, decision environment and/or decision approaches may have on current and future decisions.
* present and future decisions that the USAF and the program office must make, and the interaction among decisions--past, present, and future.
* information needed to make decisions and how, in general, that information may be obtained.
* current risk management issues, concerns, and premises.
* potential areas susceptible to random changes and uncertainties.

From the above, we were able to determine and accomplish the following:

- The major elements of risk in the various phases and oganizational levels of the WSA can be considered in terms of two classes--internal program uncertainty and external program uncertainty. The former is due mainly to lack of information while the latter can be considered as random uncertainty that is beyond any control from within.
- Risk of cost overrun, risk of schedule slippage and risk of not meeting quality requirements are the major risk issues in the internal program class, while risk of budget cut, risk of resource scarcity, and risk of priority change are of major concern in the external program class. All these risks are to be monitored and controlled. Because of the multiplicity of risk monitoring and control objectives in each class, a methodological framework with multiobjective analysis capability was deemed a logical choice.
- To cope with the inherent complexity and multitude of uncertainties in the WSA process, there is clearly a need for an integrated and comprehensive decision aid that weaves together a number of carefully selected risk analysis tools and methodologies. For this purpose, several existing risk assessment and management methods were evaluated, out of which a potentially useful subset was chosen. The subset includes network modeling and analysis, particularly PERT, VERT, and GERT, the partitioned multiobjective risk method (PMRM), the surrogate worth trade-off (SWT) method, Bayesian decision analysis, and several other risk quantification and evaluation approaches. A

hierarchical, multiobjective risk assessment and management framework built upon the recommended tools was then proposed for the WSA process.

- To translate the integrated framework into a working tool, we proposed the use and development of a decision support system (DSS). A DSS offers a great opportunities for packaging or modularity, allowing various components (modules) to be added, removed, or set aside as the needs arise.
- To test the feasibility and effectiveness of the developed hierarchical multiobjective framework, a specific risk management problem (adopted from one used by the Defense Systems Management College at Fort Belvoir, Virginia), was solved. A prototype DSS was developed and used to demonstrate the proposed concepts.

II. General Recommendations

By its nature, a feasibility study addresses a broad range of issues and it must do this mostly in generalities, necessarily avoiding the specifics. In the completed study, we have identified desirable features, components, and characteristics of the comprehensive WSA risk assessment and management system, indicated how these elements should be packaged into one feasible yet powerful unit, and developed a prototype DSS to demonstrate the concepts. With the ultimate aim of developing a comprehensive risk assessment and management DSS for the entire weapons system acquisition process, the results from the feasibility study must be further crystallized and consolidated as well as extended to include all areas of risk and all phases of the process.

Future work should thus follow a two-pronged strategy, one involving crystallization and consolidation and the other is more toward extension.

The first of these is centered around a packaging concept of consolidating existing tools and methodologies into a working DSS that is powerful and versatile enough to deal with most WSA risk issues and challenges (of any scope and level of complexity) and yet is easy and flexible enough to use. The second represents an extension effort and is directed more toward methodological improvements. These include i) refining existing risk quantification and evaluation tools and/or developing new ones to better cater to the specific needs of the WSA process, and ii) developing or refining coordination strategies for coordinating risk assessment and management activities at the various levels of the USAF organization. Typical tasks for the first type of study should include the following:

A) Expand the presently developed prototype DSS to allow the project manager (PM) to consider more general aspects and attributes in his decision process.

B) Develop modules at the directorate level that respond to the specific needs that the directorates have throughout the program's life cycle.

Typical tasks for the second type of study are:

C) Explore the concept of hierarchical network and decision tree models (as illustrated in Figure I.1) and develop methodological procedures for them.

D) Develop a coordination scheme between the PM and the directorates that will facilitate information flow through the use of hierarchical network and decision tree models.

III. Proposed Future Study

Based on the general recommendation set forth in the previous section, we propose to follow-up the completed feasibility study on risk management for weapons system acquisition with a two-phase study. Although both phases build on results derived from the feasibility study, there are distinctive attributes associated with each phase as well as a temporal logic in the sequence.

The first phase, based on Recommendation A, aims principally at completing the development of a relatively general but usable risk assessment and management methodology from the program manager's perspectives, building upon the existing prototype DSS model. The emphasis here is placed upon risk quantification and evaluation

The second phase is to carry out the remaining recommendations 1) by at both developing a comprehensive risk assessment and management DSS for a selected program office and 2) by extending, refining, and strengthening a hierarchical-multiobjective framework and methodology for the overall WSA risk assessment and management process.

In the terminology of the WSA process, we may view the just-completed feasibility study as a conceptual exploration, the proposed Phase I study as a demonstration and validation, and the proposed Phase II study as a full-scale development.

IV. Phase I Study--Risk Management for Weapons System Acquisition: A Project Manager's Perspectives

The overall objective of Phase I is to develop a usable risk management methodology for weapons system acquisition at the program manager level that is comprehensive in nature and that makes explicit use of advanced state-of-the-art tools developed in such fields as risk assessment and management, decision analysis, multiple-criteria decision making, etc. More specifically, the tasks in this study will include the following:

a) Replace the present use of PERT for project scheduling with VERT, thus allowing the use of probability distribution functions within the scheduling process. Other network models will also be explored.

b) Quantify the objectives indentified in the feasibility study:

   risk of cost overrun
   risk of schedule slippage
   risk of not meeting quality requirements
   risk of budget cost
   risk of resource scarcity
   risk of priority change

Note that only the first two objectives were quantified during the feasibility study, and mostly in a superficial way (in order to test the overall methodology).

c) Apply the partitioned multiobjective risk method (PMRM). This would require the quantification of the appropriate probability distribution functions and the part-timing of the frequency domain.

d) Apply the surrogate worth trade-off (SWT) method for the overall multiobjective risk-based decision-making problem. This would enable the project manager to quantitatively evaluate the various trade-offs associated with the various non-commensurate objectives.

e) Demonstrate the working mechanism and potential usefulness of the developed methodology using the modified and upgraded prototype DSS.

And, in anticipation of and preparation for the Phase II study, we shall also identify an interested and willing project manager within Wright-Patterson Air Force Base for whom a specific decision support system will be developed in Phase II.

V. Phase II Study--Risk Management for Weapons System Acquisition: A Comprehensive Hierarchical-Multiobjective Framework

Phase II is comprised of two components:

(1) development of a DSS for a specific project manager (in charge of weapons systems acquisition).

(2) development of a more comprehensive risk-based hierarchical multiobjective framework for weapons system acquisition that builds on the results from the already completed feasibility study and from Phase I

The anticipated tasks in this phase can be found in Recommendations B, C, and D, Section I.2. The following are some of our general thoughts on those tasks.

The development of specific modules for each directorate should parallel the development of the PM's DSS. Once a complete version of the prototype has been developed for the PM, it can be modified to respond to the more detailed needs at the directorate level. Specifically, the network or decision-tree model will be altered to focus on the subtasks associated with each directorate. (For example, the manufacturing management directorate's objective is to assure that a system can be produced in the most cost-effective manner. This involves producibility studies, design reviews, quantification of production risk, and production plans. The development of a specific DSS with modules aimed at these duties will improve the directorate's performance.) Some of the specific tools and extensions that will be useful at this level include:

* extension of the work breakdown structure and method of moments

* subjective probability assessments

- cost-estimation techniques
- cross-impact analysis
- probability-, decision-, fault-, and event-tree analysis
- reliability analysis
- network analysis

The coordination scheme, which will reside in the data-base management system of the DSS, is envisioned as some form of hierarchical networking scheme that uses hierarchical decision trees and possibly hierarchical work-breakdown structures (See Figure I.1).

Finally, the development of the coordination scheme will allow the program office to take full advantage of the micro-based DSS's. By incorporating existing methodologies and tools from hierarchical multiobjective coordination, we will be able to link the PM with his directorates. This will provide the PM with the specific information he needs from his directorates when he needs it. It also provides the PM with an insight into the effects of his decisions on each of his directorates. As for the directorates, they will be given a better understanding of their goals as they relate to the overall goals of the program. The coordination scheme will ensure that each directorate understands what the others are doing so that they can work together toward the same goal. It will help the directorates to understand the actions of the PM and also help them to support him.

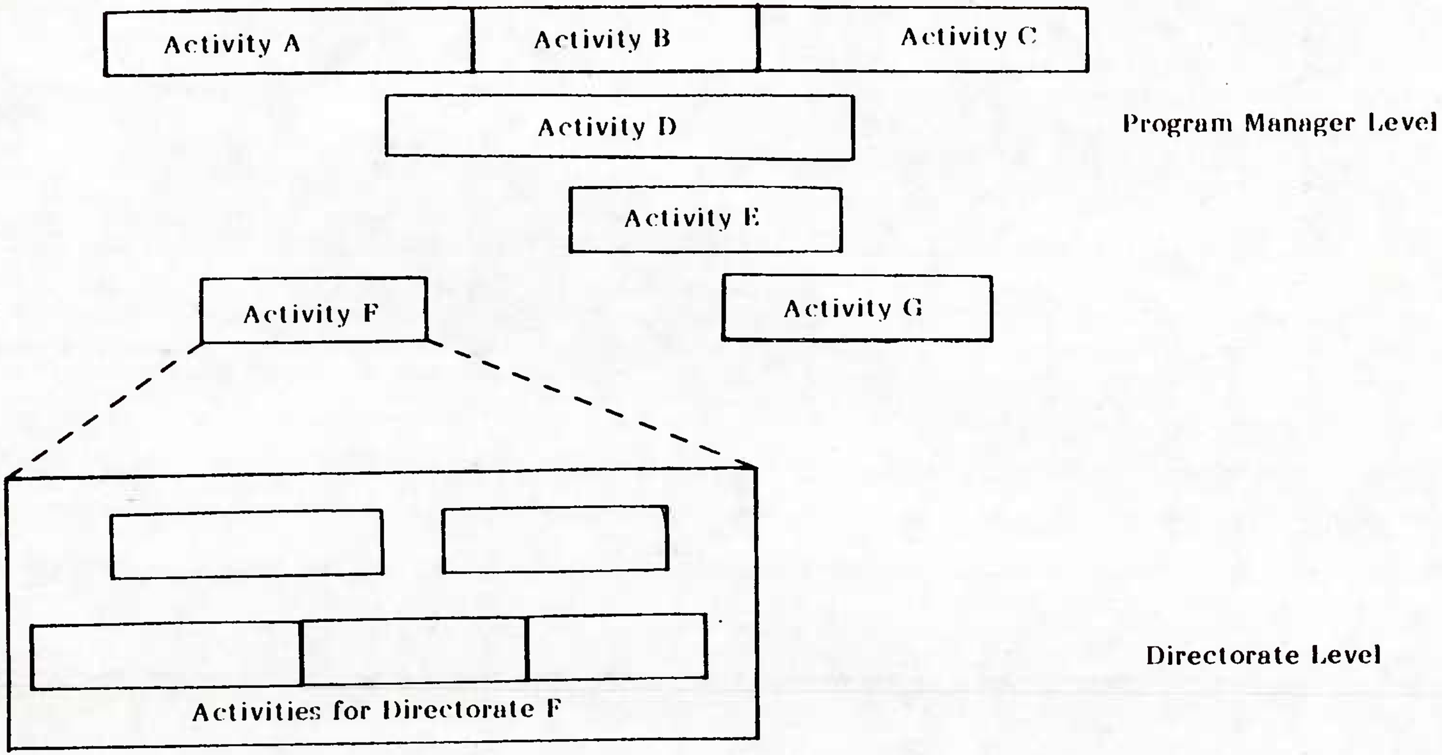

Activity A
Activity B
Activity C
Activity D
Program Manager Level
Activity E
Activity F
Activity G
Activities for Directorate F
Directorate Level

Figure I.1. "Hierarchical Networking"

1. Risk and Uncertainty in the Weapon Acquisition Process--A Unified Framework

1.0. INTRODUCTION

How to deal with the risks and uncertainties associated with the development of new technologies is one of the most complex and perplexing problems that a program manager must deal with during the weapon system development and procurement process. New technology can range from minor modifications of existing systems to radical, far-reaching innovations, and may result in a new product, a new process, or a combination of both. Yet program managers for the development of new technologies must be able to make decisions concerning schedules, budget targets, performance requirements, and other aspects of the program, under a very uncertain future.

Because of the inherent uncertainties associated with developing and/or modifying technologies, significant risks are involved with any program. Such risks include time delays, cost overruns, failure to meet performance requirements and, in general, the success or failure of the program. It is for this reason that the Department of Defense and Air Force acquisition management directives require that risks be continually addressed throughout the development of major weapon systems.

Currently, no standardized procedures are in place to help program managers account for these risks. Because the failure of a major weapons system is both costly and harmful to national security, the need for a sound and well-grounded risk assessment and management methodology must be emphasized. It is to this issue that we are addressing ourselves.

The principal aim of the study is to assess the feasibility of (i) the development of an integrated methodology for the overall risk assessment and management of weapons systems acquisition (WSA), and (ii) the translation of the integrated methodology into a working tool in the form of a comprehensive decision support system (DSS). This report summarizes our main findings and presents a plan for future works. Section 1 identifies the elements of risks and uncertainties associated with weapons system acquisition based on our view of the acquisition process summarized in Appendix B. We focus our attention to the program office and, in particular, the program manager and the elements of risk and uncertainty that he must face. We also present a general framework which can summarize the major elements of the decision-making- process throughout a program's activities in the directorates of the program office. The risk assessment and management decision aid, which is based on the developed framework is an integration of tools and concepts, including decision analysis, hierarchical and and multiobjective decision making, network analysis and a number of risk assessment and management methodologies. Future work can be directed at completing the details of this framework as a unified decision aid for use by any program office and its various divisions to use in evaluating and managing the major areas of risk during the entire acquisition process.

A large body of knowledge concerning risk identification and management is available. A review of this knowledge is found in Section 2 and Appendix B, where we also summarize and compare a number of currently available methods and indicate some of their shortcomings as well as provide some suggestions for combining and improving them.

In Section 3, we discuss the use of a decision support system (DSS) for risk management during the entire weapon acquisiton process. We particularly focus on the production and deployment stage and discuss several selected tools and concepts which we combined into a unified package as a prototype DSS. In order to demonstrate the capabilities of our prototype DSS and provide a sampling of its outputs, we obtained (adapted from Ingalls, 1984a) a sample problem relating to the production and deployment phase of a project and applied the DSS to this problem. A detailed description of the problem and a summary of the results are also found in Section 4.

It is worth keeping in mind that the present project was a feasibility study and consequently the developed prototype DSS is limited in both its scope and use. The DSS is intended to demonstrate the fundamental strengths and capabilities of the developed framework. We are hopeful that it provides the foundations upon which a more representative and useable DSS can be developed in the future.

The success or failure of any program can be based on many different factors. The entire weapon acquisition process is tedious and complicated, consisting of interlocking decisions, many simultaneous activities and various planned and unplanned events. Typical decisions in the process involve make-or-buy options, quantity, quality and timing of products to be acquired, selection of contractor, and management, control and coordination of system development. Within each of these decisions lies an element of risk and uncertainty. There is a need to account for these elements of risk and uncertainty in a satisfactory way to ensure successful implementation of a procurement program.

In this section we identify the major areas in the weapons system acquisition process as faced by the program office, where the assessment and management of risk are essential. This is based on our view of the process summarized in Appendix A. We attempt to identify and classify the specific needs and requirements of these major areas as a means of describing a unified framework that can be used to evaluate and manage the major areas of risk throughout the acquisitions process by each component of the program office. The remainder of this section focuses on the risk activities of the directorates in the program office. We outline this phase in greater depth, to set the stage for the following chapters where a prototype decision support system is developed.

1.1 Uncertainties in the Acquisition Process

Careful examination of the acquisition process (See Appendix A) reveals that the program office must continually identify, evaluate, and manage the risks and uncertainties during the entire life of the program. Figure 1.1 provides a simplified view of the acquisition process and indicates the specific times when risk assessment and management are necessary.

The uncertainties found in the weapon system acquisition process can be categorized in a number of different ways. One useful classification divides uncertainty into four groups: target, technical, internal program and process uncertainties (Lenox, 1973). A summary of this classification scheme is given in Table 1.1.

Target uncertainties correspond to the uncertainties which are generated in the process of reducing a need or military requirement into cost, schedule and performance goals. They relate back to the perception of enemy threat and the resulting needs because as the perception of the threat changes, the needs and goals will also change. Some specific areas of uncertainty which occur as a result of target uncertainty include uncertainty in the specification of the need, uncertainty in the specification of desired operational capabilities, uncertainty in the process of generating the requirements of the system and uncertainty in the physical characteristics that the system must possess to satisfy the needs.

Internal program uncertainties involve those which originate within the program as a result of the manner in which the program is organized, planned and managed. They are not the inherent uncertainties of the problem itself but are those uncertainties which are under the direct jurisdiction of the program office. Examples of some internal program uncertainties include the uncertainties involved in setting technical, cost and schedule targets, the uncertainty involved in selecting the appropriate acquisition strategy (e.g., how much prototyping is necessary, how much testing is required, etc.) and uncertainty in program management which can occur as a result of an improper balance between cost, schedule and performance.

Process uncertainties are those which originate outside the program, but directly affect the program's outcome. These uncertainties are under the jurisdiction of officials and agencies outside the program office such as the President, HQ USAF, industrial suppliers, etc. Some examples of process uncertainties include uncertainty in the availability of funds, uncertainty in the availability of resources and uncertainty in the priority assigned to the program. The deterministic values assigned to these uncertain entities often form the constraints under which the program office must work. The PO must be able to choose a flexible program which is relatively constant under changes in these uncertain elements and must be ready to make adjustments as necessary.

The last major type of uncertainty in this classification deals with the question of whether it is possible to develop the desired system at all (e.g., technical uncertainty). It is the smallest if the system is within the state-of-the-art. If the system deals with new technologies that have yet to be developed, technical uncertainty can be very large in the early phases of the acquisition process and will hopefully decrease as the program advances. The assessment of technical uncertainty can have a critical impact on the program outcome. If the assessment is too optimistic, then the program will be underbudgeted and the targets set by the PO will undoubtably be exceeded. These problems could ultimately lead to program failure. An unduly pessimistic outlook can be equally damaging. Such a program may never get budgeted in the first place.

From an examination of Table 1.1, the basis of several other classification schemes can be proposed:

(i) the causes of uncertainty

(ii) whether the uncertainty is caused by the decisions of people outside the PO or not

(iii) whether the uncertainty comes from a lack of information or some other uncontrollable factors.

(iv) which phase of the acquisition process the uncertainty is found.

All of the various schemes for classifying uncertainty can be useful in breaking the problem into its component parts and in helping to distinguish between the causes and the effects. The causes of uncertainty should be carefully identified, because our developed risk assessment and management framework is directed at quantifying the impact of these uncertainties on the system cost, schedule and performance throughout the weapon acquisition process. The likelihood and impact of cost overruns, schedule slippages, undesired system quality or performance, budget cuts, resource scarcity and program priority changes (i.e., the "risks") each have a direct influence on the program outcome (see Figure 1.2). Their identification and management throughout the acquisition process is what the following framework is all about.

1.2. Specific Risk Assessment and Management Needs in WSA: A Framework

Since our ultimate aim is to develop a comprehensive risk assessment and management aid for WSA, in this subsection we examine further the specific needs to which such an aid must respond. Based on these requirements and specifications, a master plan or framework for developing a WSA assessment and management system will be subsequently outlined in Section 3.

The type and complexity of risk assessment tools required during the weapons system acquisition process are dependent upon the phases of the program. Uncertainty is a time-related concept. The amount and accuracy of information increases as the program moves through its phases. Normally, this additional data reduces many of the uncertainties in the program. If proper trade-offs and decisions are made during the course of the program, then the risk of program failure should have near-zero probability by the time it reaches the production and deployment phase. If as the program progresses the risks cannot be reduced, then the program either defies successful deployment or is so prone to unforeseen difficulties that its successful completion is impossible. Thus, it can be seen that the level of program risk is a function of both the uncertainty in the program and the decisions that were made during the course of the program. This means that risk assessment and management procedures must be tailored to the quality and quantity of information present and the types of decisions which must be made during each of the phases.

The required risk assessment and management procedures also depend on the focus of authority. The acquisition process is composed of several hierarchies of decision making (See Figure 1.3). In this hierarchical view of the acquisition process, HQ USAF and higher authorities must make decisions about the fate of each of the different Air Force defense acquisition programs. The program managers must report to HQ USAF and make operating and planning decisions related to their individual programs. The functional specialists, which represent each of the directorates or divisions within the program office (e.g., systems engineering, program contol, test and evaluation, etc.) report to their program manager and make operating and planning decisions related to their individual specialities.

A good risk assessment and management framework should (i) handle the changing "risky" decisions throughout the acquisition life cycle for the different levels of decision making, (ii) help coordinate the flow of available information between the various hierarchies and subsystems, and (iii) be tailored to the "types" of risk decision needs and quantity and quality of information present in each phase and hierarchy of the acquisition process. Table 1.2 indicates some of the typical types of decisions which must be made by each of the levels of authority during the course of a program. For example, during Phase I (i.e., concept exploration), the main objectives for the program office (the PM and functional specialists) are to see whether any of the proposed concepts are feasible and to see whether they satisfy the cost, schedule, logistic supportability, and performance requirements levied by the Department of Defense. In Phase II, the program office must help select the contractor, decide on the criteria by which each proposal will be evaluated, and whether additional iformation (e.g., prototyping) is necessary. During Phases III and IV, the P.O. must direct the development, production, and deployment of the weapon system, help institute technical changes, and manage the acquisition of follow-on quantities.

The types of decisions made by HQ USAF (and higher authorities) varies very little during the different phases. They normally consist of defining and reevaluating the system needs and requirements, setting budgets, schedules, and performance targets, assigning priority levels, and deciding whether each program should proceed to its next phase.

Risks must be recognized, quantified, evaluated, and managed during every phase and in every level of the acquisition process in order to make better -informed decisions. Because we wish to provide a useful tool for risk assessment and management within an acquisition program, the focus of our risk assessment and management framework (and the resulting decision support system) is on the program office (i.e., the program manager and his functional specialists and/or directorates). The decisions made by HQ USAF and higher authorities are viewed as uncertain inputs into the PM's decision (See Figure 1.4.).

In order to tailor the risk assessment and management framework to the needs of each of the directorates and the program manager, we looked at the types of risk-related activities which are performed by each of the directorates (See Table 1.3 for a summary of these activities throughout the acquisition process). The following is a short discussion of each of the directorates' typical activities:

program control--involved with planning, scheduling, estimating budgeting, analyzing, and forecasting program progress. Identifies critical events, identifies and tracks "program" risks (e.g., cost, schedule, and technical performance), proposes alternative solutions to identified or potential problems, and conducts "What if?" exercises.

contracting directorate--sets award amounts, delivery schedules, contract terms (i.e., contract evaluation factors), and payment arrangements based on technical and program risk considerations.

integrated logistics support--involved in logistics planning.

Makes sure that support considerations (e.g., reliability, maintenance, operation, training, etc.) are included in the requirements and design. Defines and plans for support requirements that are optimally related to design and acquires support during the operational phase at minimal cost. Identifies, tracks and proposes solutions to "logistic" problems (risks).

manufacturing management--involved in production planning. Makes sure production feasibility is analyzed, areas of "production" risks (e.g., in the fabrication, assembly, installation, checkout, manufacturing method, etc.) are identified, and proposes plans for potential and/or observed production problems.

engineering management--involved in defining system performance parameters and configuration, planning and control of technical tasks, integrating reliability, maintainability, and safety, and optimizing technical performance with cost, schedule, and logistic supportability to meet program objectives. Heavily involved in identifying, tracking, and planning for technical risks.

test and evaluation--involved in the evaluation of the program's technical and operational feasibility. In particular, its objectives are to assess system specifications, assess program risks/tradeoffs, assess logistic supportability and survivability, verify technical order completeness, gather training program and environmental impact data, and determine system performance limitations.

configuration management--oversees system functional requirements from "design to" specifications to "build to" specifications for the subsystems. In particular, they define and verify the configuration of items, control changes in these items, monitor their implementation, and track the configuration of units.

computer resources management--oversees the development and operation of the computer subsystem of a weapon system. Designs, codes, checks, tests, installs, operates, and supports the computer function. Identifies "computer risks" and proposes plans for potential and observed problems.

The risk activities identified in Table 1.3 provide some general guidelines for choosing the appropriate tools to be included in risk assessment and management decisions aids for each of the directorates. Understanding the flow of risk information between the program office and its directorates (which can be summarized in diagrams such as Figure 1.5) in each phase of the acquisition process helps to identify information requirements and provides the guidelines for coordinating risk information flow. These tables and figures (along with an understanding of the quantity and quality of the risk information) form the framework upon which a risk assessment and management decision aid can be designed.

TYPES OF UNCERTAINTY	AREAS OF UNCERTAINTY	CAUSED BY	FOUND IN WHICH PHASES	DECISIONS MADE BY PROGRAM OFFICE	DECISIONS MADE OUTSIDE PROGRAM OFFICE	MISSPECIFICATIONS CAN LEAD TO COST OVERRUNS, SCHEDULE SLIPPAGES, UNDESIRED QUALITY AND ULTIMATE PROGRAM CANCELLATION
Target Uncertainty	In the nature of the need and/or desired operational capabilities	. political situation . national policy goals . nature and extent of enemy threat . intelligence information	0*, 1, 2, 3, 4	No	Yes	Yes
	Introduced through the process of generating requirements for the system	. ill-defined concept formulation strategy	0*, 1, 2, 3, 4	No	Yes	Yes
	In the physical characteristics that the system must possess to satisfy the needs	. ill-defined need . lack of technical data . inaccurate information . political situation	0*, 1*, 2, 3, 4	No	Yes	Yes
Technical Uncertainty	Technical Uncertainty (Is it possible to build at all?)	. No historical data for new technology	0*, 1*, 2*, 3	Yes	Yes	Yes
Internal Program Uncertainty	Uncertainty in initial process and technical and target estimates	. No historical data for new technology . lack of technical information	2*, 3	Yes	No	Yes
	Uncertainty in selection and acquisition strategy (e.g. prototyping vs. no prototyping, etc.)	. lack of technical information	3, 4*	Yes	No	Yes
	Uncertainty in program management	. improper balance between cost, schedule, and performance	0*, 1*, 2*, 3*, 4*	Yes	No	Yes
External Process Uncertainty	Uncertainty in funding	. other needs (programs) . mission uncertainty . Presidents budget . political considerations . DOD policies		No	Yes	Yes
	Uncertainty in resource availability (besides funding)	. other programs . scarce resources	3, 4*	No	Yes	Yes
	Uncertainty in program priority	. other programs . DOD policies . mission uncertainty . political and congressional considerations	0*, 1*, 2*, 3*, 4*	No	Yes	Yes

* phases in which greatest uncertainty is most often found

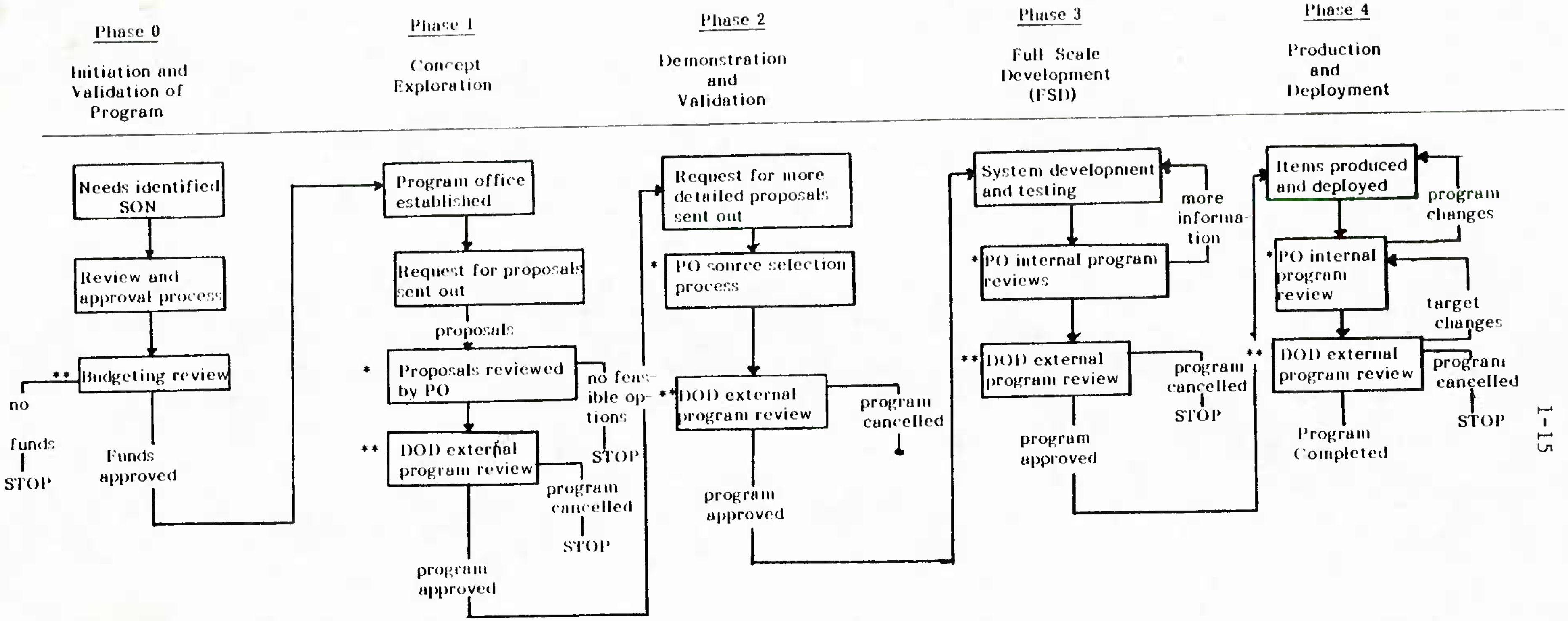
Table 1.1. Categories of Uncertainty in the Acquisition Process summarized from discussion of uncertainty in Lenox, Hamilton T. 1973.

	Phase 0 Initiation and Validation	Phase 1 Concept Exploration	Phase 2 Demonstration and Validation	Phase 3 Full Scale Development	Phase 4 Production and Deployment
HQ USAF and higher authorities	° what are the needs? ° what are the functional requirements? ° what are the initial cost, schedule and performance targets? ° what priority should be given to the program? ° should the program be funded?	° have the needs changed? ° do the targets need to be adjusted? ° should the priority change? ° should the budget be adjusted? ° should the program proceed to the next phase or be cut?	° have the needs changed? ° do the targets need to be adjusted? ° should the priority change? ° should the budget be adjusted? ° should the program proceed to the next phase or be cut?	° have the needs changed? ° do the targets need to be adjusted?	
Program Manager (PM)		° is it possible to develop program within HQ USAF targets? ° what is the expected cost, schedule, perfomance and risks for : (i) development (ii) production (iii) operation (iv) maintenance for each concept?	° which contactor should be selected? ° is prototyping necessary? ° what is the expected cost, schedule, performance and risks for: (i) development (ii) production (iii) operation (iv) maintenance for each proposal?	° what is the planned budget and schedule? ° is the contractor on schedule and within budget? ° does the program satisfy technical requirements? ° are any planning adjustments needed for development, production and deployment, operation and maintenance?	° are any planning adjustments needed in budget schedule or performance for: (i) production and deployment (ii) operation (iii) maintenance ° how should engineering changes be incorporated into the system? ° how should follow-on items be acquired?
Functional Specialists (directorates or divisions of PO)		° what is the expected cost schedule and permance (and risks) for: (i) development (ii) production (iii) operation (iv) maintenance (as appropriate for specialty) for each concept?	° is more detailed information required for specialty?		

Table 1.2. Typical decisions made by the three levels of authority in each phase of acquisition program.

	Phase I Concept Exploration	Phase II Demonstration and Validation	Phase III Full Scale Development	Phase IV Production and Deployment	Remarks "risky areas"
Program Control	N/A	N/A	° ID and track cost, schedule and performance risks ° propose alternative solutions to identified or potential problems ° conduct "what if" exercises	° ID and track cost, schedule and performance risks ° propose alternative solutions to identified or potential problems ° conduct "what if" exercises	"program risks" cost schedule performance
Contracting	Set budget, delivery schedule, contract terms and payment arrangements tailored to program risk	Set budget, delivery schedule, contract terms and payment arrangements tailored to program risk	Set budget, delivery schedule, contract terms and payment arrangements tailored to program risk	Set budget, delivery schedule, contract terms and payment arrangements tailored to program risk	uses "program risks" considerations
Integrated Logistics Support	ID and evaluate supportability risks and impacts on program for each proposed system concept	ID and evaluate supportability risks and impacts on program for each proposed system concept	° ID and track supportability risks ° propose alternative solutions to identified or potential supportability problems ° conduct "what if" exercises for supportability considerations	° ID and track supportability risks ° propose alternative solutions to identified or potential supportability problems ° conduct "what if" exercises for supportability considerations	"Logistics Risk" operation reliability maintenance manabiligy training & skills packaging, handling, transport
Manufacturing Management	N/A	ID and evaluate potential production risks and impacts for each proposal	determine production risks from data generated during this phase	° assess and track production risks ° propose plans for potential and observed production problems	"producibility" risk fabrication assembly installation checkout scheduling program surveillance
Engineering Management	° Define performance parameters and configuations with reasonable technical risk ° Analyze technical risk of proposed concepts	° Define performance parameters and configuations with reasonable technical risk ° Analyze technical risk of proposed concepts	° ID and track technical risks ° optimize technical performance with cost, schedule, logistic supportability (under risk) to meet objectives	° ID and track technical risks ° optimize technical performance with cost, schedule, logistic supportability (under risk) to meet objectives	"technical risk" technical design reliability maintenance safety
Test and Evaluation	Evaluate technical and operational risks for each proposed concept [working with other diretorates]	Evaluate technical and operational risks for each proposed concept [working with other diretorates]	° ID and track risks ° correct and plan against technical deficiencies ° asses program risks/tradeoffs	° evaluate system under uncertain (changing) environment ° evaluate risks in system changes ° assess program risks/tradeoffs	"Performance Risks" environmental impact technical performance operational needs effectiveness supportability survivability
Configuration Management	define "design to" specification using risk consideration for entire system	define "build to" specifications using risk considerations for each configuration item (subsystem)	define "build to" specifications using risk considerations for each configuration item (subsystem)	N/A	uses "technical risk" considerations
Computer Resources Management	ID and evaluate potential computer risks for each concept	ID and evaluate potential computer risks for each concept	° ID and track computer risks ° propose alternative solutions for potential problems	° ID and track computer risks ° propose alternative solutions for potential problems	"computer risks" design coding installation operation
Program Manager	Summarize all risks and impacts of each proposed system concept	Summarize technical, cost, supportability, production and schedule risks and impacts for each proposed system	° Evaluate and manage all development risks ° Choose appropriate action for identified problems using risk considerations	° Evaluate and manage production and deployment risks ° Evaluate and manage technical and cost risks when engineering changes are required ° Evaluate and manage program risk when acquiring follow-on quatities	all previous risks

Table 1.3. Typical Risk Related Activities for the Program Manager and his Directorates


Phase 0
Initiation and Validation of Program
Phase 1
Concept Exploration
Phase 2
Demonstration and Validation
Phase 3
Full Scale Development (FSD)
Phase 4
Production and Deployment
Needs identified SON
Review and approval process
** Budgeting review
no funds
STOP
Funds approved
Program office established
Request for proposals sent out
proposals
* Proposals reviewed by PO
no feasible options
STOP
** DOD external program review
program cancelled
STOP
program approved
Request for more detailed proposals sent out
* PO source selection process
** DOD external program review
program cancelled
program approved
System development and testing
more information
* PO internal program reviews
** DOD external program review
program cancelled
STOP
program approved
Items produced and deployed
program changes
* PO internal program review
target changes
** DOD external program review
program cancelled
STOP
Program Completed

* indicates where risk assessment and management is required in PO
** indicates where risk assessment and management is required in DOD

Figure 1.1. Simplified view of acquisition process

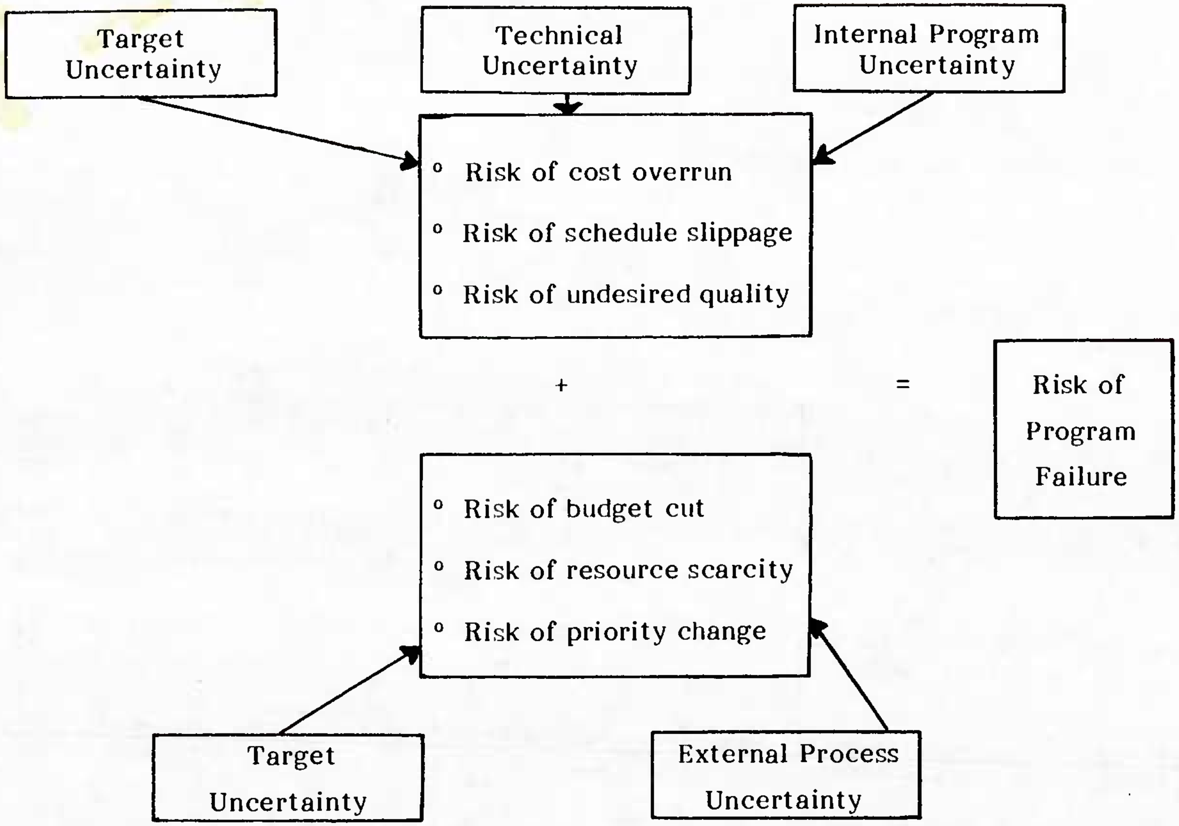
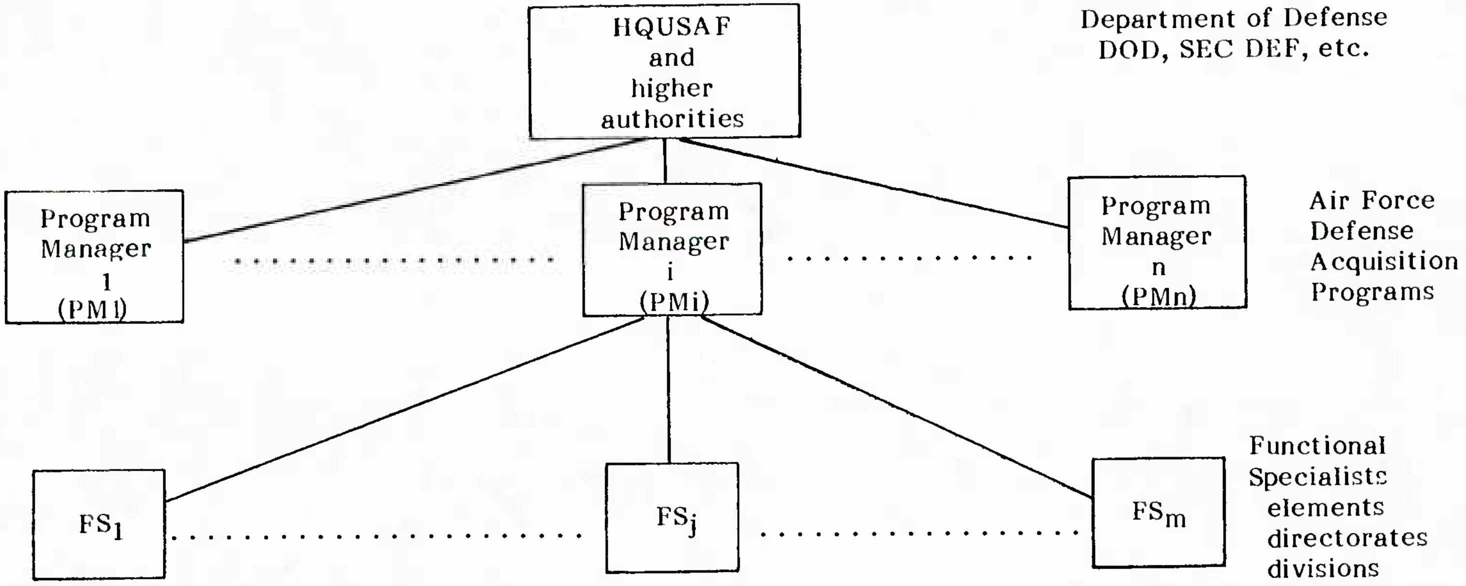

Target Uncertainty
Technical Uncertainty
Internal Program Uncertainty
° Risk of cost overrun
° Risk of schedule slippage
° Risk of undesired quality
+
=
Risk of Program Failure
° Risk of budget cut
° Risk of resource scarcity
° Risk of priority change
Target Uncertainty
External Process Uncertainty

Figure 1.2. Relationship between uncertainties, risks and program failure in weapon system acquisition process.


HQUSAF and higher authorities
Department of Defense
DOD, SEC DEF, etc.
Program Manager 1 (PM1)
Program Manager i (PMi)
Program Manager n (PMn)
Air Force Defense Acquisition Programs
FS$_1$
FS$_j$
FS$_m$
Functional Specialists
elements
directorates
divisions

for example:

1) systems engineering
2) configuration management
3) program control
4) management support
5) contracting
6) manufacturing management
7) test and evaluation
8) integrated logistics support

Figure 1.3. Levels of authority in the weapon system acquisition process.

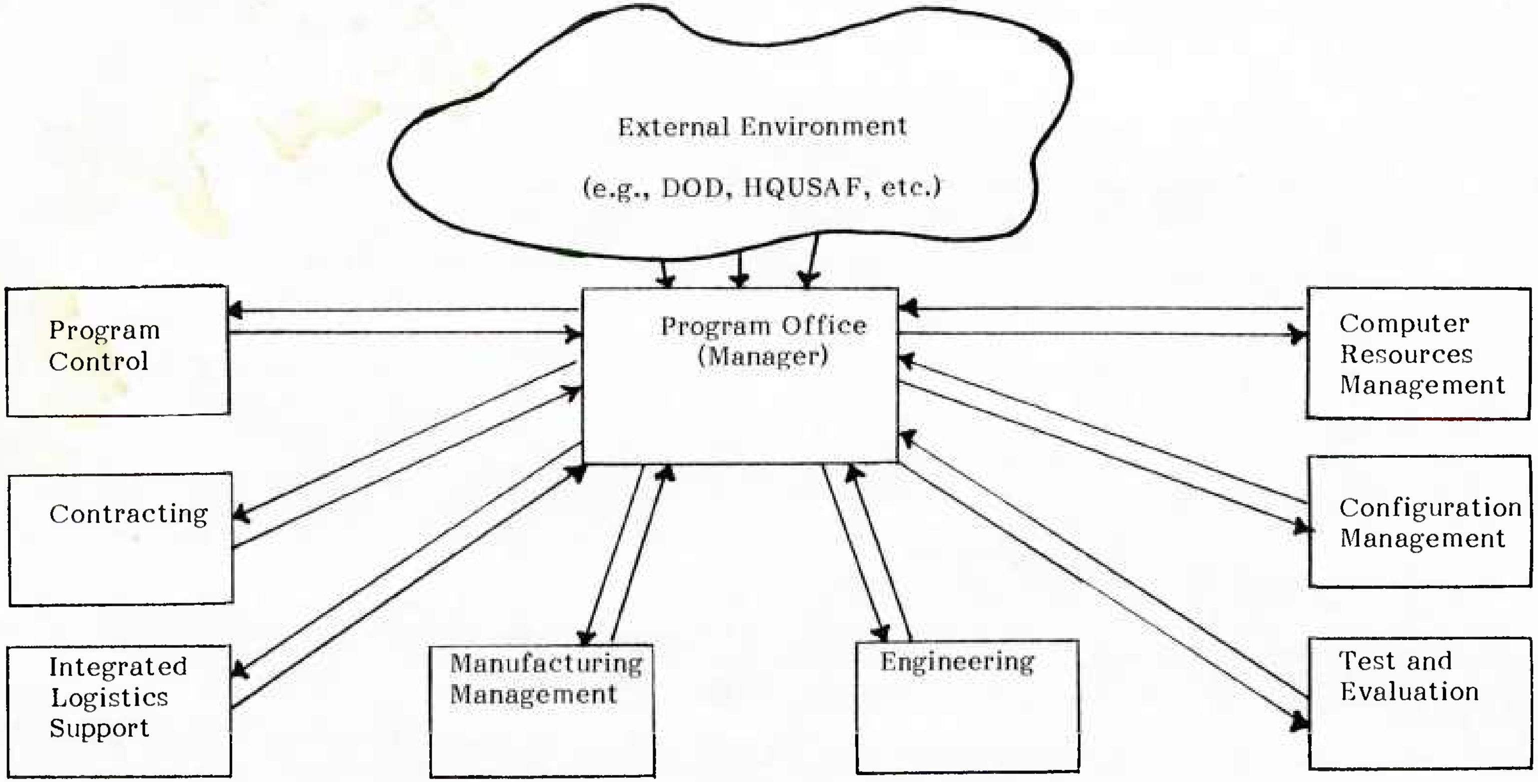

External Environment
(e.g., DOD, HQUSAF, etc.)
Program Office (Manager)
Program Control
Contracting
Integrated Logistics Support
Manufacturing Management
Engineering
Computer Resources Management
Configuration Management
Test and Evaluation

Figure 1.4. Focus of risk assessment and management framework

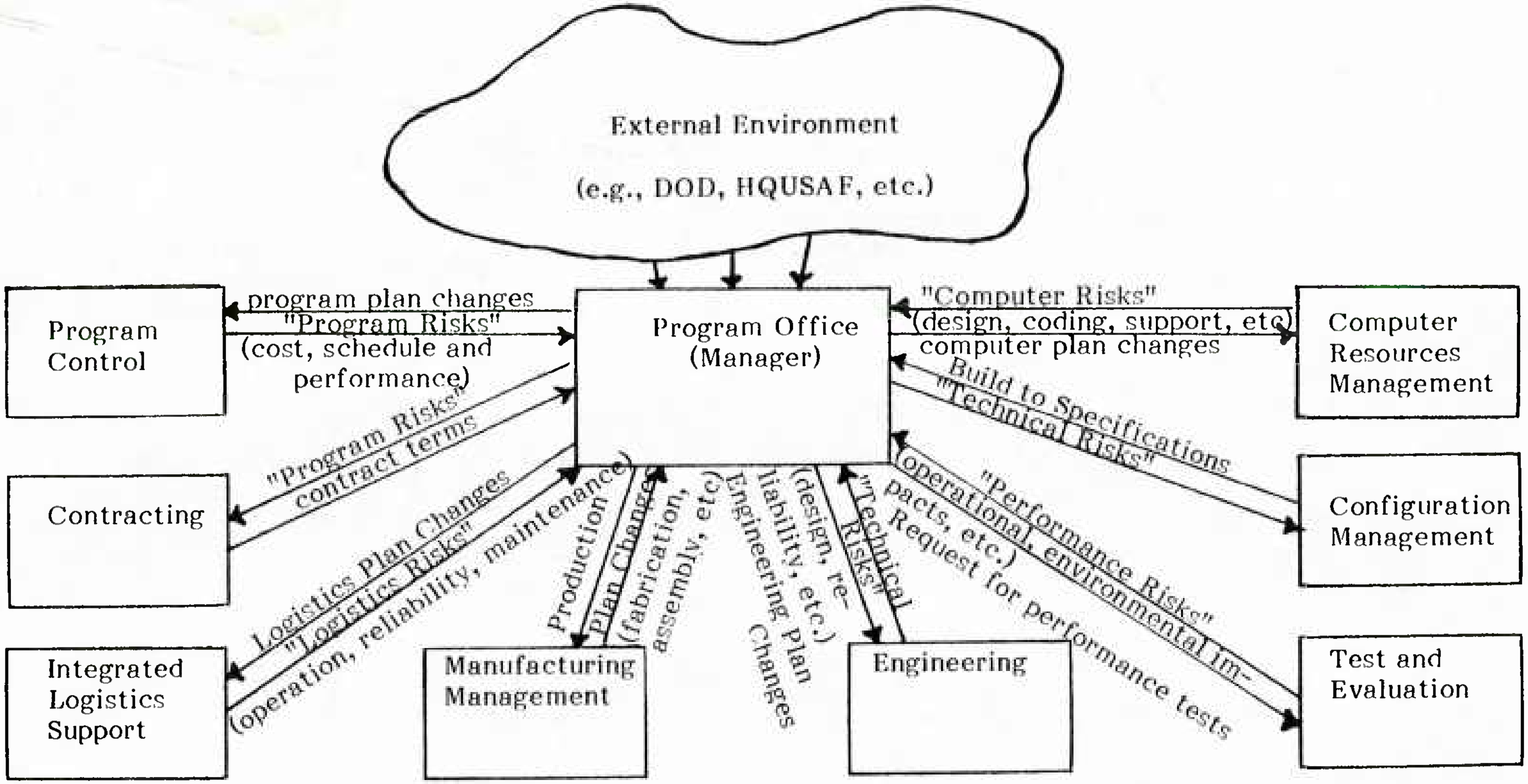

External Environment
(e.g., DOD, HQUSAF, etc.)
Program Control
program plan changes
"Program Risks"
(cost, schedule and performance)
Program Office (Manager)
"Computer Risks"
(design, coding, support, etc)
computer plan changes
Computer Resources Management
Build to Specifications
"Technical Risks"
Configuration Management
Contracting
"Program Risks"
contract terms
Integrated Logistics Support
Logistics Plan Changes
"Logistics Risks"
(operation, reliability, maintenance)
Manufacturing Management
Production Plan Change
(fabrication, assembly, etc)
Engineering Plan Changes
(design, reliability, etc.)
"Technical Risks"
Engineering
"Performance Risks"
(operational, environmental impacts, etc.)
Request for performance tests
Test and Evaluation

Figure 1.5. Typical information flow in risk assessment and management framework during Phase III.

2. Risk Assessment and Management Methodology

The previous section focuses on the specific needs and requirements of the WSA risk assessment and management problem. In this section, we discuss what tools are available or need to be developed to respond to such needs. In particular, we describe a general risk assessment and management philosophy, summarize some selected risk analysis tools, and propose a methodological framework for integrating various tools and concepts that reflect our vision of the ultimate decision support system. We shall be brief in this section. Appendix B provides a more detailed discussion and review of risk assessment and management methods.

2.1. Risk Assessment and Management Process

Risk is the possibility of suffering harm, loss, danger, failure, or some kind of adverse effects as a result of taking an action or a sequence of actions. There are thus two basic elements associated with risk: the magnitude and the likelihood of harm or adverse effects. To describe a risky situation, we must therefore adequately describe these two basic elements. Risk is clearly induced by some uncertainties and these may be of different types. Some uncertainties are caused by natural random or uncontrollable forces from outside the system or context, and these are naturally uncontrollable by any means generated within the system. Precipitation, wind, and earthquakes are but a few examples of such forces. In the WSA process as viewed from the program office's perspectives, decisions and/or directives from the command level or higher may also be viewed as uncontrollable factors (uncontrollable from within the program office) and can be a major source of uncertainty to the program manager's domain of operation. Another type of uncertainty arises from lack of information and may have nothing to do with any natural random factors. A tank commander in a battlefield may wish to know the enemy strength in order to develop an appropriate attack strategy. Although there is nothing naturally random about the enemy strength, any estimate he uses--which will only be as good as the quantity and quality of intelligence information he has on hand--will usually be a source of uncertainty, and hence of risk. Between the two extremes are uncertainties that are caused by both mechanisms.

To perform the complete process of risk assessment for a particular problem, the following tasks need to be carried out (see, for example, Rowe [1981]):

1) Risk identification, which involves identification of the nature, types, and sources of risks and uncertainties. In general, the major types of risks are financial, health-related, environmental, and technical (e.g., performance and supportability). The end products of this task are a complete description of risky events and elements of major concern along with their causative factors and mechanism.

2) Risk quantification, which entails formulating appropriate measures of risk and estimating the likelihood (probability) of occurrence of all consequences associated with risky events as well as the magnitude of such consequences.

3) Risk evaluation, which includes selection of an evaluation procedure (e.g., optimizing expected value, trade-off analysis) and analysis of various possible impacts of risky events.

4) Risk acceptance and aversion, which requires decision making regarding both an acceptable level of risk, and its equitable distribution. This phase of risk assessment also involves the development of risk control (i.e., measures to reduce or prevent

risk).

5)Risk management, which involves the formulation of policies, the development of risk contol options (i.e., methods to reduce or prevent risk), and execution of such policy options.

2.2. What are Available

There are a number of tools which have been developed to perform one or more tasks in the overall risk assessment and management process. These tools are indeed diverse in nature, emphasis, purpose, and degree of comprehensiveness and sophistication. Appendix B reviews a large collection of these tools based on several criteria. It is evident from the review that no single tool can adequately support all tasks that need to be done in the overall process of risk assessment and management. Nor can any one method claim to be a general purpose procedure that can deal with all types of risk (financial, health, environmental and technical) and in all types of risky situations. For example, work breakdown structure (WBS) should be a very useful device for identifying risky elements associated with costs. By itself however, it is not set up for risk evaluation purposes. Cost-benefit analysis, on the other hand, is an evaluation tool used to appraise various alternatives based on monetary measures. It is not suitable for risk identification purposes. As another example, consider the well-known multiattribute utility theory approach. Such a method may be an appropriate risk evaluation tool for a class of problems with moderate-to-high frequency of risk and moderate-to-low damage. However, they may fail to capture the possible devastating effects of the low-frequency, high-damage characteristics typical in extreme events. Here, as a typical expected-value approach, extreme events with a low probability of occurrence are given the same proportional weight and importance (in the multiobjective commensurate process) regardless of their potential catastrophic and irreversible impact. Yet it is a commonly acknowledge fact that the outcome of a catastrophic accident that may cause 10,000 deaths with a low frequency of 10^{-5} is neither perceived nor accepted to be in the same category of more common accidents that occur with a much higher frequency of, say, 10^{-1}, but may cause the death of one person each time.

Because of the diversity of risk problems that may arise and of the tasks that need to be done, a general purpose method, even if it can be developed, would be almost without content and, thus, will most likely be useless. What is needed is therefore an ensemble of tools that collectively span the whole spectrum of risk assessment and management tasks for a particular problem encountered.

In the WSA problem, typical types of risk emphasized are financial risks (cost overrun, budget cuts, schedule slippage, etc) and technical risks (e.g., substandard performance, supportability, etc.). A possible collection of tools that may be useful for developing a comprehensive WSA risk assessment and management system will be identified subsequently.

2.3. What is Needed: An Integrated Methodological Framework

Weapon system development and acquisition, as a project, normally evolves through various phases in the time dimension to complete its life cycle. These phases include project initiation, conceptual exploration, demonstration and validation, full-scale development, production and deployment, and retirement. Each phase consists of many interrelated activities and tasks to be performed, and a large number of interconnected decisions to be made in an environment filled with different levels of uncertainties. The program manager has the responsibility of making many of these critical decisions and of managing the project to ensure efficient and effective progress toward completion.

To cope with the inherent complexity and multitide of uncertainties, there is clearly a need for an integrated and comprehensive decision aid that will allow the program manager to make more informed decisions in a timely and efficient manner. Such a decision aid should i) provide the program manager a well-balanced picture of the project, ii) allow the program manager to access various data bases quickly and conveniently and iii) furnish an ample selection of decision/risk analysis tools that collectively cover a wide variety of anticipated decision and risk assessment situations. In response to such a need, we propose the development and use of a decision support system (DSS). The general philosophy and concept of DSS as well as its specific content suitable for decision making, and risk assessment and management in weapon system acquisition are dicussed in the next section.

Since we perceive weapon system acquisition as a project and the concerns of the program manager are planning, management and control of the project, network-based methodologies appear to be natural and logical candidates to choose from.

Cursory inspection of a typical weapon system acquisition project reveals that, despite its appearance, the program structure is far from being rigid. The program is marked with considerable uncertainties. First, it contains a number of decision points whose outcomes cannot be taken for granted. Activities succeeding these decision points which operate under the assumption of getting favorable decision outcomes in the present program plan, may need a back-up plan should a decision outcome be otherwise. Some activities also have a probability of not being performed in the present format due to the likelihood of unforeseen circumstances.

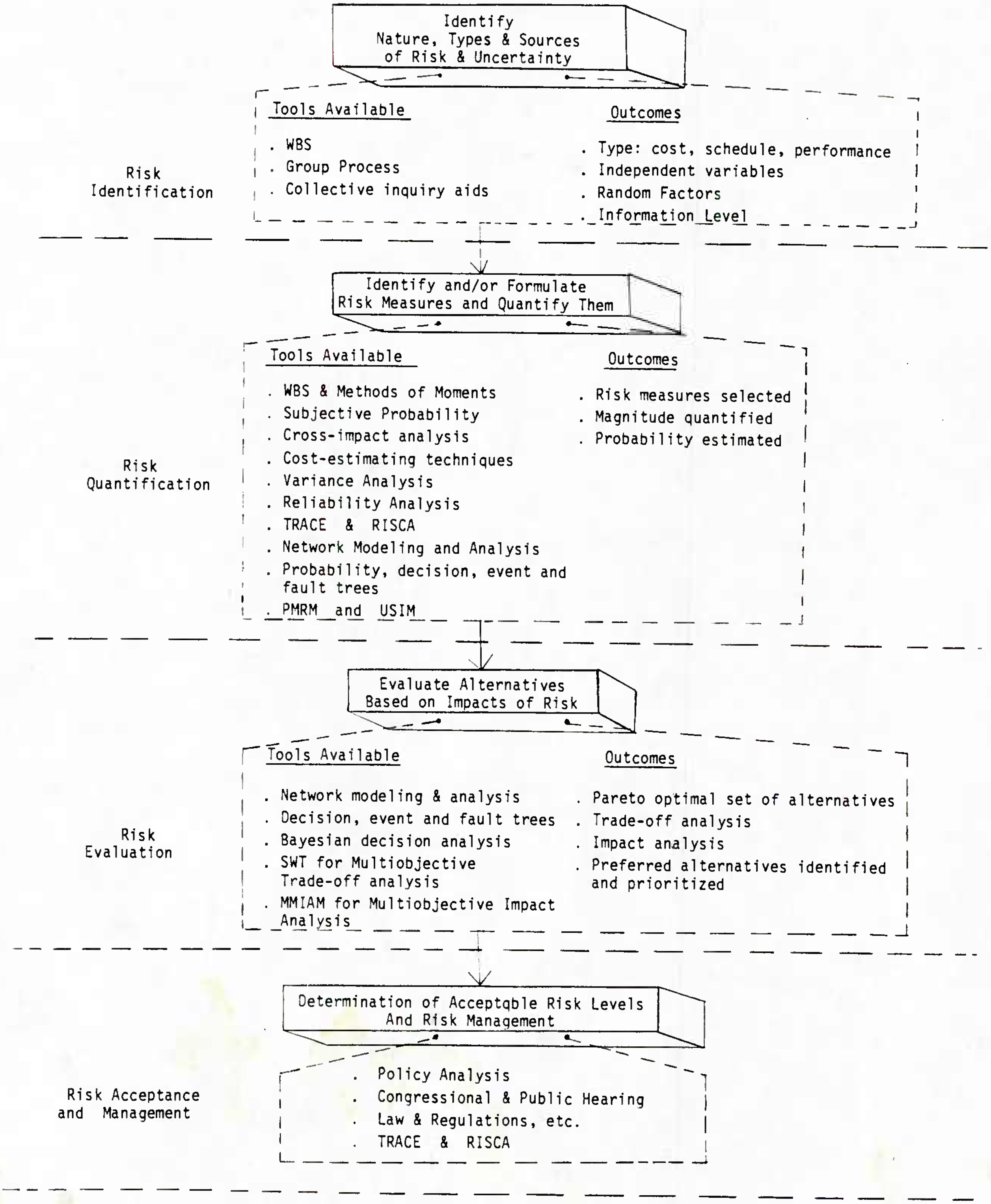
This may necessitate consideration of alternative activities and strategies. Network-based techniques that can handle less rigid structure thus appear to be quite appropriate. Of these, GERT and VERT stand out as they facilitate formal and comprehensive quantitative risk assessment in terms of project time, cost and performance. SCERT, on the other hand, furnishes opportunities to deal with risk aspects associated with other factors, but mostly in a qualitative and less formal fashion. Moreover, SCERT is still in a developmental stage, although preliminary versions have been successfully applied to some large engineering problems.

The network-based techniques just mentioned mostly rely on simulation to generate the magnitudes and associated statistics about project completion data, project cost and performance. Except for SCERT, no specific mechanism is provided to combine this information in an appropriate way to aid the decision maker in making the final decisions. This is where we envision such techniques as decision analysis and multiobjective risk trade-off (discussed in Appendix B) playing a significant role. Outputs from network-based procedures such as GERT or VERT can be used as a basis for formulating appropriate risk measures which can, in turn, be used for multiobjective risk trade-off analysis in the same spirit as discussed in Appendix B.

With this preliminary impression of the weapon system acquisition, we envision an interactive decision support package combining an appropriate tool in the network class with one of the multiobjective risk trade-off analysis tools (or decision analysis) as a potentially promising system to satisfy the program office needs. Such a package should be developed so that it i) is user-friendly, ii) has great flexibility and the capability of handling a wide range of decision situations with respect to the weapon system acquisition, iii) has a quick turn-around time so that an emergency decision can be made, iv) is built on a modularity concept, where components of the system can be modified or replaced without the need to change the entire system, v) has the capability of handling the hierarchical decision-making structure of the program office, and vi) has the capability of quantifying the impacts of ecisions made at time t = k on the system at a later time, say t = k + n. The MMIAM, for example, is a method well-suited to this purpose.

Although the packaging will be done in the form of a DSS, Figure 2.1 shows interrelationships of the DSS components along the large dimension (e.g., logical steps).

Figure 2.1 A Procedural Framework for WSA Risk Assessment and Management


Identify Nature, Types & Sources of Risk & Uncertainty
Tools Available
. WBS
. Group Process
. Collective inquiry aids
Outcomes
. Type: cost, schedule, performance
. Independent variables
. Random Factors
. Information Level
Risk Identification
Identify and/or Formulate Risk Measures and Quantify Them
Tools Available
. WBS & Methods of Moments
. Subjective Probability
. Cross-impact analysis
. Cost-estimating techniques
. Variance Analysis
. Reliability Analysis
. TRACE & RISCA
. Network Modeling and Analysis
. Probability, decision, event and fault trees
. PMRM and USIM
Outcomes
. Risk measures selected
. Magnitude quantified
. Probability estimated
Risk Quantification
Evaluate Alternatives Based on Impacts of Risk
Tools Available
. Network modeling & analysis
. Decision, event and fault trees
. Bayesian decision analysis
. SWT for Multiobjective Trade-off analysis
. MMIAM for Multiobjective Impact Analysis
Outcomes
. Pareto optimal set of alternatives
. Trade-off analysis
. Impact analysis
. Preferred alternatives identified and prioritized
Risk Evaluation
Determination of Acceptqble Risk Levels And Risk Management
. Policy Analysis
. Congressional & Public Hearing
. Law & Regulations, etc.
. TRACE & RISCA
Risk Acceptance and Management

3. A Decision Support System for Weapon System Acquisition Risk Management

In the previous section, we identified a decision support system (DSS) as a logical choice for packaging various risk analysis modules into one integrated system. Since it will play such a central role, we will now describe the underlying philosophy and basic structure of a typical DSS. Specific components of the WSA risk-assesment DSS that we envision will then follow.

3.1 What is a DSS?

A decision support system (DSS) is an intelligent interactive man-machine decision aid. It helps decision makers make more informed decisions faster by allowing them i) to get quickly access to multiple data bases, and ii) to perform sophisticated data processing and system analysis techniques with great speed, accuracy, and efficiency. The DSS can also be tailored to the particular skills and needs of the user. This quality of a DSS is particulary useful for the computer novice or people who have little or no background concerning the technical nature of the models or analyses utilized (e.g., network modeling and risk analysis) but would greatly benefit from the information such models and analyses could provide.

The DSS proposed here is envisioned as a tool to help improve strategic, managerial, and operational decision making throughout the weapon system acquisition process. This DSS will be tailored to all phases of the acquisiton process and will possess the following attributes:

(i) ease of use--does not require expertise in the area of program scheduling or risk assessment

(ii) produces output usable by the program manager

(iii) is tailored specifically for the Department of Defense (DOD) weapon system acquisition process

(iv) integrates network creation, schedule management, risk assessment, and trade-off and impact analyses

(v) is designed for use on microcomputers--i.e.. the IBM-XT

A prototype DSS with the above attributes has been developed in this project. Its limited scope for the production and deployment phase can be extended, however, to a DSS with a broader range of capabilities and wider applicability to encompass all phases of the weapon system acquisition process.

3.2 Why a Decision Support System?

Making decisions about large and complex problems is a difficult task. Until recently, decisions concerning large-scale problems have mainly been based on intuition coupled with experience, ingenuity, and value judgment (possibly aided by verbal, but logical, reasoning), simple calculations, and simple graphic devices, such as graphs and charts. However, in today's society, as more and more demands are placed upon our normally limited resources (from the combined effects of new societal needs and the rapid advance of technology), it becomes obvious that more efficient and effective decision-making approaches are needed. Two basic premises underline modern-day decision making:

(1) The decision maker's wisdom and value judgment can never be replaced by any completely mechanistic process.

(2) The decision maker will generally make a better decision if he/she is well informed about relevant aspects of the systems within which he/she is making decisions.

The first premise implies that whatever decision tools are employed and whatever their sophistication, the decision maker(s) must still form an integral part of the decision-making process--at least in the final stage of the process. The second premise, on the other hand, implies that before an important decision is made, a system should be systematically analyzed in sufficient detail that relevant results can be presented to the decision maker. As the human mind has a limited capacity to process and comprehend large amounts of information at any one time, careful selection of results is needed to avoid overwhelming the decision maker with too much information. Also, great care should be taken in the methods of presenting the information. Furthermore, the credibility and accuracy of all information should be constantly checked to avoid possible ill-fated decisions.

To satisfy the above requirements, a good decision-making procedure for large and complex problems should possess the following desirable characteristics:

1) a good data base--to ensure credibility and accuracy
2) a fast, efficient, and comprehensive process of transforming data into intelligent information--to ensure that various relevant factors are properly taken into account
3) an effective mechanism for interacting with the decision maker through a decision support system.

A DSS furnishes a means of achieving such goals while providing great flexibility in utilizing data bases and models in a convenient and easy-to-use format. In the context of the acquisition process, a well-designed DSS would aid the program manager with all of the decisions he must make throughout a program's duration. In particular, during the early phases of the acquisition process (i.e., concept exploration and demonstration and validation), program or process selection decisions are based on data at the primitive level (data-focus). During the final phases of the acquisition process, the operating, planning, and management decisions are based on more intelligent information, which is obtained by passing primitive data through some analytical models (e.g., network models, trade-off analyses, risk analyses, etc.). A properly designed DSS would allow for this flexible usage of various data bases and models according to specific needs, with fast turn-around time, thus providing a convenient mechanism for mixing the value elements and factual elements to help the PM make decisions in the most effective way.

3.3 Components of a Decision Support System

Advances in DSSs have increased rapidly with the development of more powerful and sophisticated mini- and micro-computers. These new computers have allowed for improved interaction between the system and user and thus providing greater power, flexibility, and ease of use of the DSS. From the DSS user's point of view, these interaction capabilities between the system and the user (i.e., the dialog component) encompass the entire system. According to Bennett [1977] the dialog "experience" can be divided into three parts:

(i) The action language--what the user "can do" in communicating with the system. It includes such options as the keyboard, touch panels, joy stick, voice command, mouse functions, and any other inputting devices.

(ii) The display (or presentation) language--what the user "sees." The display language includes options such as type of character or line printer, display screen, graphics, color capabilities, plotter, audio capability, and any other outputting processes or devices.

(iii) The knowledge base--what the user "must know." The knowledge base consists of all the things that the user needs to bring with him to a session with the system in order to use the DSS effectively.

Although the user only works with the dialog component (i.e., action language, display language, and knowledge base), it is obvious that there is more to a DSS then just this. A decision support system is a combination of (i) optimization, simulation, and heuristic models (the model base), (ii) an extensive data base, and (iii) an information management system which handles the dialog between user, models, and data. Figure 3.1 summarizes the relationships between these three components.

The model base can be considered to be the brains of the system. It allows the user to retrieve, manipulate and evaluate the information available to him through the data base. The data base not only contains numerical information but can also contain functional relationships between data items and other descriptive information about the problem at hand. The capabilities of the management system include model base management (MBM), data base management (DBM), and dialog generation and management (DGM). The DGM system (DGMS) provides the interactive interface between the user and the system, which is what makes the DSS such a powerful tool in decision making.

3.4 DSS as a Packaging Tool for Risk Assesment and Management in WSA

In Section 1 of this report, we noted that a good risk assessment and management decision aid should address the specific needs of the program manager and each of his directorates and that the decision aid should also be tailored to the quality and quantity of information available in each of the acquisition phases. In order to aid the program manager and the directorates in making program decisions, the decision aid should have the following capabilities (adapted from Ingalls, 1984b).

1) Network generation capability--It should have an easy-to-use process for network generation which requires a minimum of user inputs. The network model should allow for easy tiering and interaction of subnetworks--"hierarchical networking." The networks developed by the lower levels (i.e., the functional specialists or directorates) should represent activities controlled at the top-level of the network (i.e., by the program manager).
2) Schedule management capability--It should be able to identify the critical path, allow the user to update the program as it proceeds, and allow the user to easily perform "What if?" exercizes by inputting changes and receiving feedback on schedule impacts.
3) Risk identification capability--It should provide a systematic procedure (possibly in the form of a work breakdown structure) that will identify risks throughout the acquisition process. Each directorate should have its own version of this, and the decision aid should be able to compress the information from these individual work breakdowns into a form useful to the program manager.
4) Risk quantification capability--It should provide easy-to-use procedures for quantifying risks. A number of different procedures should be available (e.g., subjective probability tools, cross-impact analysis, cost estimating techniques, reliability analysis, etc.), each tailored to the quality and quantity of the available information.
5) Risk evaluation capability--It should allow the user to easily

input uncertainty parameters into the network and estimate cost and schedule risks for use by the program manager and each of his directorates. It should also allow for analysis of system performance risks and program failure risks through procedures such as fault tree analysis, event tree analysis, Bayesian decision analysis and an enhanced form of network analysis.

6) Risk management capability--It should help the decision maker select an appropriate "risky" plan of action through procedures such as multiple-objective optimization (e.g., the surrogate worth trade-off method, Haimes et al. 1975), trade-off analysis, and impact analysis (such as the multiple-objective multistage impact analysis method of Gomide and Haimes, 1984).

A large number of tools and methodologies in the areas of network creation, schedule management, risk assessment, and risk management are curently available. These are summarized in Section 2 of this report. However, in their current form, each of these tools and methodologies suffers from a number of deficiencies:

1) difficult to use--designed for use by "experts," or input requirements are prohibitive
2) output not suitable for use by PO--must be translated by an "expert" before it is in a form that can be understood
3) designed for a different application--terminology and parameters are inappropriate for weapon system acquisition risk management
4) do not intgrate the six basic capabilities previously identified
5) cannot be used on a microcomputer--designed for use on a mainframe computer.

A well-designed decision support system would correct each of these deficiencies. In particular, by modifying and tailoring some of the currently available programs (e.g., network models, SWT, PMRM, etc.) to acquisition risk management needs, improving their user interaction capabilities, and developing some additional risk tools (e.g., a modified work breakdown structure), it would be possible to design a decision support system that will work on a microcomputer with hard disk storage (e.g., IBM-XT).

3.5. Examination of the Risk Assessment and Management DSS

The list of six desired capabilities for a risk assessment and management decision support system given in Section 3.4 allows us to identify a number of useful classes of tools to be included in the DSS:

1) extension of work breakdown structure and method of moments
2) subjective probability tools
3) cross-impact analysis
4) cost estimation techniques
5 heuristics, variance methods, charts and graphs
6) reliability analysis
7) network modeling and network analysis
8) analysis using the probability tree, decision tree, fault tree and event tree
9) Bayesian decision analysis
10) multiple-objective optimization,, trade-off analysis and impact analysis.

From the framework developed in Section 1 of this report, we identified the phases in which each of these tools would probably be of the most use and by whom. Tables 3.1 and 3.2 summarize these results and provide the guielines for designing the DSS model base for the program office and each of its directorates. The model base management system would select the appropriate tools and methodologies and tailor them to the needs and specifications of each of the directorates and the program manager during each of the phases of the acquisition program.

The data base for the DSS would be composed of the hierarchical networks, work breakdowns, and tree diagrams for each of the directorates. The data base management system would coordinate the information sharing between the directorates' and the program manager's data and would provide the means to accomplish data consolidation for the higher levels in he hierarchies (e.g., the program manager or the head of he directorate if a directoate needs to be divided into subsystems for easier handling).

The dialog management system would provide all of the "nice" features of a good DSS, including:

1) color graphics capability
2) use of the "mouse" for input/output
3) hard copies for all graphs, charts, and diagrams
4) progress report and bar chart generation with user interaction
5) intelligent screen layout for data input
6) menu-driven subroutines for each of the directorates and the program manager
7) help messages, error alerts, etc.

Each of the described components of the DSS for risk assessment and management (See Figure 3.1) would be available on a microcomputer with hard disk capability (e.g., IBM-XT) and written in a common high-order language (e.g., Pascal or FORTRAN). A system with all of the capabilities we have mentioned should be of great use throughout a weapon system acquisition program.

In order to demonstrate a number of features that we envision for the larger DSS, we developed a limited prototpye (which could be utilized as a module in the larger DSS) for use by the program manager during phases III and IV of the acquisition process. A detailed description of this model follows.

	1 & 2	2	2	2	2	2	2 -3	2-3	3	3-4	
Tools and Methodologies / Directorate		Extension of work breakdown structure and method of moments	Subjective probability tools	Cross estimation techniques	Heuristics variance methods charts graphs	Reliability analysis	Network modeling Network analysis	Probability, decision, fault and event trees	Bayesian decision analysis	Single and multiple objective optimization, trade-off analysis, and impact analysis (MMIAM)	Remarks
Program Control	X	X	X	X	X		X	X	X	X	Identifies, quantifies, evaluates and manages program risks
Contracting				X						X	Uses risk considerations in developing contract terms
Integrated Logistics Support	X	X	X	X	X	X	X	X	X	X	Identifies, quantifies, evaluates and manages logistics risks
Manufacturing Management	X		X	X	X		X	X	X	X	Identifies, quantifies, evaluates and manages production and manufacturing risks
Engineering Management	X	X	X	X	X	X	X	X	X	X	Identifies, quantifies, evaluates and manages technical developmental risks
Test and Evaluation	X	X	X	X		X	X	X	X		Identifies, quantifies and evaluates all risks related to system performance
Configuration Management	X						X			X	Uses risk considerations in developing configuration designs
Computer Resources Management	X	X	X	X	X	X	X	X	X	X	Identifies, quantifies, evaluates and manages all computer risks

Table 3.1 Usage Breakdown of Risk Assessment and Management Tools within Each Directorate

Process	1 & 2	2	2	2	2	2	2 - 3	2 - 3	3	3 - 4	Remarks:
Tools and Methodologies / Phase in Acquisition Program	Extension of work breakdown structure and method of moments	Subjective probability tools	Cross impact analysis	Cost estimation techniques	Heuristics variance methods charts graphs	Reliability analysis	Network modeling and network analysis	Probability, decision, fault and event trees	Bayesian decision analysis	Single and multiple objective optimization, trade-off analysis and impact analysis (MMIAM)	Risk-related activities
Phase 1 Concept Exploration	M - H	H	H	M - H	M - H	L	L	M - H	M	L	Identify and evaluate risks and impacts of system to: i) evaluate proposed concepts ii) define technical requirements
Phase 2 Demonstration and Validation	H	M	H	H	H	M - H	M	M - H	H	M - H	Identify and evaluate technical, cost, supportability and schedule risks to: i) evaluate proposed systems ii) define system specifications
Phase 3 Full Scale Development	H	L	M	M	H	H	H	H	M - H	H	Identify and reduce all acquisition risks Plan and control system development while reducing technical, cost, schedule and supportability risk.
Phase 4 Production and Deployment	L	L	L	M	M	L	H	H	M	L	Plan and control production and deployment to reduce risks. Evaluate technical and cost risks when engineering changes are required. Evaluate program risk when acquiring follow-on quantities.

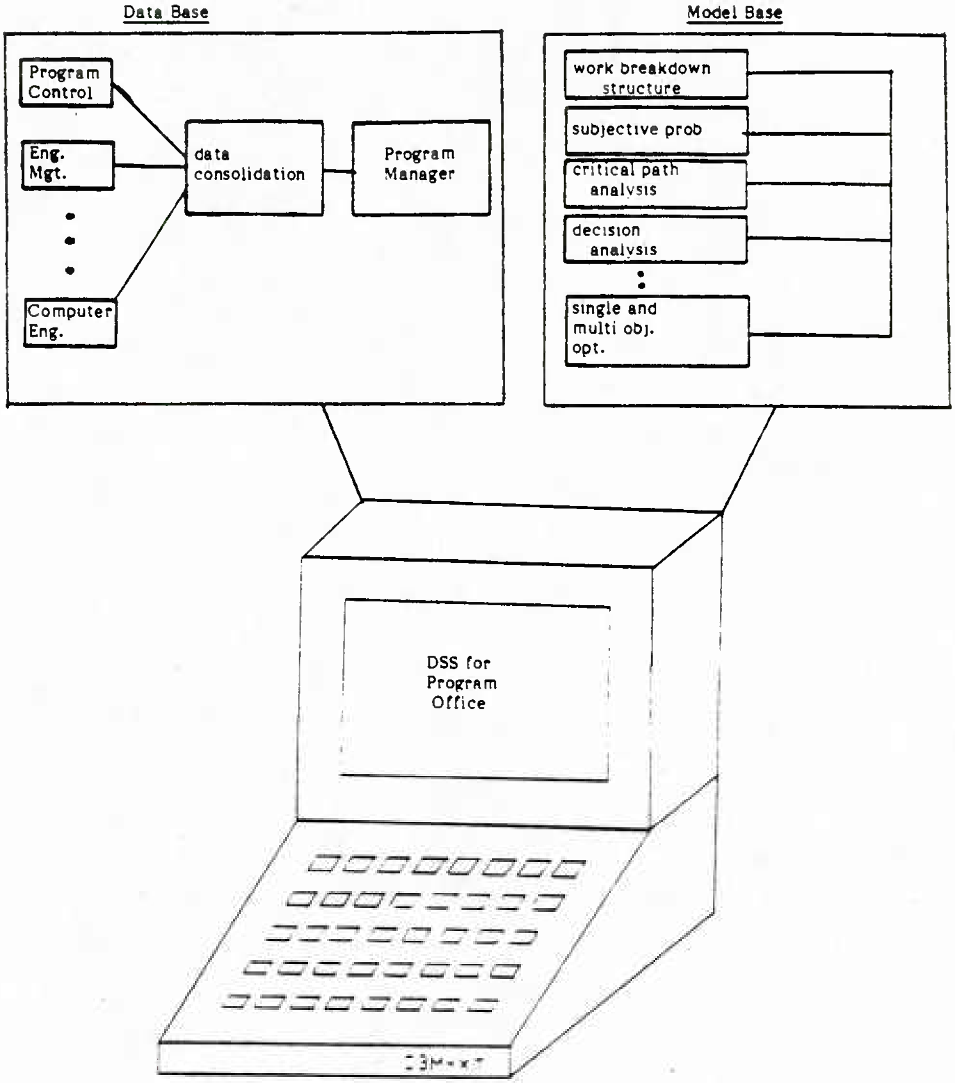
Table 3.2 Usage Breakdown and Classification of Tools for Risk Assessment and Management within the Program Office.

Usage Breakdown

H - high amount of expected usage
M-H - moderate to high usage depending on data availability
M - moderate usage
L - little to no usage

Classification of Tools by Stage:

1 - risk identification
2 - risk quantification
3 - risk evaluation
4 - risk management


Data Base
Program Control
Eng. Mgt.
Computer Eng.
data consolidation
Program Manager
Model Base
work breakdown structure
subjective prob
critical path analysis
decision analysis
single and multi obj. opt.
DSS for Program Office

Data Base Mgt. System	Model Base Mgt. System
Provides appropriate coordination of risk information flow between the directorates and program manager	Provides separate routines tailored to each directorates' for each of the phases

Dialog Management System

Provides "user friendly" input/output features

- mouse
- color graphics

Figure 3.1.

The "Envisioned" DSS for the Entire Weapon System Aquisition Process

4. A Prototpye DSS for Project Risk Management

A common string that runs through all weapon systems development and procurement programs is the need for project risk management. Project risk management provides a program manager with an integrated package of techniques that he can use in dealing with any unexpected changes in his program plan. These techniques enable the program manager to develop a revised program plan by adjusting aspects of the scheduling and funding of the full-scale development, production, and deployment phases of the program. Such a plan must be able to meet certain constraints and objectives in an optimal manner. These tools also help to quantify the elements of risk associated with a program and present them in a clear and logical manner, improving the program manager's ability to deal with risk as it arises during a program. By integrating these techniques into the framework of a microcomputer-based decision support system (DSS), the program manager is provided with a user friendly, interactive mode for using the Project Risk-Management Module. Now that the requirements of such a system have been touched upon, it is time to identify the problem that the program manager faces.

4.1 Problems and Risks in Program Planning and Management

The program manager (PM) is ultimately responsible for all technical and business decisions associated with his program. Although the PM usually assigns functional specialists to deal with specific tasks, it is still his responsibility to integrate and coordinate their efforts. Some basic needs that are essential to successful program management include (Huffman [1981]):

- a teamwork relationship within the program office
- an in-depth understanding of all the program objectives

- program plans which are well prepared and highly visible
- accurate and timely information concerning actual progress or planned work
- notation and evaluation whenever the plan makes a deviation from what actually happens
- determination and implementation of corrective action based upon trade-off judgements
- follow-up on corrective action
- friends, not enemies, for the program

These needs along with other requirements will be addressed later in terms of the Project Risk-Management Module.

A development program can be characterized by a combination of interdependent activities involving production as well as research and development. Some of the general activities present in most weapon systems programs include (from Ingalls, 1984a) hardware development, software development, software validation and verification, logistics planning, producibility engineering planning (PEP), facility start-up, long-lead material acquisition, systems production, initial spares production, training equipment production, and technical documentation. Each of these activities have specific difficulties, but some general aspects can be summarized in terms of scheduling and funding uncertainties. These uncertainties introduce risk into the procurement process. Other complications can arise because the program must be accomplished within the limited amount of funds available and because certain of its activities must be done in a prespecified order. These requirements place constraints on the program and impede the attainment of certain predetermined objectives.

When a weapon systems program is in the planning and proposal phase of development, planners must set some schedule and cost estimates for each activity involved with the program. However, while these plans are being developed, trade-offs exist between the need to make the program appealing and the desire to cover all possible events. In other words, planners would like to inflate their estimates in order to ensure that the program will come in on time and within the budget, but the added funding and time requirements may jeopardize the program's viability. Thus, the proposal that is submitted for approval is usually a compilation of most likely schedule and funding estimates. Once a program has been approved and a full-scale development has begun, many risk factors can affect the ability of the program to meet its constraint levels and objectives. They include risk of immature design, software risk, changes in the production rate, and inadequacies in facility start-up funds, long-lead funds, logistics support and system availability. A summary (from Ingalls, 1984a) of the causes of these factors and their effects on a program can be found in Appendix C.

4.2 OBJECTIVES AND TOOLS IN PROJECT PLANNING

Now that the problems facing a PM have been specified, it is time to take a look at the management objectives. First, we must realize that over the course of a program there are many specific objectives related to individual activities and time frames. However, they can be quantified in terms of three general objectives which can be minimized. First, the risk of cost overruns measured in dollars per unit should be minimized. Second, the risk of schedule delays measured in "shortages" should be minimized. Finally, the risk of element failure measured in performance levels of the system should be minimized. The importance of these objectives is realized when a program is being reviewed for further funding. The Congress, as well as the media, view uncontrolled cost growth, schedule slippage, and low performance levels as signs of program failure. This may lead to termination of the program, especially in the case of controversial programs. Therefore, in order for a program to be successful, the PM must be able to keep the objectives under control.

Although the structure of a program plan is usually inflexible, there are certain procedures that the PM can use to help control his objective values. These procedures include better estimation and management methods, expansion of constraints, manipulation of decision variables, and trade-off analysis. Some of these tools will rarely be valuable to most programs. For instance, there will be a limit on better estimation and management methods available to a well-planned program. Also, constraint expansion involves the increase of available funds, which is considered to be the "last resort" approach to solving problems. This leaves the manipulation of variables and trade-off analysis as the most promising tools for project risk management.

Manipulation of variables involves certain key decision variables that deal with the budgeting and scheduling of individual activities. One of these tools involves stretching (or compressing) the cost of an activity over time. Essentially, this action will determine the level of intensity of an activity and directly affect the program funding requirements and completion time. Another tool uses scheduling variables and involves the starting dates of the activities. By postponing (or moving ahead) the starting dates of certain activities, the PM has the ability to move certain funding requirements into different time periods. Again, this action will help the PM meet his constraint levels at the cost of some schedule slippage. Up to this point, there has been no mention of the performance objective. However, there is one tool that affects the performance of a program and it involves the production rate. By changing the production rate, the PM is able to meet funding constraints; however, this change can affect the unit cost of each item as well as the ability of the program to meet production levels. For some programs, failure to meet production levels may affect the national defense and degrade performance levels.

Methodologies for trade-off analysis allow decision makers involved with a multiple-criteria decision-making problem to arrive at a preferred solution. The PM may be able to define several feasible solutions with several sets of objective values. There will also be trade-offs associated with each set of objective values that describe how a change in one objective affects the other objectives. The use of the surrogate worth trade-off (SWT) method along with this information helps to quantify the decision maker's preferences. The results obtained from this analysis will be feasible, optimal (if enough functional information is known to allow for the use of optimization techniques), and preferred, in the eyes of the PM.

4.3 CONSTRAINTS AND COMPLICATIONS IN PROGRAM PLANNING

The previous set of project risk-management tools may have seemed to be all-powerful, but some factors exist that limit their effectiveness. These limiting factors involve constraints and uncertainties. First of all, four major constraints exist in most procurement problems: the amount of funds available to the program per year, the total amount of funds allocated to each activity, certain production schedules that must be met, and precedence relationships that may exist between activities (i.e., certain activities cannot start until others are finished). The budget and production constraints are usually set when a program has been approved. However, the DOD is apt to change them over the course of the program.

The scheduling constraints come about because of the dependence that exists between certain activities. Furthermore, the presence of uncertain system parameters introduces risk into the procurement process. These risks occur because random variables are found in the process. In general, these random variables represent the duration of activities, the cost of activities, and the quality or performance of activities along with future budget uncertainties. Specifically, they can involve software errors, production rates, maintainability, usability, and supportability. The quantification of these random distributions in terms of variables and parameters of the program is an important part in the development of a DSS. The accuracy with which these and other functional relationships are developed will have a direct impact on the acceptance and reliability of the results generated during the decision process. The handling of these constraints and risks will be detailed in the description of our prototype DSS.

4.4 A DSS for PM's Problems

The PM's need for a DSS should be evident. His responsibilities have become far too extensive and important to be neglected in our approach. The main purpose of the program office is to collect and analyze all information relevant to the program's management and completion. The DSS we have developed for this purpose addresses many of the needs and requirements of the PM. Some of them include

- the ability to handle risk issues
- the ability to deal with multiple objectives
- the ability to optimize a program plan
- the ability to provide high visibility of the program plans
- identification of areas of concern and impending trouble

- ease of use by a nontechnical experts.

Figure 4.1 presents the specific components we have used in our analysis.

As described earlier, a DSS is comprised of, a data base, a model base, and a user interface. The data base should include objectives, constraints, time-cost relationships, and variable values. Functional relationships in a generic form should be present in the data base and, after specific problem identification, the specific parameters can be input into the generic forms during network model development. Our model base includes the program evaluation and review technique (PERT) for network analysis, the PMRM for quantifying risk, an optimization package for generating Pareto optimal solutions, the SWT method for determining a preferred solution, and the MMIAM for impact analysis. A detailed description of each of these components can be found in Appendix D. The project risk-management module in our system is in effect a combination of PERT and the PMRM used to deal with development and production activities.

The interfacing techniques that are used in our prototype take advantage of the latest technologies. The use of the "mouse" and intelligent screen layouts makes the DSS very user-friendly. After initial network modeling, the input routines require little or no specialized knowledge of network analysis and only basic knowledge of the program activities. The output generated during network and risk analysis is presented as one screen in the form of a bar chart of program activities with attached risk and objective function values. There are also additional menues that can be accessed in order to look at more detailed risk or trade-off information.

4.5 EXAMPLE PROBLEM

In order to develop our prototype, we had to identify a specific problem of the sort that the PM must often face. We opted for a class exercise from a risk management workshop provided to us by Dr. Ted Ingalls of the Defense Systems Management College at Fort Belvoir, Virginia. The problem statement follows.

PROBLEM (Refer to Figure 4.2)

Your service is undergoing a budget cut. Because you have had some development test problems (although you believe you have now made the necessary fixes) and because you are not yet "locked-into" a production program, your program is a prime candidate for being cut. You must identify the impacts of giving up $50M in FY 86 (then-year $). The funds may come from R & D or production. You also must provide profile that will give up $500M over the next 5 years of the POM. At 1330 today, you must make a presentation that provides the following:

(1) your revised program plan (schedule and budget) identifying where the cuts will be taken

(2) the risks associated with each element cut, along with the risk-handling techniques you intend to use for each element to mitigate these risks

SOLUTION APPROACH

The limited time horizon and budget of this project necessarily constrained the scope of the developed prototype DSS. For instance, only one risk factor-- change in production rate--is included in the analysis. Also, because of a lack of information, we were not able to develop suitable time-cost relationships to allow us to use optimization and the SWT method in our prototype. Currently, it relies on the PM's expertise to optimize the solution. However, the DSS will help to identify feasible solutions with which the PM can work. Specifically, it is aimed at providing a revised program plan, due to a budget cut, that takes risks into account. After the data base has been expanded and functional relationships developed, the DSS will be able to identify Pareto optimal solutions on its own. Although the data base is limited, the contents and structure of the model base and interfacing methods provide our prototype with some interesting and novel approaches to solving the project risk-management problem.

4.6 Analysis of Components

This section will analyze the specific methods, techniques and functions that were actually implemented in our prototype DSS to solve the example problem. The prototype DSS does not include all of the pertinent components, and the functional relationships are somewhat simplistic. However, it represents the capabilities and efficacies of such a decision support system.

4.6.1 Network Analysis

The PERT component constitutes the foundation upon which the entire prototype is, built. The capabilities of PERT allow the organization, management, and quantification of information needed in project risk-management.

During the development of this component, we have made some adaptations that distinguish our approach from standard packages. These adaptations and general assumptions will be discussed in terms of the following basic steps:

- the input of schedule and cost information
- network modeling
- critical path analysis
- distribution of expected completion time

The first criterion that PERT must satisfy is the ability to deal with the uncertainties involved with development and production activities. PERT handles these uncertainties by assuming a beta distribution of each activity's duration time. In order to develop these distributions, PERT requires that three time estimates be obtained. The user must provide for each activity estimates of

a = the optimistic time--execution goes extremely well

b = the pessimistic time--everything goes badly

m = the most likely time--execution goes as expected

We also require that planned budgets must be given for each activity in our analysis, and they will be specified at the same time as a, b, and m. The values we use in our specific example can be found in Table 4.1.

The first adaptation we made to the PERT procedure may significantly improve the use of network analysis techniques. By using a different method of sorting, the computer is able to generate the network model from a set of simple precedence relationships. This makes our system valuable to a user with little knowledge of networking techniques. We have set the following precedences for our example,

HARD < PEP, LLFD, FCSU

SOFT < PEP, SWVV

PEP < INSP, TNEQ, TDOC

DTOT < INSP, TNEQ, TDOC

This is a significant advantage because the user does not have to develop a network diagram: the computer can generate it. The diagram developed for our example can be found in Figure 4.3.

The next step in the network analysis procedure is the calculation of a critical path. The critical path modeling (CPM) procedure identifies the sequence of connected activities that require the most time to complete. A detailed description of this process can be found in the appendix. This path represents the activities that the PM must emphasize. We have also developed a method for accounting for the variance present in each activity when specifiying the critical path. This method produces a criticality index for each possible path a program could follow. The PM can use the indexes to identify other activities that may not be on the critical path but deserve to be watched carefully. The results for our example can be found in Table 4.2.

The final task which the PERT component accomplishes is the quantification of a probability density function for program completion time. The procedure for the development of this function is quite straightforward. The overall distribution is assumed to be normal, with a mean of μ and a standard deviation of σ. The analytical probability density function for a normal distribution is

$$f_x(x) = (1/\sigma\sqrt{2\pi})e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

In order to quantify this function, we must first identify the mean program duration (μ) and its standard deviation (σ). These values can be determined from the activities in the critical path:

For our example

μ = 57.01 months

σ = 5.76 months

These values are then inserted into the probability density function, which is used along with the duration times and expected-value concepts in the PMRM to quantify the risks.

4.6.2 Functional Relationships

In assessing relationships for our example problem, we were able to quantify two objective functions:

$f_1(*)$ = cost overruns (unit cost)

$f_2(*)$ = schedule delays ("shortages")

We have already explained how PERT develops the distribution of $f_2(*)$, so we will now outline the process we used to develop the distribution of $f_1(*)$.

First, we identified the key variables that are involved with the unit cost as:

		Example Values	
x_1	= length of facility start-up activities	8	Months
x_2	= length of long-lead activities	7	
x_3	= length of PEP activities	10	
α	= production rate	100	
E	= contractor experience	5	Years
D	= Direct production funds per unit	1.91	Million dollars
F	= manufacturers fixed costs	100	

We then made the following assumptions:

1) The production rate (α) can be expressed as a random variable distributed normally with mean μ and standard deviation σ.

2) μ is the planned production rate and σ is a function of x_1, x_2, x_3, and E.

3) $\sigma(x_1, x_2, x_3, E) = 10/x_1 + 10/x_2 + 200/x_3 + 300/E$, So, for our example values, $\sigma = 16.68$.

4) The unit cost is inversely proportional to α. Therefore, we define

$$f_1(*) = 1.91 + F/\alpha$$

4.6.3 Partitioned Multiobjective Risk (PMRM) Analysis

The PMRM provides our DSS with the ability to quantify and represent risks in a logical and detailed manner. Although we only deal with one random variable here, the PMRM can be used for all the areas of risk present in the procurement problem. The general steps that are involved in the PMRM are (Asbeck and Haimes [1984]):

1) Find probability density functions.
2) Partition the probability axis to provide a fuller risk description.
3) Map the probability partitions onto the objective value axis.
4) Find conditional expectation values for each partition.
5) Generate functional relationships between conditional expectations and policy choices.
6) Use optimization and the SWT method to generate Pareto optimal solutions and a preferred solution.

In the development of our prototype we were not able to complete steps 5 and 6. However, steps 1 to 4 are discussed here in the context of both objective functions. Also, details on the entire procedure can be found in the appendix.

For our example problem we were able to apply the PMRM by using an analytical probability density function. As described in the previous sections, we used normal distributions for both functions. When more risk factors and random variables are included in the analysis, random generation and Monte Carlo simulation techniques must be used to develop probability density functions.

Partitioning of the probability axis is intended to provide the user with a more complete view of the distribution of risk. The partitions separate optimistic, pessimistic and middle-of-the-road values and represent them as additional objective values to be minimized. In general, if these ranges are bounded by $\mu \pm \sigma$, the optimistic and pessimistic ranges will each contain 15.9% of the values and the middle-of-the-road range will contain 68.2% of the values. In particular, the completion time ranges will be bounded as follows:

0 to $\mu - \sigma$ will contain the optimistic completion times;

$\mu - \sigma$ to $\mu + \sigma$ will contain the middle-of-the-road completion time;

$\mu + \sigma$ to ∞ will contain the pessimistic completion time;

where μ and σ are unique to the current schedule.

The final step in the PMRM procedure, for our purposes, is the calculation of the conditional expectations for each partition. First, we have to define the low, medium and high value partitions as D_1 , D_2 , and D_3. We now define the expected value within partition D as a conditional expectation

$$E[X/D_i] = \frac{\int_a^b xp(x)dx}{\int_a^b p(x)dx}$$

where a is the lower bound of D_i and b is the upper bound. The function p(x) is the probability density funtion and x represents the objective function values. The conditional expectations along with the overall expected value of each objective can now be presented to the decision maker for each alternative. The advantage the PMRM has over other risk assessment methods is its ability to represent the impacts that policies may have on the extreme and most probable cases along with the overall impact. The results of our analysis can be found in Figure 4.4.

4.7 Discussion of Use

The prototype DSS we have developed meets most of the requirements that were identified earlier. In particular, the system combines two very powerful elements, PERT and PMRM, to form the Project Risk Management Module. The capabilities that this module provides to the program office include

- the ability to handle risk
- the simplifiction of replanning and rescheduling
- high visibility of program plans
- identification of areas of concern
- comparison between alternatives

The most important aspect of our DSS, however, is the ease with which these complicated components may be used. The only technical requirement put on the user is the ability to identify schedule and cost estimates for each activity along with the activities that immediately follow one another.

A list of general steps that will summarize the use of our system include the following:

1) Enter schedule and cost estimates along with precedence relationships for each activity
2) Enter funding constraints for each of the next 5 years
3) Enter planned production rates for the years that involve production

The DSS will then develop a network model, define the criticality of possible critical paths, and quantify, partition and evaluate the objective functions for an initial program plan. The following information will be available onscsreen:

- a network model with the critical path highlighted
- the next five years of the current program plan, represented as a bar chart
- the current objective values, displayed along the border of the bar chart
- any yearly funding constraints that have been violated--these will flash at the bottom of the screen.

After examining the DSS-supplied information, the user will be in a position to proceed with the next steps:

4) Find the feasible plan. A "mouse" will be available to carry out the following options:
    - move an activity
    - stretch an activity
    - change a production rate
    - change a constraint
5) When a feasible plan is found, recalculate the objective values to reflect the risks involved.
6) The user can repeat steps 4 and 5 to investigate different options in order to generate the alternatives open to him.
7) The user can then present the different alternatives he was able to generate along with his recommendation to DOD for approval.

4.8 Results and Extensions

In its current form, our prototype DSS can provide the PM with many valuable results. First of all, the user interface is "friendly" and lends itself to simple use by non-experts. Second, our system provides a risk quantification method which can deal with the complex risks and interdependicies involved with weapon systems development and production. Finally, it provides the PM with a unique way of generating alternative program plans along with the assoicated risks. However, this system is only a step in the right direction. By extending and improving upon this basic approach our prototype will evolve into a much more complete tool for program management. Some of the features we foresee include

1) generation of Pareto optimal program plans and trade-off analysis to determine the preferred plan
2) more detailed handling of all areas of risk and uncertainty
3) impact analysis to determine the future effects of current trends and decisions
4) integration of the performance ojective in the formulation
5) report generation and other management aids
6) resource allocation

Most of the work associated with these improvements will involve the research and quantification of the many functional relationships and interdependencies present in the procurement process.

Activity	Name	Budget	Optimistic	Most Likely	Pessimistic
Hardware Development	HARD	50	9	14	23
DT/OT	DTOT	10	11	17	28
PEP	PEP	20	7	10	17
Software Development	SOFT	40	9	13	22
Software V & V	SWVV	60	14	21	35
Logistics	LOGS	35	22	33	55
Initial Spares	INSP	200	11	16	27
Training Equipment	TNEQ	105	20	30	50
Tech. Documentation	TDOC	30	12	18	30
Facility Start-Up	FCSU	100	5	8	13
Long-Lead Fund	LLFD	40	5	7	12
		Millions	Months	Months	Months

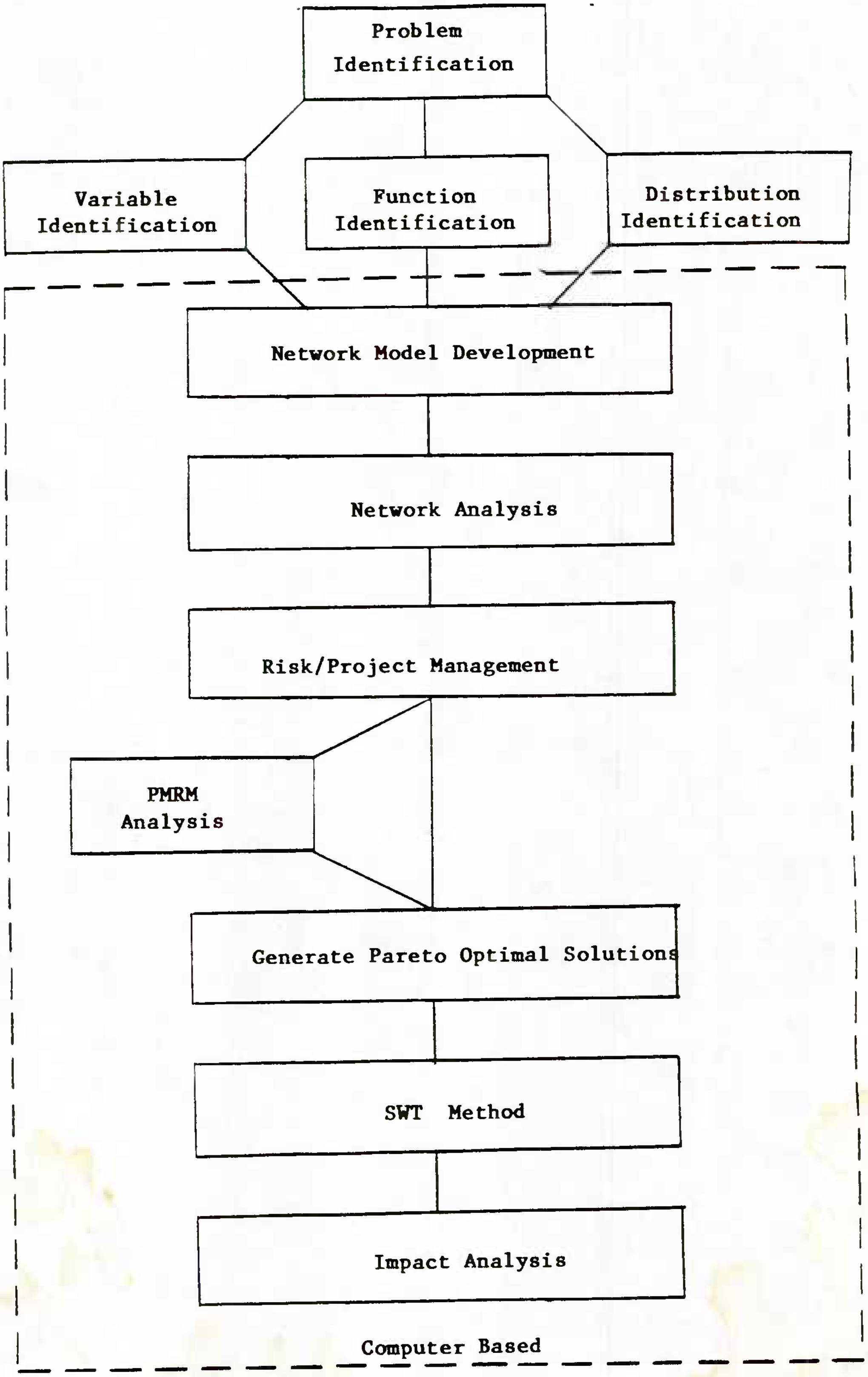
Table 4.1. Time Estimates for Activities

Activity	From Node	To Node	Mean	Variance	Earliest Start	Earliest Finish	Latest Start	Latest Finish	Total Float	Free Float	Critical Path
HARO	1	3	14.67	5.44	0	14	0	14	0	0	***
OTOT	1	4	17.83	8.03	0	17	7	24	7	7	
SOFT	1	2	13.83	4.69	0	13	1	14	1	0	
LOGS	1	5	34.83	30.25	0	33	21	54	21	20	
SWVV	2	5	22.17	12.25	13	14	33	54	20	21	
NULL	2	3	0	0	13	46	14	14	1	1	
FCSU	3	6	8.33	1.78	14	47	46	54	32	32	
LLFO	3	6	7.50	1.36	14	14	47	54	33	33	
PEP	3	4	10.67	2.78	14	38	14	24	0	0	***
INSP	4	5	17.00	7.11	24	24	38	54	14	16	
TNEQ	4	5	31.67	25.00	24	24	24	54	0	30	***
TDOC	4	5	19.00	9.00	24	36	36	54	12	18	
NULL	4	6	0	0	24	54	54	54	30	30	

Criticality Index

Path	C.I.
HARD, PEP, TNEQ	1.0
SOFT, PEP, TNEQ	0.981
HARD, FCSU, TNEQ	0.965
HARD, LLFD, TNEQ	0.951
DTOT, TNEQ	0.931

Table 4.2. Critical Path Analysis


Problem Identification
Variable Identification
Function Identification
Distribution Identification
Network Model Development
Network Analysis
Risk/Project Management
PMRM Analysis
Generate Pareto Optimal Solutions
SWT Method
Impact Analysis
Computer Based

Flow Chart of Prototpye DSS

Figure 4.1

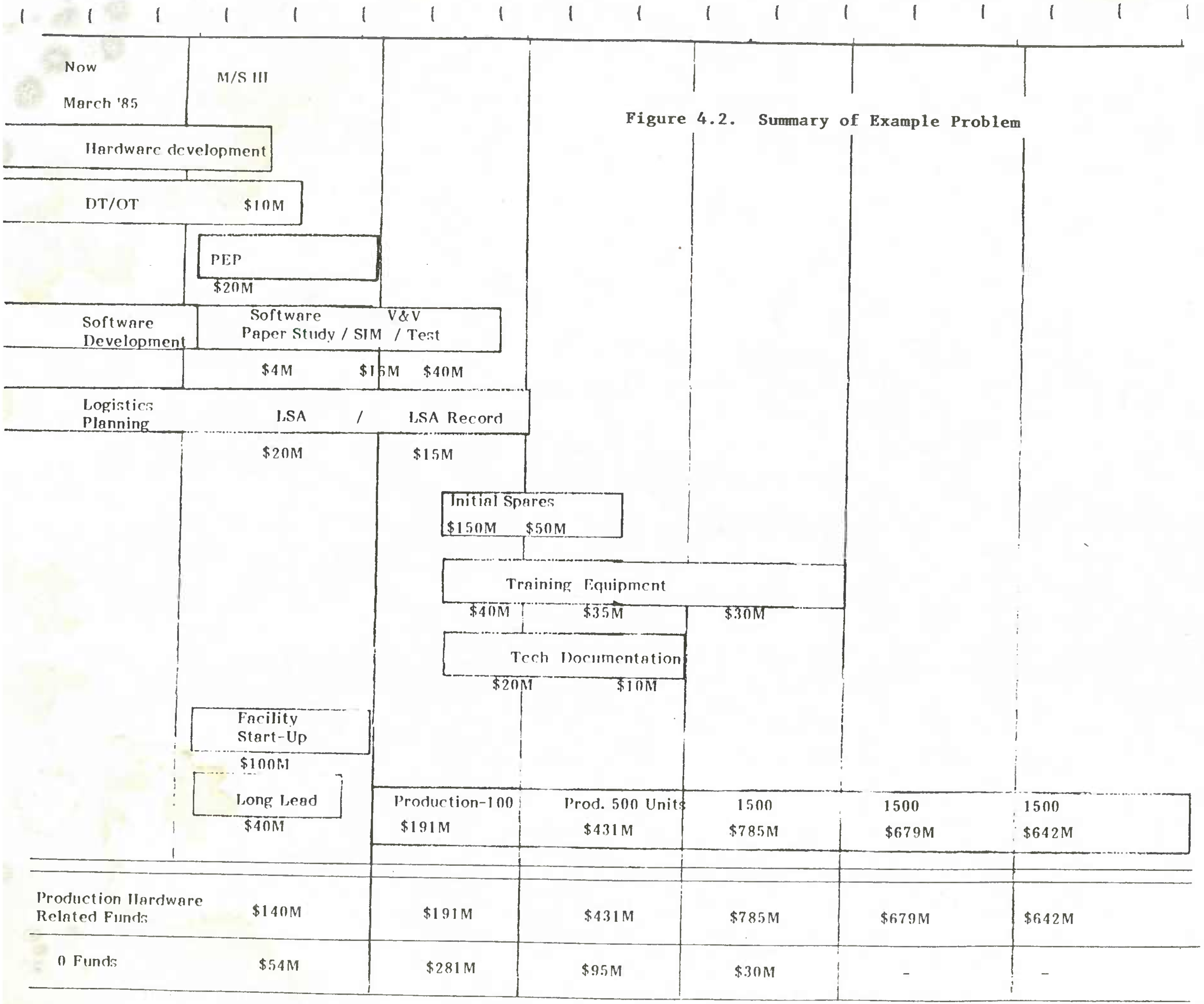


Figure 4.2. Summary of Example Problem

Now
March '85
M/S III
Hardware development
DT/OT $10M
PEP
$20M
Software Development
Software Paper Study / SIM
V&V / Test
$4M
$15M
$40M
Logistics Planning
LSA / LSA Record
$20M
$15M
Initial Spares
$150M $50M
Training Equipment
$40M
$35M
$30M
Tech Documentation
$20M
$10M
Facility Start-Up
$100M
Long Lead
$40M
Production-100
$191M
Prod. 500 Units
$431M
1500
$785M
1500
$679M
1500
$642M
Production Hardware Related Funds
$140M
$191M
$431M
$785M
$679M
$642M
0 Funds
$54M
$281M
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$30M
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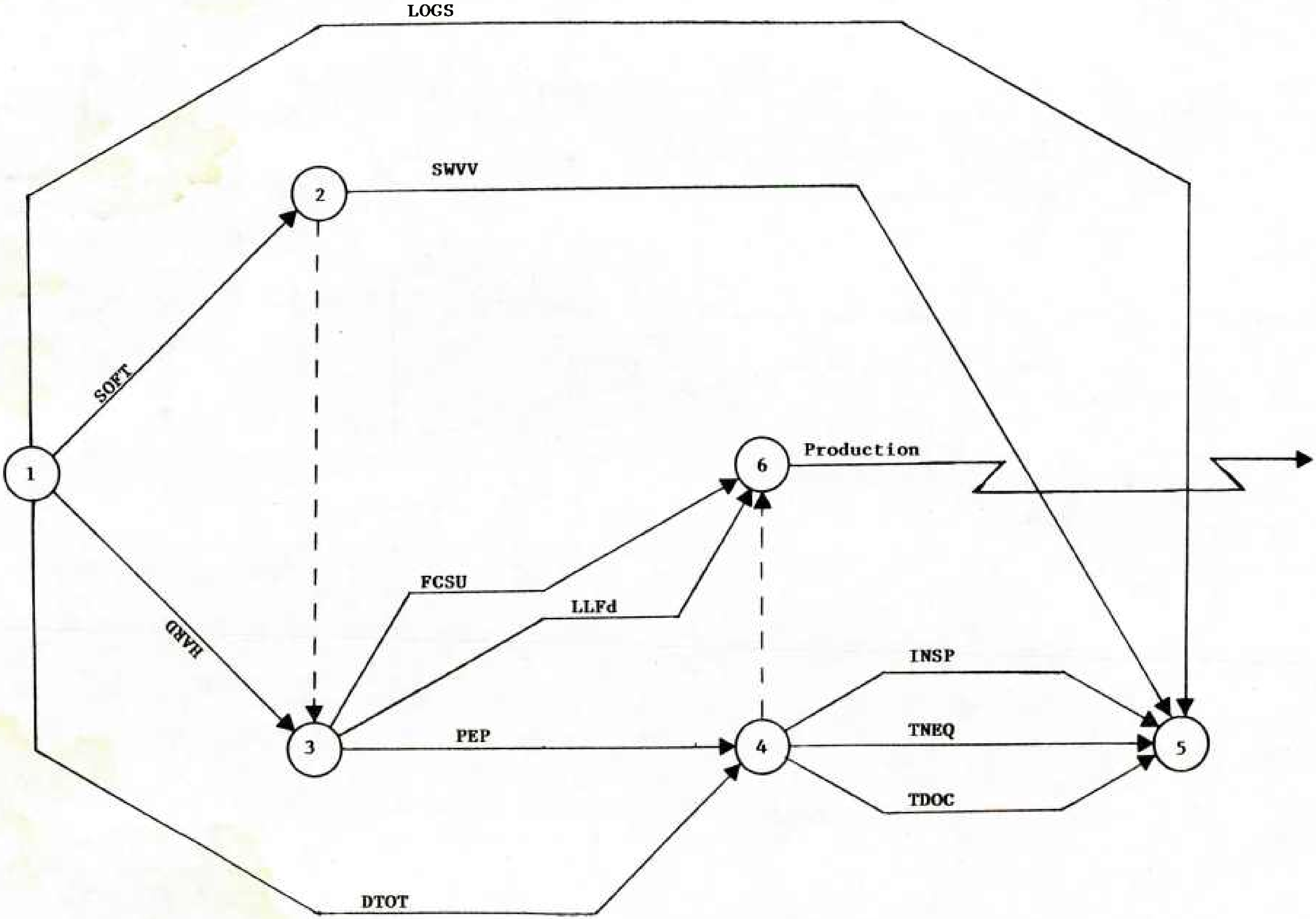
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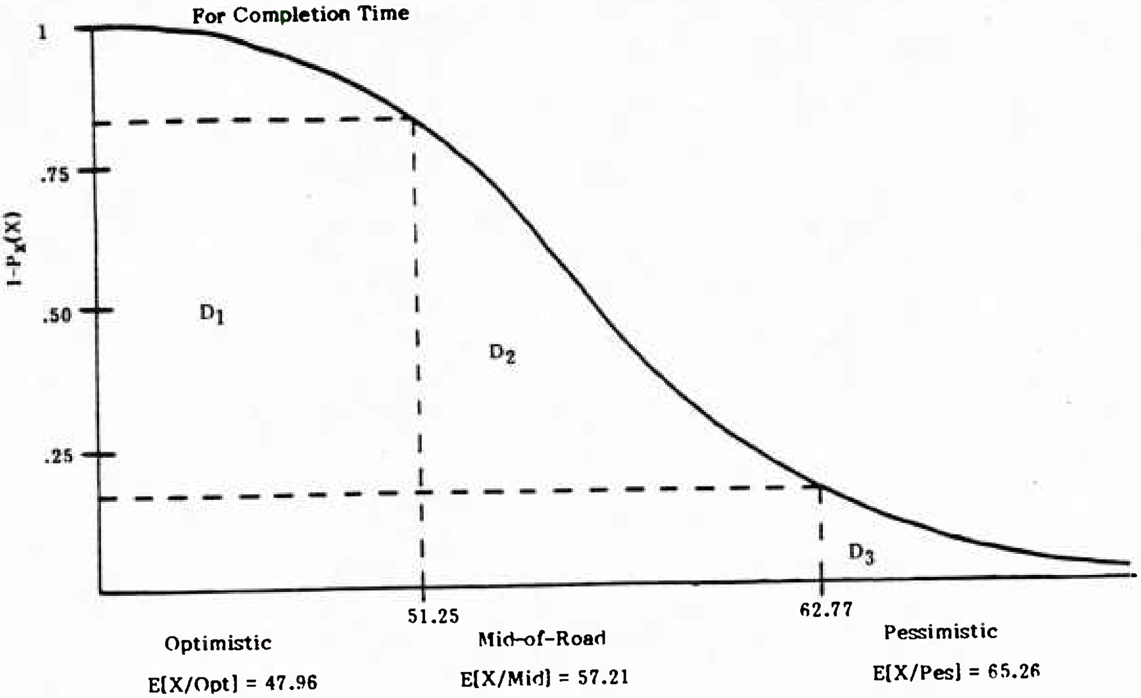
Figure 4.3. Network Diagram



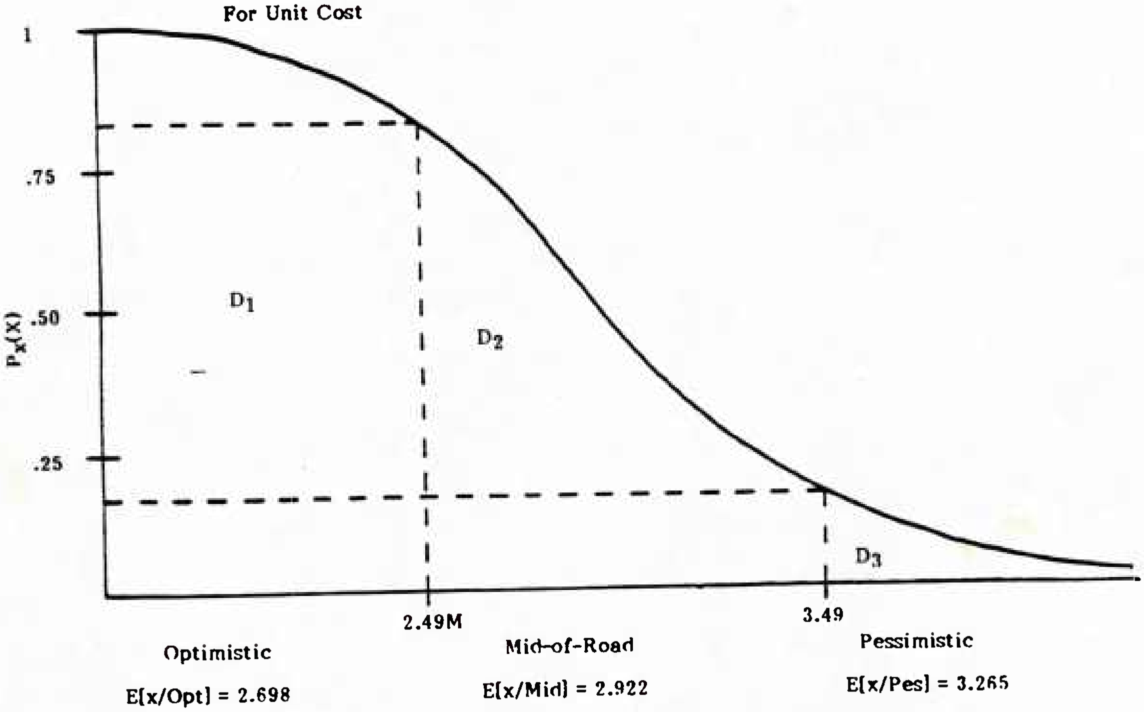


Figure 4.4. Computational Results for PMRM Analysis

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APPENDIX A

The Acquisition Process

In general, the weapons systems acquisition process consists of an initiation phase followed by four major phases: concept exploration, demonstration and validation, full scale development, and production and deployment (see Figure A. 1). A program begins when one of the major commands identifies the need for a weapons system. The process officially begins when a major command issues a Statement of Operational Need (SON) for review by the AFSC and AFLC, thus entering the initiation phase.

During the initiation phase the AFSC and AFLC personnel assess the technology and constraints which are required to satisfy the needs, identify known solution candidates, and estimate necessary resources for need satisfaction. They send the SON plus their comments to HQ USAF for review and validation. If the Secretary of Defense (SECDEF) (or the Air staff for small programs) approves the program, the concept exploration phase begins. Although the program has been officially approved, it still must compete with other needs in the Planning, Programming and Budgeting Office for funding. If sufficient funding is available, the process of identifying and evaluating alternatives (i.e. concept exploration) actually begins.

To oversee the various phases-- concept exploration, the acquisition process, and the phases that follow--a program office (PO) is established and a program manager (PM) is designated. Usually, industrial contractors propose alternative solutions and Federal laboratories or research centers are solicited for their ideas through a document called the Request for Proposal (RFP). The RFP is structured to encourage competition and innovation. Its contents focus on the operational needs that must be resolved, cost and schedule thresholds, operating environment, and performance and logistics supportability objectives. After the proposals are received, the best alternatives are selected by a PM-led review team on the basis of four criteria: cost, schedule, logistics supportability, and technical performance. During this early phase of the program, not only should the proposals be reviewed using the preceding criteria, but also the various elements of uncertainty in each proposal should be identified and an attempt made to quantify their effects on the expected cost, schedule, logistics supportability, and technical performance. In this manner, the four criteria along with their risks can be utilized in the decision-making process. Such risk evaluation is critical, because failure to recognize the possibility of cost overruns or schedule delays may lead to serious problems in the future. The impacts of these "risky" situations must be evaluated.

Once the best-candidate solutions or policy is chosen, HQ USAF prepares a draft decision coordinating paper (DCP) which documents the results from the concept exploration phase. In particular, the program description, mission need revalidation, goals and thresholds, acquisition strategy summary, program alternatives and recommendations, relevant issues, and risk/impact analysis are contained in the DCP. The DCP goes through a review process (see Figure A.1) and finally reaches the hands of the SECDEF. The decision to proceed is officially documented by the signing of a separate decision memorandum by the SECDEF. This initiates the demonstration and validation phase.

With the proposed solutions at hand, the demonstration and validation phase attempts to refine these selected alternatives through extensive studies and analyses, hardware development (as appropriate), and limited tests and evaluations. The objective is to obtain enough information to validate one or more of the selected solutions and to provide a basis for deciding whether to proceed into full-scale development phase. The emphasis at this point is to try to reduce the previously identified technical and economic risks and uncertainties surrounding the candidate solutions as well as to reevaluate the needs.

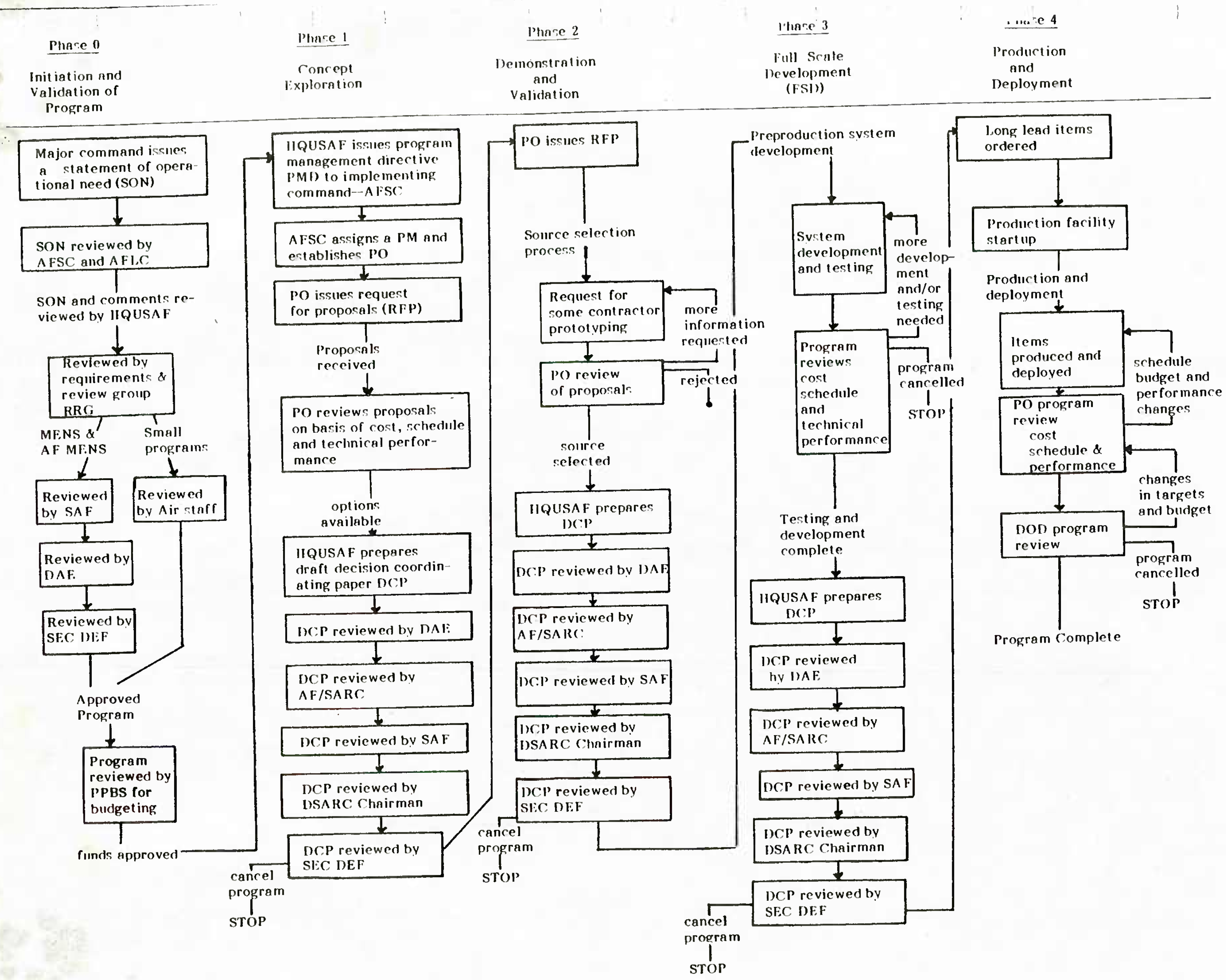
In order to validate one or more of the selected alternatives, the most common approach is for the PO to issue another RFP to obtain initial system and hardware configuration specifications, refined cost estimates, and refined schedule projections from competing contractors. After the proposals are received, a source selection board evaluates and then selects the best proposed systems, as in the concept exploration phase. The competing prototype contractors then begin a prototype fabrication phase to further define their projections. These prototype systems must allow performance objectives to be evaluated, but do not have to resemble the final operational system in other characteristics. The PO then decides whether more testing and/or further development is needed, whether to cancel the program, or whether to move on to the full-scale development (FSD) phase. This decision is again based on cost, performance, and schedule and supportability considerations and their risks. Each prototype system must be adequately developed, so that good estimates for the above criteria and their risks can be evaluated.

At the end of this phase, alternative solutions should have been validated and demonstrated; the technical, cost, supportability and scheduling risks should have been identified and quantified as well. With this information, HQ USAF prepares an updated DCP which is sent through the review process and finally to the SECDEF for approval. Official approval by the SECDEF sends the program to the full-scale development (FSD) phase.

During the full-scale development phase, the system and the principal items necessary for its support are designed, fabricated, tested, and evaluated. The result is to obtain a preproduction system that closely resembles the final system in order to provide documentation and test results on which to base the decision on whether it is appropriate to enter into the production and deployment phase. Throughout the FSD phase, the program office conducts many program reviews which evaluate how closely the contractor is staying within budget, performance, and schedule constraints as well as reevaluating the potential risks of cost overruns, performance deficiencies, and schedule problems and their impacts. This results in critical design review (CDR). At the CDR, the government has its last chance to make (without significant additional costs) any amendments to the system design before it is committed to hardware.

The PO also conducts system testing and evaluation, which helps to identify and assess potential acquisition risks so that they can hopefully be reduced. Also, operational performance is evaluated and system deficiencies are identified. Once the system is developed and the testing is completed, the DCP evaluation process is again initiated and the SECDEF's approval initiates the production and deployment phase.

The objective for the production and deployment phase is to efficiently produce and deliver effective and supportable systems to the operating units, but this objective is seldom met. This phase includes the production of all system hardware, spare parts, support equipment, data, software, etc. It also includes verification of specification compliance, evaluation of production progress against the planned strategy, and further testing and evaluation. Many unexpected events, such as Federal budget cuts, equipment failure, changes in the need, etc., can produce cost overrruns, schedule slippage, and reduction in the quality and quantity of items produced. In other words, failure to adequately account for risks and uncertainty can ultimately lead to the failure of the entire program in this final phase. It is again very important to identify the areas of uncertainty and to evaluate and manage the risks in order to develop a flexible plan for production and deployment. Such risk assessment and management must be continually addressed throughout this phase.



Phase 0
Initiation and Validation of Program
Phase 1
Concept Exploration
Phase 2
Demonstration and Validation
Phase 3
Full Scale Development (FSD)
Phase 4
Production and Deployment
Major command issues a statement of operational need (SON)
SON reviewed by AFSC and AFLC
SON and comments reviewed by HQUSAF
Reviewed by requirements & review group RRG
MENS & AF MENS
Small programs
Reviewed by SAF
Reviewed by Air staff
Reviewed by DAE
Reviewed by SEC DEF
Approved Program
Program reviewed by PPBS for budgeting
funds approved
HQUSAF issues program management directive PMD to implementing command--AFSC
AFSC assigns a PM and establishes PO
PO issues request for proposals (RFP)
Proposals received
PO reviews proposals on basis of cost, schedule and technical performance
options available
HQUSAF prepares draft decision coordinating paper DCP
DCP reviewed by DAE
DCP reviewed by AF/SARC
DCP reviewed by SAF
DCP reviewed by DSARC Chairman
DCP reviewed by SEC DEF
cancel program
STOP
PO issues RFP
Source selection process
Request for some contractor prototyping
more information requested
PO review of proposals
rejected
source selected
HQUSAF prepares DCP
DCP reviewed by DAE
DCP reviewed by AF/SARC
DCP reviewed by SAF
DCP reviewed by DSARC Chairman
DCP reviewed by SEC DEF
cancel program
STOP
Preproduction system development
System development and testing
more development and/or testing needed
Program reviews cost schedule and technical performance
program cancelled
STOP
Testing and development complete
HQUSAF prepares DCP
DCP reviewed by DAE
DCP reviewed by AF/SARC
DCP reviewed by SAF
DCP reviewed by DSARC Chairman
DCP reviewed by SEC DEF
cancel program
STOP
Long lead items ordered
Production facility startup
Production and deployment
Items produced and deployed
schedule budget and performance changes
PO program review cost schedule & performance
changes in targets and budget
DOD program review
program cancelled
STOP
Program Complete

Figure A.1: Details of the weapon system acquisition process

APPENDIX B

B. Risk Assessment and Management Methods: A Review

The purpose of this section is two-fold: the first objective is to present a general overview, philosophy, and general precepts of the process of risk assessment and management. The second objective is to review a collection of tools and techniques that are available for assessing and managing risks associated with weapon system acquisition from both a theoretical and a conceptual viewpoint. This section provides the groundwork for Sections 3 and 4 in the report, where a number of promising methods are selected for a more detailed evaluation within the specific context and needs of the weapon system acquisition process.

B.1 The Process of Risk Assessment and Management *

Although the study of risk assessment and risk management (as both an art and a science) is not new, its acceptance as a major teaching and research discipline has emerged primarily in the last decade. The development of valuable theory (especially in the social and behavioral sciences related to the perception and acceptance of risk), the appearance of methodologies (especially in the mathematical sciences and engineering) concerned with risk, and the unprecedented growth of public awareness of the risks that modern society must face concerning health, the environment, and other areas--all these indicate a burgeoning that necessitates and justifies the discussion and careful execution of risk assessment and management, particularly in large development projects such as weapons system development.

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* This section is adapted from "Risk Assessment and Management in a Multiobjective Framework," Y.Y. Haimes and M.R. Leach, in Decision Making with Multiple Objectives, Y. Y. Haimes and V. Chankong (eds), Springer-Verlag, Hamburg, 1985 (in press).

Today risk assessment and management are the domain of almost every Federal, state, and local agency as well as large and small corporations. Most public policies are formulated with explicit considerations of health and safety. Federal agencies such as the U.S. Environmental Protection Agency, the Nuclear Regulatory Commission, the Federal Drug Administration, the Federal Aviation Administration, the U.S. Army Corps of Engineers, the Department of Defense, etc., have distinctive teams and programs that address risk management in their respective mandates and areas of responsibility.

In the risk assessment and management process there are a number of situations (reflecting the degree of uncertainty) that can be encountered and a number of steps that need to be performed. To avoid common ambiguities of terms and terminologies, the following definitions will be used--not as universal definitions, but as a useful means of communicating with the reader:

Risk situations--situations in which the potential outcome can be described by reasonably well-known probability distributions.

Imprecision situations--situations having potential outcomes that cannot be described in terms of objectively known probability distributions, but which can be estimated by subjective probabilities.

Uncertainty situations--situations in which potential outcomes cannot be described in terms of objectively known probability distributions.

Risk assessment--a complete process that encompasses all of the following five elements or steps: risk identification, risk quantification, risk evaluation, risk acceptance and aversion, and risk management. The term risk will be generally used in this paper to connote situations of both risk and uncertainty.

Risk identification--identification of the nature, types, and sources of risks and uncertainties. Risk identification, as the first stage of risk assessment, aims at a complete description of risky events and elements of major concern along with their causative factors and mechanisms.

Risk quantification--formulation of appropriate measures of risk and estimation of the likelihood (i.e., probability) of occurrence of all consequences associated with risky events as well as the magnitude of such consequences.

Risk evaluation--selection of an evaluation procedure (e.g., optimizing expected value; trade-off analysis) and analysis of various possible impacts of risky events.

Risk acceptance and aversion--decision making regarding both an acceptable level of risk and its equitable distribution. This stage of risk assessment also involves the development of risk control (i.e., methods to reduce or prevent risk).

Risk management--formulation of policies, the development of risk-control options (i.e., methods to reduce or prevent risk), and the execution of such policy options.

The last two stages of the risk assessment process--risk acceptance and aversion and risk management--overlap to a large extent and require the subjective judgment of the appropriate decision makers in trading-off the noncommensurate beneficial and adverse consequences resulting from the ultimate "acceptable risk" decision. The existence of these fundamental trade-offs among conflicting and noncommensurate multiple objectives and attributes demands the consideration of risk management as an integral part of the overall decision-making process--which is the imperative premise assumed in this report (Haimes [1981]).

Briefly stated from the perspective of multiobjective decision-making, the risk assessment and management process consists of two major phases that partially overlap:

(a) Information is quantitatively processed and evaluated through well-developed procedures and methodologies, including the quantification of risk and uncertainty and the development of alternative policy options. The methodologies of risk assessment are techniques that utilize a scientific approach toward estimating the probabilities and performing risk assessment (while excluding the explicit application of value judgments).

(b) Value judgment is introduced, within the overall decision-making process, concerning what risks and their associated trade-offs are acceptable, what selections are preferred, what policies are desirable, what constitutes the ultimate decision (the best-compromise solution), and what actual actions should be taken.

It is worthwhile to note that the setting of value judgment is critically important; it is an integral part of any decision-making process and thus is integral to the risk assessment process itself. This process also serves as an educational medium for the decision makers in their interaction with the analysts; it can help identify and articulate the issues upon which there is an agreement among decision makers and also those for which there is no agreement; it also helps to make the implicit explicit (doing this, however, at the expense of embarassing decision makers under certain circumstances).

In many cases of policy analysis, a formal decision-making procedure is appropriate. Many of these procedures deal with only one primary goal or objective function. This approach usually simplifies the problem both conceptually and computationally, but may prove to be inadequate when decisions of great complexity are to be made. An alternative approach is to use a decision-making procedure that allows for the consideration of several objectives that may be conflicting and noncommensurable.

Haimes [1981] discusses the usefulness of assessing risk within a multiobjective framework. A complete evaluation of risks in terms of their trade-offs with other objectives (for example, cost) necessarily lends itself to a multiobjective analysis. Risk analysis and multiobjective decision making are further related by the roles that the analyst and the decision maker play in both. The role of the analyst in multiobjective decision making is to model the system, quantify objectives, determine trade-offs, and assist the decision maker in interpreting the results. Similarly, in risk analysis, the analyst's job is to identify and quantify risks. In each case, the decision maker supplies the value judgments and preferences and, in the case of risk analysis, determines the level of acceptable risk. Thus, the ultimate efficacy of risk assessment lies in its incorporation and utilization in the overall decision-making process.

Two traditional measures of risk are the expected value of damage and expected utility. Kaplan and Garrick [1981] believe that these approaches are not adequate. They point out that such scalar representations of risk can be derived only at the expense of losing a great deal of information. The expected-value approach also tends to equate a low-probability, high-damage scenario with a high-probability, low-damage scenario, when these situations are actually quite different . McCord and de Neufville [1982] have demonstrated empirically that there are weaknesses in the practical use of the expected utility theory in its present form, and they question the appropriateness of expected utility decision analysis as currently practiced.

In many cases the decision maker will be more interested in the low-frequency, high-damage events than in the overall probability disribution. Public perception of catastrophic risks is an important consideration. Fairley [1981] states that records of zero occurrence of catastrophic accidents from technologically based industrial operations (such as nuclear power generation) are often cited as evidence of the safety of such operations. He reaches the conclusions that such records are actually of little comfort in ruling out the possibility of such catastrophic events. Clearly, there is a need for risk analysis methodologies that allow for consideration of such risks. This capability can be found in multiobjective approaches, such as the partitioned multiobjective risk method (PMRM) (Asbeck [1982] or Asbeck and Haimes [1984]), the risk/dispersion index method (RDIM) (Rarig and Haimes [1983]) the multiobjective statistical method (MSM) [Haimes et al. [1980]), the uncertainty sensitivity index method (USIM) [Haimes and Hall [1977]).

The ultimate goal of any multiobjective decision-making methodology is to provide the decision maker(s) with the most useful information in the most effective manner and to aid in arriving at a policy choice in a logical and consistent way. It is also important not to overwhelm the decision maker(s) with too much information, or else confusion may result. A good risk analysis method, therefore, should express risks to the extent possible, in a clear, complete, and concise manner. Information concerning various impacts and trade-offs is also of great value. A decision-making mechanism should be provided which can help the decision maker arrive at a policy based directly on value judgments and preferences.

In addition to considering multiple objectives, risk analysis can be further extended by considering explicitly the element of time. Simply determining the probability of a certain event, which is the case in many risk analysis techniques, does not give any indication of short-,medium-,or long-term risks, or of how risks change over time. Since risks that may not be detectable for an extended period of time can arise from technological developments (for example, acid rain or many carcinogens), there is a growing need to develop risk assessment methodologies that explicitly address such long-range impacts.

Haimes [1984a] considers this problem and suggests the integration of impact analysis with risk and uncertainty assessment to form a more complete analysis. Specifically, the multistage multiobjective impact analysis method (MMIAM) (Gomide [1983] or Gomide and Haimes [1984]) could be used. This method explicitly develops the trade-offs between various objective functions at different stages of the planning horizon. These dynamic trade-offs are interpreted as the impacts that decisions made at one point in time may have on the state of the system at a future point in time. The quantification of risk impacts is an important step toward a more resilient risk and uncertainty assessment and a more robust decision-making process. Leach [1984] and Leach and Haimes [1985] further integrate risk and impact analysis in a multiobjective framework.

B.2 Selection and Classification of Methods for Preliminary Review

We will now select, classify and review methods for assessing and managing risks associated with weapons system acquisition. There are indeed a large number of such techniques proposed in the literature and only some will be selected for review here. To help us in our selection, we perceive a particular weapon system acquisition and development as a project--a customized one-time endeavor--designed to fulfill specific needs of a particular command. The major concern here are the planning, management, and control of such a project. With this perception and bias, our selection and classification scheme and subsequent discussions revolve around two interrelated general aspects of weapons system acquisiton

- risk assessment and management
- project planning, management and control

For comprehensiveness, methods selected for review are those that attempt to deal with the whole or parts of either or both of these aspects. Together they represent a wide variety of tools ranging from the very specific (dealing with specific parts or aspects of risk assessment and management or project management) to the very comprehensive (dealing with both aspects comprehensively). We believe it is useful to start with this broad list in order to give an overall picture of what methods are available. The methods are then categorized into three classes based on their conceptual foundations and rationale: (i) the heuristic class, (ii) the formal analysis class, and (iii) the network class.

The heuristic class is a mixed bag of heuristic devices aimed at specific parts of risk assessment/management or project management. Heuristic methods selected for review in this report are variance analysis, work breakdown structure (WBS) simulation, and the method of moment. Other such devices to be mentioned are Gantt or bar charts, hierarchical decision modeling, and other graphic aids.

The formal analysis class consists of those methods that have formalized structure and are predicated on some well-established intellectual roots. Methods of this sort selected for review are mostly concerned with risk assessment and risk management in a more general setting than simply project management and control. These include decision-multiattribute utility theory, multiobjective optimization/risk trade-off methods, economics-based methods, and simulation models.

The network class is a collection of network-based techniques primarily intended for project management, control, and evaluation. However, most network techniques selected for review here do have as one of their principal focal points the explicit or implicit consideration of the risk aspects of project management. These include PERT/CPM, GERT, SCERT, VERT, WoPAST, RISCA, TRACE, and MICE, a risk management model developed by L.R. Ireland and many others.

B.3 Review Criteria

To keep in tune with the ultimate goals of this review task, we shall focus on the following characteristics of each method under review.

1) Goal. What is the principle objective of the model? Does it address all aspects of risk assessment/management and of project management and control? If not, what particular part (or parts) does it focus on? To be more specific, we shall probe to see whether any or all of the following key issues are addressed by each method in the context of project planning, management, and control.

Risk identification. This involves identification of the type, nature, and sources of potential hazards (damages or adverse effects) and uncertainties. In the context of planning, executing, and managing a large scale project such as weapons system acquisition, four factors are of principle concern--time, cost, logistic supportability, and performance. Consequently, typical "adverse effects" to be addressed in these situations are delay of the project, cost overrun, shortage of resources, and substandard performance.

Risk quantification. This involves (i) estimation of possible levels (magnitudes) of all potential adverse effects identified earlier and (ii) estimation of the likelihood (probability) of occurrence of each of those levels. For example, we may want to estimate how long a project completion data may be delayed under various circumstances and what are the likelihoods of such delays.

Risk evaluation/acceptance. This involves identification of possible impacts of various potential adverse effects as well as determination of acceptable level and distribution of risk. For example, before a decision can be made or policy formulated regarding delay or cost overrun of a project, all the significant impacts of such a delay or cost overrun for the overall program, the executing agent, or society as a whole should be first fully appreciated.

Risk management. This involves formulation of policies, development of risk control measures (i.e., methods to reduce or prevent risk), and the execution of such policy options.

2) Logical Basis. Is the method well structured and easily comprehensible? Is it justifiable on a theoretical basis and/or an empirical ground? What are the intellectual roots, rationale, and the underlying assumptions upon which the method is grounded? This should provide a good indication of how well developed a method is.

3) Treatment of Risk and Uncertainty. Are risk and uncertainty elements treated explicitly or implicitly (or not at all)? How flexible is such a treatment, and is it user-friendly? The motivation for focusing on this issue should be obvious.

4) Supporting Tools and Inputs. What basic tools does a user need in order to apply the method? What type and amount of data and other inputs are required? The analysis of this issue should give a good indication of the knowledge base needed by the user to use the method. It should also

indicate he level of complexity flexibility, and feasibility required by the method.

5) Application Characteristics. What are typical steps or procedures used in applying the method? What needs to be done at various steps and for what purpose? This should give an indication how the method is actually carried out in typical applications.

6) Application Experiences. Has the method been applied to real problems? If so, what types of problems? What are the sizes and levels of complexity of those problems?

7) Pros and cons. What are the theoretical and practical advantages and disadvantages of these methods? What inherent limitations does each method have?

In what follows, we review selected methods in the three classes mentioned above using the following format. First, a brief description of each method is given which highlights the main features listed above. However, no attempt is made to itemize the description into clear subheadings reflecting the aforementioned features. Such features are instead incorporated into tables at the end of each section (one for each class) to highlight and contrast the stated characteristics of the methods in each class.

B.4 Review of Methods in the Heuristic Class

Methods in this class are composed mostly of heuristics rather than being based on some formalized or complicated theoretical principles. We select for review only those methods that either have application potential or have already been applied in some real situations.

1) Variance Analysis (see, for example, Kerzner, 1979; Archibald, 1976). This is a fairly well-known method designed primarily for measuring deviations of the actual project cost and schedule from the budgeted cost and the planned schedule, respectively. In terms of the "goal" described earlier, the method thus focuses only on specific parts of risk quantification (i.e., determining the magnitude of potentially adverse effects). Also, consideration is given only to those parts of a project's risk and uncertainty that are associated with cost and time. There are two basic premises for considering both the cost and time variation simultaneously:

* The cost variance compares deviations only from the budget and provides no measure for comparison between work scheduled and work accomplished.
* The scheduling variance provides a comparison between planned and actual performance but does not include costs.

Variances can be calculated in terms of three basic variables:

* Budgeted cost for work scheduled (CBWS) is the budgeted amount of cost for work scheduled to be accomplished in a given time period.
* Budgeted cost for work performed (BCWP) is the budged amount of cost for completed work plus that budgeted for level of effort or apportioned effort activity completed within a given time period. This is sometimes referred to as "earned value."

- Actual cost for work performed (ACWP) is the amount reported as actually expended in completing the work accomplished within a given time period.

Using these definitions, the following variances are defined:

cost variance = BCWP - ACWP

scheduled variance = BCWP - BCWS

Thus, the cost variance is the difference between the budgeted cost and the actual cost of a project at a given level of completion. The schedule variance is a monetary measure that expresses the project delay in terms of budgeted costs. The schedule variance can also be expressed in terms of time (hours, days, or weeks) instead of dollars. These two variances are easily represented by plotting budgeted and actual costs versus time, as shown in Figure 2.1.

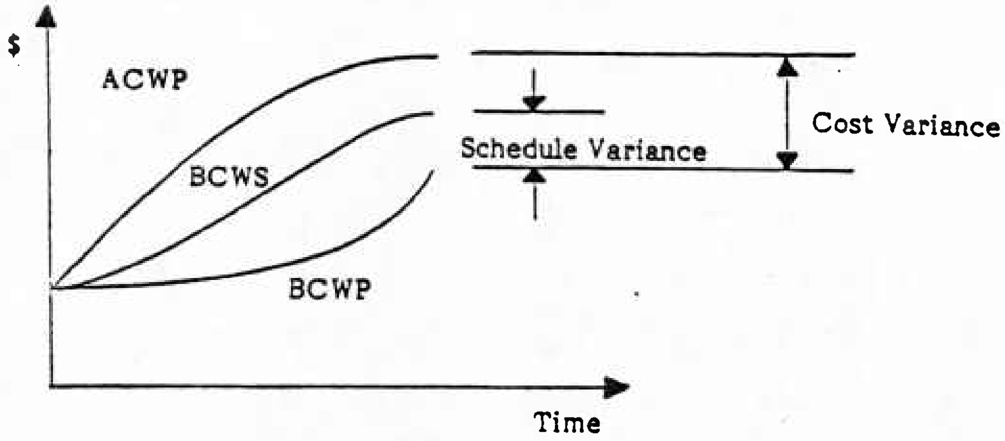


Figure B.1 Cost and Schedule Variances

As can be seen, the logical basis for this tool is cost accounting combined with common sense. The required computational work is simple. And the input data required are the budgeted cost for various stages of the project, the planned schedule, and the actual cost for various completed work. Thus, good cost accounting reports are required in using the method.

Although variance analysis does not explicitly treat the elements of risk and uncertainty, it can be viewed as part of risk quantification tools. It is, however, not a complete risk quantification tool since there is no attempt to estimate or quantify the level of uncertainty involved. The method is not useful for project planning. Rather it is useful for on-line project evaluation and control. Cost and schedule variances can be noted and the sources of variance pinpointed so that the actual project performance can be brought closer to the planned performance.

In the preparation of this report no well-documented practical applications were found; however, according to Martin (1976), the method has been received with mixed feelings by various managers: some are very enthusiastic about the method, while others are most critical, believing it is a waste of time. Dunne and McClary (1981) also reported similar resuls based on responses of military R & D project managers.

2) Method of Moments (McNichols, 1976). Unlike variance analysis, the method of moments focuses mainly on the probabilistic nature of costs. More precisely, it is designed primarily to estimate the probability distribution function (PDF) and the cumulative distribution function of the total cost of the project. Like variance analysis, the method of moments can be viewed as a tool for performing one part of risk quantification task (i.e., estimating the likelihood of various adverse effects). Also, it only addresses risks associated with cost elements, rather than dealing with all four elements of project management (cost, time, resources, and performance). In this method, each cost component is assumed to have a known PDF. To compute an overall cost PDF, a form of the required PDF is assumed, with the parameters of distribution to be determined. The method

proceeds by calculating the moments (mean, variance, skewness, etc.) of the component PDFs. Using these values and the assumed type of the overall PDF, the parameters of the overall PDF are calculated, thus determining the required PDF. This, in turn, is used for further risk assessment/managment, based on project cost.

The intellectual root for this method is clearly predicated on the theory of probability distribution. From the above discussion, all major assumptions required should be clearly evident, the most important being the type of overall PDF. As a supporting tool, the user should be familiar with the analysis of moments associated with probability distributions. Inputs essential to the method are an understanding of how the total cost is broken down into various components, sufficient knowledge of the probabilistic nature of these cost components, and some information on the probabilistic nature of the total cost.

Formal practical applications of the method have not been found during the preparation of this report (perhaps due to the many major assumptions required). The method may, however, be useful when a more detailed, rigorous approach to risk quantification associated with project cost is impossible or impractical.

3) Work Breakdown Structure (WBS) Simulation (Raiffa, 1968, and Military Standard, 1975).

This method has exactly the same goal and intellectual roots as the method of moments, uses similar concepts, and requires similar supporting tools and inputs. The only basic difference is that, in the WBS simulation, the form of the PDF for the overall cost is not assumed. Rather, the form as well as associated parameters of the reqired PDF are obtained by performing computer simulation based on the assumed PDFs of the component costs. Some practical applications of the method in the area of military procurement and operation have been reported by the Office of the Chief of Naval Operation (e.g., Jordan and Klein, 1975) and other military offices (e.g., Directorate of Cost Analysis, Deputy of Comptroller, Armament Division, Eglin AFB, FL, and Directorate of Cost and Management Analysis, Comptroller, Headquarters, Air Force Systems Command, Andrews AFB, DC).

4. Miscellaneous Tools for Cost Estimations

Structuring of cost estimates is a very valuable and widely used procedure in project management. Cost, together with time, when presented in the context of a network diagram or a work breakdown structure, will provide a complete picture of the project or program to the program manager. In general, cost estimation techniques must deal with costs at several levels:

a) cost estimates--for tasks not yet started

b) budgets--for tasks that are in contract negotiation and planning°

c) actual costs--for tasks in progress or completed

d) forecasted costs-to-complete--for tasks that are in progress and remaining tasks to be completed.

A number of different aspects of cost analysis have been utilized to help control project costs. A brief description of these concepts and techniques follows [adapted from Adams, et al., 1978]:

(i) Industrial Engineering Standards for Costing--In this method, a task is broken down into its component parts. Whenever possible, standardized costs (i.e., costs established by historical industrial experience and generally accepted industry-wide) are assigned to the component parts. The cost estimate of the task is just the sum of the estimates for its component parts. This approach is quite accurate for "state-of-the-art" projects where little uncertainty is involved.

ii) Parametric or Statistical Costing--Parametric and statistical costing are similar techniques which use basic technical characteristics of the product to estimate the costs of major portions of the project or the project itself. Statistical techniques are utilized to develop relationships for these technical characteristics from historical data. This technique seems to be more accurate when used on individual subassemblies or subsystems, with the costs then being summed to develop the project estimate.

Parametric or statistical costing techniques are best used when the detailed information needed for engineering estimates is not available, when accuracy is not particularly important, or when speed and low cost of developing the estimate is of high importance.

iii) Life Cycle Costing (LCC)--The life cycle cost of a system is the total cost of acquiring and owning the system for its entire life. It includes the cost of development, acquisition, operation, support, and disposal. Life cycle costing (LCC), then, involves the consideration of life cycle costs, or segments thereof, in the decisions associted with the development and acquisition of the product. Thus the "down-stream" costs of the project must be estimated and considered by the project manager as his project is designed.

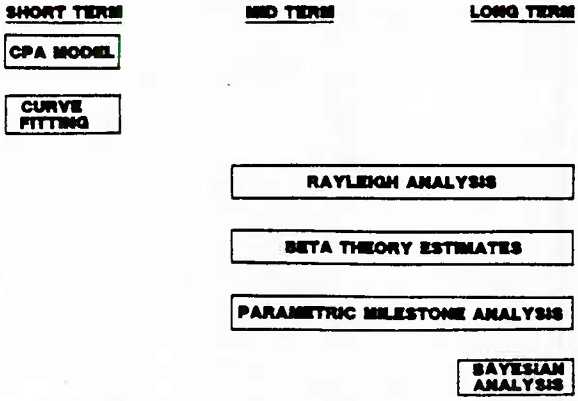
The concern for life cycle costing originated with the government in the development of weapon systems. It was found that weapons were being developed and procured with an eye only to acquisition costs, schedules, and project performance. As a result, decisions were being made which, while holding acquisition and production costs down and keeping performance up, were making the costs of ownership--which costs include the maintenance and operation of the system--prohibitive. LCC is an attempt to identify the down-stream ownership costs associated with early design decisions and make this added information part of the project manager's decision process.

iv) Design-to-Cost--Design-to-cost (DTC) is a management concept wherein rigorous cost goals are established during the early development of the project effort, and the entire project is managed toward the achievement of these goals. This is accomplished by practical trade-offs between the performance, schedule, and cost aspects of the project. Cost, as a key project variable, is addressed on a continuing basis and may take precedence over both schedule and product performance characteristics.

Techniques for predicting such items as product life, manpower costs, component reliability, and maintenance requirements as a function of product design are just beginning to emerge. Nevertheless, they are being developed, and project managers from both government and proviate industry can expect to see increasing pressure to analyze and include life cycle costing techniques in their project management systems.

v) The DARPA Method--The method that the Meridian Corporation has developed for DARPA takes advantage of several techniques to deal with risk assessment and management. This approach is meant to supplement traditional practices and aid the program manager in analyzing and assessing the risk of cost growth in order to initiate preemptive action. Basically, the method breaks risk into three types--short term, mid term, and long term--and concludes that no single method exists that is appropriate for all three. Several aspects from theoretical and empirical models along with statistical theory are combined in order to address all risk. The different methods that were used and the types of risks they address are summarized in the following picture.

RISK ASSESSMENT INDICATORS


SHORT TERM
MID TERM
LONG TERM
CPA MODEL
CURVE FITTING
RAYLEIGH ANALYSIS
BETA THEORY ESTIMATES
PARAMETRIC MILESTONE ANALYSIS
BAYESIAN ANALYSIS

These methods were integrated to form a user-friendly package oriented toward the special needs of the PM. In particular, in each category of risk they provide

- short term
    * evaluation of earned value data
    * cost prediction
    * cost analysis
- mid term
    * cumulative cost analysis
    * expenditure pattern analysis
- long term
    * estimate at completion
    * confidence limits
    * probability estimates

This approach has been used by DARPA and provides the foundation for future activities in risk management and control.

5. Miscellaneous Tools for Project Management. In this subsection, some heuristic tools used primarily for project management, evaluation and control will be briefly mentioned. These tools, which do not address the elements of risk and uncertainty, include Gantt (bar) charts, hierarchical decision modeling, and miscellaneous graphic aids. The boeing Method which is also discussed here does, however, address the issue of risk assessment and management explicitly.

A Gantt chart (see, for example, Sage, 1977; Cleland and King, 1968) is used primarily to schedule component tasks of a project and to monitor the progress of each task. A Gantt chart is constructed by first dividing a project into component tasks. The estimated starting and ending time of each task is then determined. These are plotted against time in the form of bar charts. The current time and progress of each task are indicated, so it is immediately obvious which tasks are behind (or ahead of) schedule and by how much. The Gantt chart is simple and easy to understand and has the advantage of portraying scheduled and actual progress simultaneously. Gantt charts have some drawbacks, however. The interdependency of the tasks is not presented. Moreover, such charts are not useful for risk and uncertainty analysis. As can be seen, the major project element emphasized here is time (schedule), while other elements (cost, performance, and resources) are not explicitly considered. Gantt charts are quite well known and have indeed been widely applied for project monitoring (see, for example, Dunn and McClary, 1981).

Other graphic aides (see, for example, Kelly, 1982) for project monitoring and evaluation include flow diagrams, project data sheets, and assessment charts. They all emphaisze the cost and schedule of the projects. Like Gantt charts, these graphic tools are based on pure common sense. Their primary functions are for bookkeeping and/or organization of data for visual inspection or for other more complicated analysis. These project evaluation tools have also been widely applied for project

Table B.1 Summary of Main Features of Methods in the Heuristic Class

Method / Criterion	Variance Analysis	Method of Moments & Work Breakdown Structure Simulation	Miscellaneous (Gantt Chart, Graphic Aids, HDM)
Goal (Output)	• To measure deviations of actual cost & schedule from budgeted cost and planned schedule	• To obtain a PDF or CDF for the total project cost	• To schedule component tasks of a project • To monitor and evaluate progress of a project

Area of Emphasis (with regard to review goals)	• Risk Quantification
	  • Project cost, and
	  • Schedule
		• Risk Quantification
		  • Project cost only
			• Project Monitoring and Evaluation
			  • Cost and Schedule (GC & GA),
			  • Performance (HDM)

Logical Basis and Intellectural Roots	• Cost accounting and common sense	• Probability distribution Theory • Analysis of moments for MoM and simulation for WBS	• Common sense (GC & GA) • Group process and decision making (HDM)
Assumptions	• Assume that schedule variance can be measured in terms of deviation of budgeted costs between work performed and scheduled.	• PDFs for all component costs are assumed • Form of PDF for overall cost is assumed in MoM but not in WBS	• None
Supporting Tools & Input Requirement	• Cost accounting reports • Project planning chart	• Analysis of Moments for MoM • Computer simulation (extensive) for WBS	• Methods for measuring and aggregating expert opinion • Participation from various parties
Treatment of Risk and Uncertainty	• implicit • Partial treatment since there is not treatment of probabilistic elements	• Partial treatment since only probabilistic aspect is focused	• Minimal if any for GC & GA • HDM does provide an indirect and informal mechanism for dealing with risk and uncertainty

Application Characteristics	• Compute three basic variables
	  • BCWP..budgeted cost for work performed
	  • BCWS..budgeted cost for work schedule
	  • ACWP..actual cost for work
	• Compute two variances
	  • Cost variance = BCWP - ACWP
	  • Schedule variance = BCWP - BCWS
		• MoM • Compute various moments of component costs
		  • Use these values together with assumed form of PDF of total cost to determine parameters of PDF to total cost
		• WBS • Use computer simulation to generate PDF of total cost from PDFs of component costs
			• Obvious for GC & GA
			• HDM •Define project mission, objectives and and goals by executives
			  • Develop strategies and actions and identify relationships among mission,objectives goals, strategies & actions by project team
			  • Assemble and solicit inputs from experts

Application Experience	• Used by some project managers with mixed results.	MoM None reported WBS Widely used in Military Procurement and Operations projects.	• Numerous applications for GC & GA • None reported for HDM.
Pros and Cons	• Computed variances are useful information but incomplete for comprehensive risk analysis.	• Focus only on part of activity spectrum in risk assessment/management. • Focus only on cost element.	GC & GA is simple and easy • not good for displaying interdependency of activities • not designed for risk analysis. HDM • can provide comprehensive and balanced assessment • untested.

B.5.1 Decision Analysis/Multiattribute Utility Theory (DA/MAUT) (Keeney and Raiffa, 1976)

The traditional decision analysis or Bayesian approach to risk assessment takes advantage of a PM's prior experience in order to assess the impacts that uncertainties will have on the cost of a program. The method uses the PM's subjective judgments along with results from traditional estimation techniques in order to derive improved cost estimates. This procedure involves the use of subjective probability and random sampling in the framework of Bayesian analysis in order to determine the risk of exceeding the cost estimate. The process involves assessing the subjective "prior" probability of a primary event "a" (e.g., cost overrun, etc.). Here, in such a probability estimation, knowledge of cross-impact analysis (Gordon and Haywoard, 1968; Gordon, 1969; Enger, 1970, 1971, 1972; Turoff, 1972 and Sage, 1977) can also be very useful. With the use of random sampling, the conditional probability of an influential event "x" is determined, given that the primary event has occurred (f(x/a)). Normally, it is assumed that a marginal distribution of x, f(x), is assumed (usually normal distribution) and the posterior distribution of the primary event "a" is computed using Bayes' Theorem.

$$f(a/x) = \frac{f(a) \cdot f(x/a)}{f(x)}$$

Finally, the prior and posterior distributions are combined with the use of a weighting factor to determine an estimate of actual costs. The use of this procedure is limited because of the cost of repeated observations for expensive systems and the lack of accurate prior knowledge for highly advanced systems.

The more advanced DA/MAUT is a formal procedure to aid the decision maker in dealing with risk and uncertainty in certain decision problems where (a) the set of alternative actions is small and prespecified, (b) a set of decision criteria is to be simultaneously optimized, and (c) the status of environment is uncertain but the likelihood of occurrence of each state is known or can be estimated. After a decision problem as been properly defined, DA/MAUT entails:

- assessing the probability of each event (each state of nature).
- delineating the set of all possible outcomes, each given in terms of values of decision criteria in their natural units (e.g., cost in $, water pollution in milligram/liter, etc.)
- translating each of these multicomponent outcome values into a single indexed value to reflect "preference" and attitude toward risk on the part of the decision maker. This translation normally involves explicit construction of a multiattribute utility function that would supposedly represent the decision maker's preference structure and his/her attitude toward risk.
- formulating an appropriate decision criterion that will then be used in the final selection of alternatives. This criterion is normally taken to be expected utility, following the well-known principle of maximizing the expected utility laid down over two centuries ago by Bernoulli.
- choosing an alternative that maximizes the expected utility.

Risk and uncertainty are incorporated explicitly through construction of a multiattribute utility function and through formulation of the expected utility decision criterion. Explicit analysis of risks cannot be done conveniently, however. The theoretical bases of this method are probability theory, particularly Bayes' theorem, and utility theory. Many key assumptions need to be made. A set of axioms reflecting individual choice is required to establish the existence of a utility function as a representatation of someone's preference. Some forms of utility and/or prefrence independence conditions are also required to make possible the construction of a multiattribute utility function through decomposition. Finally, Bernoulli's principle is normally invoked to justify the use of the expected utility as the ultimate decision criterion, and the decision problem simplifies to one of choosing an alternative action with maximum expected utility. The method is well developed and has been applied to a wide range of large scale problems.

The strength of the method, as often claimed by its proponents, lies in its attempt to guide a decision maker (or project clientele) to think things through and to make value judgments along a systematic and well-structured path to bring about greater accuracy, consistency, and rationality in decision making. A full-blown application of the method, however, demands a great deal in terms of time and effort both from the project clienteles and the analyst. The greatest criticism of this method is directed toward the necessity of explicitly constructing a multiattribute utility function. This is a theoretical construct whose existence demands a large number of hard-to-verify axioms of individual choice. Indeed, it is hard to imagine that human preference can be represented by a single equation (function). Even with its existence verified, the actual construction process requires yet another set of not-so-obvious independence assumptions to allow construction through decomposition. The construction process is often very taxing for both the decision maker and the analyst. After obtaining the utility function, the succeeding steps (i.e., maximizing expected utility) to reach the final decision is mostly mechanical, with the decision maker's roles replaced by his utility function.

B.5.2 Cost-Benefit and Related Methods (See, for example, Riggs, 1982).

Cost-benefit, cost-effectiveness, and risk-benefit analysis all attempt to find an alternative with the greatest economic efficiency measures by adding up all the good and bad consequences of each alternative. Such consequences are, in turn, measured in monetary terms. To apply the methods, valuation techniques are required to express values of consequences, good or bad, in monetary terms. Some valuation techniques are based on a market mechanism where commodities and services under valuation have readily measurable market values. Some other indirect economic valuation methods rely on demand principles, shadow prices, and similar concepts. The intellectual root of these methods is clearly economic theory, with the utilitarian criterion (pursuing economic efficiency) and the market mechanism serving as two key underlying conceptual bases.

Since 1930, when the U.S. Corps of Engineers first applied the cost-benefit analysis technique to evaluate watear resources projects, the method and its variants have been extensively applied to evaluate and appraise many engineering and other development projects with considerable success. For example, cost-benefit analysis has recently been applied to analyze a proposed runway extension at Kelowna Airport, B.C., Canada (Swoveland, 1981).

The task of listing, estimating, and adding all consequences measured in monetary terms is quite straightforward. The method is relatively simple to execute for projects in which all consequences have measurable market values. The difficulty and hence the reduction in efficiency comes when trying to apply the method to projects involving intangible or "soft" values--such as "human life" or "scenic beauty"--that are very hard to "price."

For projects in which all alternatives yield the same benefits (for example, the EPA may want to look for different ways to reduce a fixed amount of toxicity at a certain chemical-waste dump site), cost-effectiveness analysis is useful. The sticky task of pricing "soft" factors (e.g., health effects) is removed in these cases and the objective, then, is to find the alternative with the least cost.

The other main drawback of these methods with regard to the weapon system acquisition is concerned with the fact that risk and uncertainty elements are not easy to incorporate and to treat with great flexibility.

As a tool for assessing risks associated with project management, the emphasis of these methods is on identifying and quantifying the magnitude of potential adverse effects. Chance elements are viewed as a characteristic of the environment that can be taken into account through the market mechanism when performing the economic valuation of various consequences.

B.5.3 Multiobjective Risk Trade-Off Methods.

Most of the techniques discussed thus far embed the elements of risk and uncertainty in some other elements. (For instance, in DA/MAUT, risk and uncertainty elements are embedded in utility functions and expected utility, and in cost-benefit analysis, risk and uncertainty are treated as part of the environment and reflected in the monetary values of various consequences through the valuation process. However, the class of multiobjective risk trade-off methods discussed here formulate explicit measure of risks and include them as additional decision criteria to be optimized simultaneously with original decision criteria. This allows the decision maker to consider risk explicitly on its own merit. Trade-off analysis between risk and other decision criteria can be carried out conveniently.

The ultimate objective in this case, then,is to assess each alternative action based on original and new risk-related decision criteria.

Multiobjective risk assessment methods address two specific issues:

(a) How should risk-related performance indices be constructed to reflect the concerns of all concerned?

(b) Given such risk indices, how should risk be evaluated against all other decision criteria? Successfully answering these issues leads to trade-off analysis.

Four tools have been developed at Case Western Reserve University to deal with issue (a).

(i) The Partitioned Multiobjective Risk Method (PMRM) (Asbeck and Haimes, 1983)

This method provides a procedure for formulating risk-related performance indices in projects where extreme events are of major concern. Extreme events are defined as events that have a low probability of occurrence but have very devastating effects should they occur. Formulation of risk-related index through the traditional "expected value" is inappropriae in this case since extreme events are not highlighted. The PMRM proposes to alleviate this drawback by partitioning the "damage" scale into various sections, as shown in Figure B. 2.

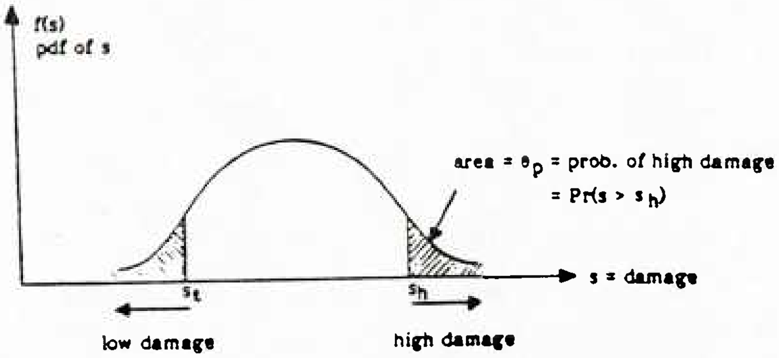


Figure B.2. Partitioning of Damage Scale in PMRM

A risk index reflecting extreme events is then formulated as the normalized expected damage of extreme events (given by $\int_{sk}^{\infty} sf(s)ds/\theta_p$. This risk index is then incorporated into the original problem as an additional objective function. Subsequent trade-off analysis can then be performed. A more detailed description of this procedure is part of the Appendix.

(ii) The Uncertainty Sensitivity Index Method (USIM) (Haimes and Hall, 1977).

This method provides a procedure for formulating a sensitivity index reflecting the uncertainty of our knowledge on key project parameters. If project management decisions are sensitive to key project parameters and if there is imperfection in our knowledge of the values of those parameters, explicit consideration of such imperfection through use of a sensitivity index seems quite appropriate. If, for example, a decision criterion is a function of decision variables $x_1, \ldots, x_n$, given that key project parameters are $\alpha_1, \ldots, \alpha_m$(i.e$f=f(x_1, \ldots, x^n:\alpha_1, \ldots, \alpha_m)$), then a sensitivity index of f with respect to parameter α_i evaluated as a certain decision point $x^*_1, \ldots, x^*_n$ can be formulated as $[\frac{\partial f(x_1, \ldots, x_n:\alpha_1, \ldots, \alpha_m)}{\partial \alpha_i}]^2$. Each of these sensitivity indices can then be appended to the original set of decision criteria for further trade-off analysis.

(iii) The Risk/Dispersion Index Method (RDIM) (Rarig and Haimes, 1983

This approach provides an alternative formulation of sensitivity index to the USIM. The heart of the RDIM is the construction of a sensitivity measure that accounts for the effects of variations in the nominal values of the random variables α. It is assumed that α_j's are independent random variables with known finite means and variances. The sensitivity measure Ω, called the dispersion index, which is interpreted as a first-order approximation the the standard deviation, is then incorporated in a multiobjective optimization formulation. The dispersion index can also be interpreted a measure of the size of the neighborhood about the nominal optimal solution in which the actual solution is most likely to occur. The method also derives a sensitivity trade-off (when using the ε -constraint formulation with the surrogate worth trade-off (SWT) method), which gives an explicit representation of the trade-offs between the sensitivity measure Ω and the other objective functions. Since the RDIM incorporates the SWT method, it generates all needed Pareto optimal solutions to the multiobjective risk problem (see Rarig and Haimes, 1983).

The dispersion index is particularly useful in decision making. The information that Ω conveys to the decision maker(s) can be readily understood: the larger the value of Ω, the greater the possibility that he actual solution will deviate significantly from the nominal solution. Since Ω is a scalar-valued quantity and is independent of the number of objectives, any decision maker who desires to minimize Ω will not be confused by a deluge of sensitivity information that needs to be analyzed at each prospective solution point (alternative policy option).

Note that the fundamental difference between the RDIM and the USIM is that the former generates a sensitivity index on the basis of probability distributions (conditions under risk), whereas the latter generates a sensitivity index without any reference to probability distributions (conditions under uncertainty).

(iv) The Multiobjective Statistical Method (MSM) (Haimes et al., 1980)

This method provides a general framework for modeling multiobjective problems with inherent stochastic elements that may be due to either probabilistic inputs or the inherent stochastic structure of the system. The MSM was developed for the U.S. Army corps of Engineers to account for the risk of flooding in the design and management of interior drainage systems. The method is an integration of multiobjective optimization (the SWT method) and statistical simulation models (Stanford-type stream flow simulation models) to assess the probability of risk events and their consequences. The risk functions in the MSM are first constructed as functions of two state variables--pond duration and pond evaluation of interior floodings. These to state variables are then related to the system's decision variables, x, using Stanford-type stream flow simulation models. Historical records associated with two random variables--precipitation and stream flow--are then used to generate conditional and joint probabilities (as appropriate) for the ultimate development of the expected value of the appropriate risk functions. The set of ordered pairs of the expected value of the jth risk function, $f_j(x^k), j = 1, 2, \ldots, J$, and its associated policy decision (x^k) for $k = 1, 2, \ldots K$ is used to generate the needed functional relationship $f_j(x)$ through a regression analysis technique. The completion of this last step yields to quantifiable risk functions amenable to optimization via the SWT method, where Pareto optimal policies and their associated trade-offs are generated as part of the risk assessment process.

To deal with issue (b)--how to evaluate risk against other decision criteria--a number of techniques are available to assist a decision maker to deal with decision problems under multiple decision criteria (see Chankong and Haimes, 1983). The multiattribute utility function approach described earlier is one of the more commonly used techniques. It deals with the multiplicity of decision criteria through the utility function. Another class of techniques relies on appropriately designed weighting schemes. Here we would like to focus on one class of multiobjective analysis tools that relies on trade-off analysis. A technique in this class and its variants developed at Case Western Reserve University are the surrogate worth trade-off (SWT) method (Haimes and Hall, 1974), the interactive SWT (ISWT) method (Chankong and Haimes, 1978), and the multiobjective multistage impact analysis method (MMIAM) (Gomide and Haimes, 1983). The specific goal of all these methods is to help the decision maker choose the best-compromise or most-preferred alternative by trading-off among various decision criteria. The intellectural roots of these methods are mathematical programming, the concept of Pareto optimality and trade-off analysis, and the concept of the marginal rate of substitution. The methods in their present versions are designed for multiobjective decision problems that can be represented by continuous mathematical programming models. In addition to standard abstract assumptions required in order to use existing optimization techniques, a minor assumption regarding individual choice (namely, that a person's indifference band of preference exists) is assumed.

Typical steps in applying these methods after an appropriate model has been constructed are (i) generate Pareto optimal (noninferior, efficient, nondominated) alternatives, (ii) obtain appropriate trade-off information associated with each generated Pareto optimal alternative, and (iii) interact with the decision maker to solicit his/her preference for those trade-offs. Added efficiency, usability, and flexibility are envisioned if these steps are executed interactively and on-line as part of a well-designed decision support system. Since the SWT method forms a core of all of the above procedure, we describe it briefly below and in more detail in the Appendix.

(v) The Surrogate Worth Trade-Off Method

This method recognizes that optimization theory is usually much more concerned with the relative value of additional increments of the various noncommensurable objectives, at a given value of each objective function, than it is with their absolute values. Furthermore, given any current set of objective levels attained, it is often much easier to turn to decision-makers (DMs) to assess the relative value of the trade-off of marginal increases and decreases between any two objectives than it is to assess their absolute average values. In addition, the optimization procedure can be developed so it is no more than assessing whether one more quantity of one objective is worth more or less than that lost by another at any given level of each of them. An ordinal approach can then be used with much less concern for the distortions that relative evaluation introduces into attempts to commensurate the total value of all objectives.

A detailed discussion of the SWT method is available in the Appendix and therefore only a brief summary of it is presented here:

(i) The SWT method is capable of generating all needed noninferior solutions to a vector optimization problem.

(ii) The method generates the trade-offs between any two objective functions on the basis of duality theory in nonlinear programming. The trade-off function between the f_i and f_j objective functions, λ_{ij}, is explicitly evaluated and is equivalent to

$$\lambda_{ij} = - \frac{\partial f_i(\cdot)}{\partial f_j}$$

(iii) The decision maker interacts with the systems analyst and the mathematical model at a general and very moderate level. This is done via the genration of the surrogate worth functions, which related the decision maker's preferences to the noninferior solutions through the trade-off functions. These preferences are constructed in the objective function space (more familiar and meaningful to decision makers) and only then transferred to the decision space. This is particularly important, since the dimensionality of the objective function space is often smaller than that of the decision space. These prefrences yield an indifference band where the decision maker is indifferent to any further trade-off among the objectives.

(iv) The SWT method provides for the quantitative analysis of noncommensurable objective functions.

(v) The method is well suited for the analysis and optimization of multiobjective functions that involve multiple decision makers.

(vi) The method has an appreciable computational advantage over all other existing methods when the number of objective functions is three or more.

The SWT method and its extensions have been extensively applied to large scale problems such as water resources (e.g., the Maumee River Basis Planning project, Haimes, 1981, Haimes et al., 1979; Das and Haimes, 1980) and energy storage systems (Chankong et al., 1981; Tarvainen and Haimes, 1981).

Returning to the problem of assessing and managing risks associated with the management of large projects, both issues (a) and (b) must both be addressed. A multiobjective risk assessment method must thus combine a suitable method (e.g., USIM, RDIM, PMRM, or MSM) for dealing with issue (a) with one (e.g., SWT, ISWT, or MMIAM) that deals with issue (b). The following steps are commonly taken in a typical appication of such multiobjective risk assessment methods:

1) Develop a mathematical programming model representing the decision problem of interest.

2) Formulate suitable risk-related indices using the appropriate procedures described here earlier.

3) Append these risk-related indices to the original model.

4) Generate Pareto optimal alternatives as well as associated trade-off information between risk-related objectives and other objectives.

5) Interact with the decision maker to arrive at a final decision.

It can be seen that this type of procedure, the treatment or risk and uncertainty can be quite explicit and flexible.

B.5.4 Simulation Models

General simulation models can be very useful tools for risk assessment and management. A typical example of such models is that developed by the General Systems Department of the University of Southern California, which applies systems dynamics simulation to the problem of managing delays and descriptions (D & D). This approach helps to manage the risk involved with D & D by linking their impacts to cost, schedule, and performance goals. The approach uses systems dynamics simulation to model the complex relationships involved with a procurement problem. The general steps involved with systems dynamics include:

1) problem statement

2) identification of key factors and causal relationships involved in the program

3) modeling of complex relationships as chains of simpler relationships

4) reformulation of the model as a flow diagram and representation of it as a set of difference

equations

5) estimation of parameters of the model
6) tesing the model to increase confidence
7) simulation of the effects of proposed changes (delays and disruptions)
8) use of trade-off analysis to determine the best alternative

This approach has been applied , with success, to a problem faced by Ingalls Shipbuilding Inc., a division of Litton Industries, in 1976. It proved to be an objective tool for the representation of D D. However, systems dynamics is not widely taught and it is therefore not a widely accepted technique. Therefore, this will not be further considered. Table B.2 summarizes the essential features of methods in the "formal analysis" class described in this section.

B.6 Review of Methods in the Network Class

The primary focus of the methods reviewed in the last section is risk assessment and management while the project management aspect plays a secondary role, if at all. The methods reviewed in this section, on the other hand, have project management as the nucleus around which other features, such as risk analysis, are built. This is hardly surprising since they are developed by the people whose primary concerns are project planning, management, monitoring, evaluation, and control. As their experience accumulates, the need to explicitly consider the elements of risk and uncertainty associated with managing large projects becomes obvious. This brings about considerable efforts in developing risk assessment and management capabilities and adding them to the existing powerful project management network-based tools. These tools have gained increasing use because of the ease with which problems can be modeled in

Table B.2. Summary of Main Features of Methods in the Formal Analysis Class

	Decision Analysis/Multiattribute Utility Theory	Cost-Benefit Analysis and Variants	Multiobjective Risk Trade-Off Methods
Goal	• To find an alternative with maximum expected utility representing aggregate preferences.	• To find an alternative with greatest economic efficiency (net benefit or expected net benefit).	• To find the best-compromise alternative which is also Pareto optimal through risk trade-off analysis.
Areas of Emphasis (with respect to review goals)	• All aspects of risk assessment in general decision making situation • Possible use for project evaluations.	• Project appraisal and evaluation.	• Risk quantification and evaluation in general decision making situation
Logical Basis & Intellectual Roots	• Probability laws • Utility theory (axioms of individual choice, Bernoulli's Principle)	• Economic theory (utilitarian economic efficiency) • Market mechanism as a means of aggregating risk and multiple criteria	• Nonlinear optimization theory • Probability distribution theory • Pareto optimal concepts • Marginal rate of substitution concept
Assumptions	• Utility and/or preference independence conditions	• Preference can always be measured in monetary terms	• Usual assumptions to use optimazation techniques • Indifference trade-off band of an individual exists
Supporting Tools and Input Requirements	• Techniques for constructing multiattribute utility function • Mathematical expectation • Data requirement is moderate • Effort requirement is extensive	• Valuation techniques to express values of consequences in monetary terms • Cost data required is extensive • Efforts required are moderate	• Optimization techniques • Trade-off analysis • Mathematical expectation • Data and efforts required may be extensive
Treatment of Risk and Uncertainty	• Risk and uncertainty are incorporated explicitly in the form of utility function and expected value • No explicit risk analysis provided	• Chance element viewed as characteristics of environment and aggregated through market mechanism • Limited use of objective probabilities	• Risk is quantified and dealth with explicitly through trade-off analysis
Application Characteristics	• Identify set of alternatives, set of states of nature and set of decision criteria • Identify values of all possible outcomes • Construct multiattribute utility function • Formulate "expected utility" and maximize	• List all consequences of a project • Use valuation techniques to express these consequences (good or bad) in monetary terms • Add all good and all bad consequences separately using discount factor • Compare the two in some appropriate way and make decision	• Develop appropriate model • Formulate suitable risk-related indices using procedures described • Append risk indices to original model • Generate Pareto optimal alternatives and associated risk trade-offs • Interact with DM to arrive at a final decision
Application Experience	• Numerous in both large and small problems (e.g., Hospital Blood Bank (Keeney, 1972), Air Pollution in New York, (Ellis and Keeney, 1972), Fire Department Operation (Keeney, 1973), Airport Development for Mexico City (de Neufville and Keeney, 1972)	• Numerous particularly in water resource and other large engineering or development projects	• Maumee Riber Basin Planning • Energy Storage System • Acid rain
Pros & Cons	• Systematic and well-structured guide to making value judgments • Demanding on users • Relies too heavily on the abstract utility function, the existence and construction of which rely on hard-to-verify abstract assumptions.	• Not all consequences can be "priced" (some valuation issues are still controversial) • Not really effective as risk assessment tool.	• Require mathematical programming formulation—can be quite extensive and data demanding • Risk measures are formulated and treated explicitly—great flexibility • When it applies, provides a systematic and structured guide for DM to make more informed

network form and because of the ability to model complex systems by compounding simple systems. In what follows, we review these tools, starting with the standard CPM/PERT for project management.

1) **Critical Path Method (CPM) and Project Evaluation Review Technique (PERT)** Moder et al., 1983.

The CPM and the PERT are two closely related project management techniques that are based on network analysis. They both focus on the time element (scheduling), although consideration of cost and resources may be brought about in the postanalysis stage. Their primary purpose is to help management determine how time delays in certain components will affect overall progress where slack time is available and what elements are crucial to remaining on schedule. This information is important for making decisions concerning allocation of capital resources and manpower. To use CPM, it is necessary to know the complete breakdown of the project tasks (or activities), their interdependencies, and their duration times. This information is presented in a network format. CPM then identifies the sequence of activities that are most critical to determining the earliest project completion date. This is done by means of computing the earliest data at which an event can occur without extending the project completion date. The difference between the two times is called slack time. Any delay in any activity in this sequence will also induce project delay by the same amount PERT is similar to CPM in purpose and method of analysis. The only basic difference is that, in PERT, the duration time for each activity is a random variable of known (or assumed) probability distribution, whereas it is treated as a known deterministic parameter in CPM. It is, however, assumed that the most optimistic estimate a, the most likely estimate m, and the most pessimistic estimate b of each activity duration time are available. By assuming the beta distribution, the mean t_e and the variance V_e of an activity duration time can be estimated as

$$t_e = \frac{a+4m+b}{6} \quad \text{and} \quad V_e = (\frac{b-a}{6}{}^{2}$$

From here, the computation and analysis proceed in the same manner as in CPM to determine a critical path based on the mean value of each activity duration time. In PERT, however, probabilistic statements about the project completion date (hence, the project delay) are possible through some additional simulation work. Special analyses that can be done with CPM/PERT are time-cost trade-off analysis, resource leveling and project cost monitoring and control.

Since their inception around the late 1950s (for both CPM and PERT), they have been applied quite extensively. CPM was developed (1956-1959) and used jointly by the DuPont Company and Remington Rand Univac (see Kelly, 1961), while PERT was developed in 1958 for the Navy's Polaris missile system project. Both of these methods have since been extensively applied in research and development scheduling, construction planning, and resource allocation.

CPM and PERT are useful for identifying bottlenecks and trouble spots in a program. However, only limited risk analysis can be done,if it can be done at all. Despite the inclusion of uncertainty in time, PERT can at best be considered as a tool for quantifying risk with regard to the time element only. Moreover, the use of three time estimates and the assumption of a beta distribution have drawn considerable criticism (Malcolm et al., 1959; MacCrimmon and Ryavec, 1964; Hartley, 1966).

2) Graphical Evaluation and Review Technique (GERT) (Pritsker, 1977; Pritsker and Happ, 1966; Pritsker and Whitehouse, 1966; and Pritsker and Sigal, 1883). We note that PERT is normally applied to projects with rigid network structures. To apply PERT, all activities as well as their interrelationships must be known, with the understanding that the project is completed if all activities are completed. Moreover, an event represented by a node in the network can occur if and only if all

activities leading to the event are completed and all activities following this event cannot be started until the event occurs. GERT was introduced in 1966 to circumvent these and other shortcomings of PERT. Indeed, GERT was developed as a network planning and management tool to deal with a project described by a stochastic (probabilistic) network structure in which

- activities have a probability of occurrence, have a choice of being perormed, and have variable completion times
- some intermediate activities may not be successful
- an event may take place provided that at least one activity leading to it is completed
- repetition of an activity is permitted
- parallel or sequential activities may be required in order to reach a goal
- alternative activities may be available and specified
- a number of possible outcomes may occur

GERT is very useful and flexible for treating the element of risk and uncertainty associated with two major project variables--time and cost. Its conceptual bases are PERT, stochastic network theory, the moment-generating function, flowgraph theory, and simulation. To apply GERT to a project it is necessary to construct a corresponding stochastic network characterized by logical nodes, probabilistic realization, and additive stochastic parameters on the transmittance.

Each node of a stochastic network consists of a logical input component and a probabilistic or deterministic output component. In order for a node to be realized, the logical condition (exclusive--OR, inclusive--OR,AND) must be satisfied by all of the branches leading into the node. All branches leading out of the deterministic node are certain to occur if the node is realized. If the node is probabilistic, then only one branch is followed, with a probability, p, of being followed. Two types of parameters can be transmitted along a branch: 1) the probability of taking a given path and 2) the distribution of the time to traverse a path.

Once a GERT network has been built, moment-generating functions are used to analyze the system. The results of this procedure yield: (i) the probability that a specific node is realized and (ii) the moment-generating function of the time associated with a node if it is realized.

GERT has been widely used and applied to such projects as those involving queing systems, inventory systems and marketing and reliability analysis as well as project management. For example, GERT has been applied to planning a marketing research project involving oil company sales negotiations and market research (Moore and Clayton, 1976). In another application, GERT was applied to help balance resources and work load in a major jet engine overhaul unit at Kelly AFB in Texas.

GERT is very versatile and makes possible a comprehensive analysis of a very complex fluid stochastic network. Computer codes of modern versions of GERT (e.g., Q-GERT) are also readily available. This versality of GERT is achieved, however, at a cost of greatly increased complexity both in terms of its theoretical basis and the tasks to be performed to apply the method. GERT is a rather formal, rigorous tool characterized by generalized logic structure.

3) The Synergistic Contingency Evaluation and Response Technique (SCERT) (Chapman, 1979).

SCERT is one of the modern network-based tools that attempts to integrate active risk assessment and management mechanisms in large scale project management. It is developed by drawing upon key characteristics of cash flow , the decision tree, and the semi-Markov process. The resulting mathematical basis is a special case of GERT, although the overall methodology is quite different. According to Chapman, the basic motivations for developing SCERT are

* the need to consider risk assessment and management in a direct and active way at a level of detail appropriate to all the necessary decisions, avoiding the passive and biased measurement approaches of most PERT based techniques
* the need for a comprehensive view of risks, whether or not they are put in probabilistic terms, if risk measurement is to be meaningful
* the need for a synergistic framework involving the efficient use of a range of special expertise with a minimum of communication interpretation problems

The main idea of SCERT is to identify all possible risks (including all four project risk variables--cost, time, performance, and resources) and to preplan actions to be taken should an emergency actually occur. The risks and corresponding actions are based upon the integration of experts' opinions.

There are four main phases in the procedure outlined in SCERT: (1) scope, (2) structure, (3) parameter, and (4) manipulation and interpretation. The scope phase consists of identifying all activities, the primary risks and primary responses, and the secondary risks and secondary responses. These are recorded on data sheets. The structure phase consists of identifying and clarifying relationships between risks and responses identified in the scope phase. This includes major and minor risk classification and general specific response classification. These are then diagrammed in a network similar to those used in PERT. The analysis does not continue as in PERT, however; instead, a stochastic decision tree, which reduces to a semi-Markov process, is formed. This diagramming process stimulates consistency and completeness checks and encourages simplifications. The parameter phase includes desired parameter identification, scenario identification, and probability estimation. This associates cost and time deviations from the base plan and probabilities with risk/response combinations to be modeled in a probabilistic manner. The manipulation and interpretation phase consists of four steps: risk computation, risk efficiency, risk balance, and budget contingency assessment. The first three steps involve determining the risks and the relationships to expected costs. The last step consists of determining an appropriate estimate for total costs.

SCERT is still in the development stage, although the basic framework and approach have been laid. Nevertheless, it has been applied to three large projects: (i) an assessment of risks associated with alternative construction schedules for a gas pipeline from the high Arctic to the Canada-US border, (ii) an assessment of the risks associated with alternative bid packages for a fixed-price contract to construct a thermal power station in Iraq, and (iii) an assessment of risks associated with the North Sea pipeline project.

Risk assessment and management provided in SCERT is mostly qualitative and it involves eliciting and aggregating the options of experts. A great amount of paperwork and effort should be anticipated.

4) The Venture Evaluation and Review Technique (VERT) (Moeller and Digman, 1981).

VERT is a computerized, mathematical, simulation-based network technique designed to systematically assess the risks involved in undertaking a program or project. Risk is analyzed with respect to three parameters that are of most concern to managers of new projects: time, cost, and performance. This makes VERT more powerful than other network techniques that consider only time and cost. It is useful as an aid in decision making in situations with incomplete information about all alternatives.

The logical basis for VERT is similar to that of other standard network-based techniques (e.g., PERT) except for the following special features: (i) six new types of node logics are introduced to allow greater flexibility and capability in modeling, (ii) thirteen statistical distributions are provided to model time, cost, and performance as random variables and (iii) mathematical relationships are introduced to relate time, cost, and performance analytically for the purpose of simulation.

Two symbols are used in forming a VERT network: (1) nodes--characterized by a certain input/output--representing milestones or decision points and (2) lines representing activities that are characterized by three parameters--the time consumed, the cost incurred, and the performance generated in completing this activity. The values of these parameters can be assigned in terms of a standard statistical distribution, a histogram, or a mathematical relationship depending on other nodes or arcs. Once the network has been constructed, VERT simulation traverses from the initial node(s) to the final node(s) to create one trial solution. This process is repeated a sufficiently large number of times in order to find a probabilistic indication of possible outcomes of the project, including success or failure.

Applications of VERT include a weapons system development project (Thomas, 1977; Moeller, 1979; Brown, 1975), flood control programs, pollution abatement methods, earthquake analysis, rail yard switching operations, fault-tree analysis, production line-balancing, and war gaming (Moeller, 1979; Moellr and Digman, 1981).

5) The Work Plan Analysis and Scheduling Technique (WoPAST) (Delgrasso and Rosenbluth, 1976).

This technique was developed to plan and schedule complex engineering programs when early goals and ideas are still fluid. The objective of this technique is to combine enhanced communications with PERT network analysis.

A WoPAST network is formed in a manner similar to PERT/CPM. In addition, WoPAST amplifies dependencies and responsibilities by identification of inputs and/or information necessary to perform tasks depicted in the network. A summary of the application of WoPAST can be outlined in eight steps:

a) Define program objectives.

b) Define and list responsibility elements necessary to meet objectives.

c) Assign personal accountability by responsibility element.

d) Generate first-pass action and dependency plans by element.

e) Optimize element schedules, reconcile element interdependency mismatches and establish a critical path.

f) Skew elements with respect to the critical path. This determines the program completion date.

g) Adjust, as required, all element plans to achieve calendar synchronization for the total job. The critical path should be the same as in (f).

h Utilizing the above plan as a format, hold regular review meetings to ascertain status and problems.

Thus, WoPAST helps to assign responsibility for different tasks to individuals or departments and enhances the communication and coordination among various working groups. It also provides for detailed monitoring of the progress of the program since areas of responsibilities are clearly defined. WoPAST, however, does not have an explicit treatment of risks or uncertainties.

WoPAST has been claimed to have been successfully applied in several engineering development programs as well as in medical research.

6) The Risk Information System and Cost Analysis (RISCA)Method

This is a modified network analysis method that quantifies development time and cost risk. RISCA takes advantage of network analysis, simulation, and Monte Carlo techniques in order to account for risk as a function of time. The procedure that RISCA uses can be summarized as follows.

1) The system is represented as a probabilistic model of events.
2) Monte Carlo simulation is used to generate sample distributions of cost and completion time.
3) The user must then analyze these distributions in the context of available alternatives in order to quantify the risk involved with each.

RISCA provides a framework for analyzing complex systems that do not lend themselves to conventional mathematical determination. Another advantage that RISCA provides is the ability to account for information that is gained over the program life cycle because it deals with risk as a function of time. The disadvantages of the RISCA method are (1) it is hard to deal with the interdependencies involved in the acquisition process, and (2) it does not deal with the risk involved with the performance parameter.

7) The Total Risk Assessing Cost Estimate (TRACE)

This is a method of determining the cost of uncertainties in order to include it in the budgeting process. TRACE provides the PM with a disciplined approach for costing the risk involved with advanced technological impacts on a program. The process involves taking uncertainties into account when estimating activity budgets and using the most likely situation estimates as the estimate for the activity. In particular, TRACE estimates the most likely cost due to risks involved with high technology. This estimate is then added to the baseline cost estimate to determine the total estimated cost of an activity. The model used to determine the TRACE estimate is a simulation model of the contractors' work breakdown structure in combination with some powerful network models (e.g., VERT, RISCA, TRACENET, RISNET, etc.). The procedure includes

1) identification of major subsystems and unfunded technicological risk and uncertainty from the WBS
2) classification of risks into eight categories in order to apply conventional cost estimating techniques
3) assumption of independence between risks and development of cost estimates and probability distributions for each contingency
4) use of VERT and Monte Carlo techniques to derive a single cost distribution for the program
5) application of inflation factors

TRACE has been applied extensively by the Army on such programs as the Pershing II, Stinger/Post, and the Remotely Piloted Vechicle program. This method helps to identify the costs of uncertainty and risk of a program before approval.

8) Other Network Models

The risk management model developed by Lewis R. Ireland of SWL, Inc.

is designed to help identify, assess, and manage the risk involved with DoD system acquisition programs. The model takes advantage of network analysis and probabiity estimation techniques to address elements of risk and to work in connection with commonly accepted project management practices. The model uses the contractors' work breakdown structure to develop an interdependent network of activities. A network analysis technique is then used to quantify the project completion time and the start and finish times of each activity. The decision maker must then set performance, completion time, and cost criteria for each activity along with a risk threshold under which he deems risk acceptable. Results from the network analysis are used to assess the probability and consequences of failure to meet the criteria that were set. The probability and consequences are then compared to the risk threshold, and trade-off options are evaluated to determine management actions. The advantage of this model over others is that it provides a disciplined method for identifying, assessing, and managing risk in the context of project management. However, as the number of activities increase it becomes more and more difficult to determine the network relationships,and criteria and threshold estimates become biased.

The Multiple-Incentive Contract Evaluation (MICE) method is used by defense contractors to evaluate the risk relative to the contract. MICE helps to identify feasible system parameter specifications and selects the optimal contract parameter. This method uses the probability distribution of performance, cost, and scheduling to evaluate the contract with respect to certain contract specifications in order to determine profitability. MICE is a network analysis method specialized to the needs of the contractor; however, it can provide the PM with expectations about the performance of the contract.

Table B.3 summarizes and contrasts the main characteristics of some of the network-based methods discussed in this section.

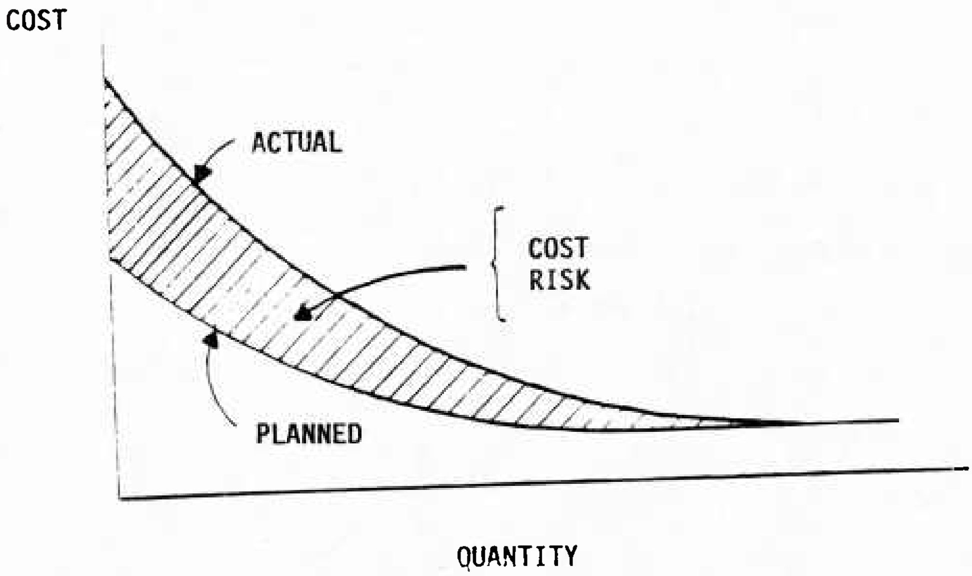
Table B.3. Network-Based Methods and Their Characteristics

Characteristic	PERT/CPM	GERT	SCERT	VERT	WoPAST
Goal	• To assist management to determine critical tasks and effects of delays of such tasks on overall project	• To deal with a project characterized by uncertainties and changes	• To provide active, systematic comprehensive risk assessment/management mechanisms in large-scale project management	• To analyze risks associated with a project in terms of time, cost and performance	• To plan and schedule complex projects when early ideas and goals are still fluid
Areas of Emphasis	• Risk quantification • time element (time-cost trade-off possible)	• Risk analysis regarding time and cost of a project	• Complete risk analysis in large scale projects	• Risk analysis in terms of time, cost and performance	• Project planning and scheduling
Logical Basis and Intellectual Roots	• Activity network • Probability theory	• PERT & stochastic network theory • Moment-generating theory • Flowgraph theory • Simulation	• Cash flow • Decision tree • Semi-Markov process	• Similar to PERT • Probability distribution theory	• Similar to PERT
Assumptions	• Beta distribution of time variable	• Statistic assumptions	• Similar to GERT	• Similar to GERT	• Similar to PERT
Supporting Tools & Input Requirements	• Network analysis • Data and effort requirements are moderate	• Stochastic network analysis • Moment-generating function • Simulation	• Decision tree • Semi-Markov analysis • Group interaction	• Simulation • Stochastic network analysis	• Extension of PERT/CPM
Treatment of Risk and Uncertainty	• Limited risk analysis can be performed	• Allows explicit and flexible treatment	• Risks are explicitly identified • Posible responses to risks are enumerated • Qualitative	• Systematically assesses risks involved in three key areas • Probabilistic indications of project success of failure is possible	• No explicit treatment
Application Characteristics	• Events and activities are mapped out as a network • Critical sequence of activities is then determined	• Stochastic network is constructed • Use moment-generating functions to analyze the network • Simulate the system	• Identify risks, possible responses, and interrelationships • Identify and estimate parameters and probabilities • Manipulate and interpret results (risk assessment)	• Stochastic network is constructed • Perform VERT simulation by traversing from initial to final nodes to create a trial solution • Repeat for sufficiently large number of times to find a probabilistic indication of success or failure	• A network is developed and person responsible for each task is identified • Input dependency is identified • Schedule mismatches are negotiated and optimal path is identified
Application Experience	• Widely used • Developed as a part of the Polaris Submarine Project	• Widely used in planning market research • Balance resource and workload in jet engine overhaul at Kelly AFB, Texas	Risk assessment in: • Construction schedules of gas pipeline • Bid packages to construct a thermal power plant	• Weapon system development • Flood control program etc.	• Some engineering development projects • Possible applications in medical research
Pros and Cons	• Efficient use of resources • Reduce project time scale • Identify troublespots and bottlenecks • Lacks flexibility • Time estimates not well known	• Very useful for modeling and analyzing stochastic systems • Complex and demanding to apply	• Has potential for comprehensive risk assessment • Qualitative • Paper works and efforts can be quite prohibitive	• Treat risk in three aspects • Effort, resources and time consuming	• Not too complex • Enhance communication among participants • Does not treat risk and uncertainty

APPENDIX C

(i) RISK OF IMMATURE DESIGN

In most programs, the result of research and development efforts is a technical data package (TDP) that is used in preparing for initial production. Therefore, the quality and thoroughness of the TDP have a significant influence on costs. More specifically, the TDP affects the first unit costs as well as the learning curve related to production. The cost risk is calculated by determining the area between the planned learning curve and the actual learning curve. (From Ingalls 1984 a.)



This cost risk can be reduced by dedicating more effort toward the TDP, in order to provide a more detailed and complete production plan. This can be accomplished through: (From Ingalls 1984 a.)

- use of production engineers in design
- completion of PEP studies
- completion of maturity phase studies on item design

- review of design drawings
- completion of producibility readiness reviews

Funding of these activities before production begins reduces the subsequent overall unit cost of production.

(ii) SOFTWARE RISK

Software has become a growing part of most advanced systems. Unlike hardware, the errors involved with software are not readily seen by the user. They appear as incorrect logic commands and become much more difficult to detect and correct as time goes on. The risks associated with software components include aspects of cost, scheduling, and reliability factors that make them very important to the overall program. The risk handling techniques used for software analysis are pencil and paper analyses, simulation and system verification. These activities can become very costly. Therefore, when allocating funds for software, the following practices become important: (From Ingalls, 1984 a.)

- Bring on software maintenance and support personnel early.
- Assure standardization of all documentation to ensure supportability.
- Have operational testers check whether the software successfully meets the operational requirements.
- Examine software for possible incremental release (modular design).

If emphasis is put on these areas early, a PM can reduce the likelihood of future software problems.

(iii) RISK FROM CHANGES IN PRODUCTION RATES

A program may be required to undergo a reduction in production funds for a particular period of time, resulting in lowered production rate.

However, this action induces a cost risk in the form of an increase in the unit cost. To account for this effect, the unit cost is separated into two components -- direct costs and fixed costs. Direct costs involve all costs that can be assigned to a particular unit, while fixed costs include all facility, equipment, and support costs which transcend the costs directly assigned to all units produced. Because the fixed costs are usually predetermined, when a cut in production funds occurs, only the direct costs are affected and the production rate decreases. This results in the necessity to reallocate fixed costs across fewer units, yielding a higher unit cost per item. For example: (adapted from Ingalls, 1984 a)

Facilities, equipment for rate, support, etc., per year ...	$200M
400 items, materials, labor, and other direct @$600,000...	240M
	$440M

A reduction of $200M would all come from the direct cost initially and would leave $40M for direct cost of items, which would cover (40M/600,000 ea) or 66 items (assuming the vendors will still sell materials at the same rate)

The original cost per item was $440M for 400 items or $1.1M per item. Now the cost is $240M ($200M for support and $40M direct) for 66 items. The cost per item now stands at $240M/66 = $3.64M which compared to the $1.1M, represents a 330% cost growth.

Over the years, program managers have been using the learning curve to deal with this risk. However, in recent years the production rate curve, which is more a function of fixed costs, has been acknowledged as being a better estimate of this risk. Therefore, knowing the impact of the production-rate curve on a production cut will result in the best allocation of funds.

(iv) RISK OF INADEQUATE FACILITY START-UP FUNDS

Facility start-up costs include the cost of tooling and test equipment that will be needed during the production phase of a program. These funds are usually required in advance of production because of the lead time associated with designing, acquiring, and setting up the equipment. The risks involved with these activities usually show up as deviations in the production rate. Generally, facilitization equipment is acquired at a level to support some predetermined production rate. If funding for these activities is cut or under-emphasized, the planned production rate may not be attainable. This will result in schedule slippages as well as unit cost overruns.

(v) RISK OF INADEQUATE LONG-LEAD FUNDS

Long-lead funds are required for the procurement of materials and parts that have unusually long lead times. This aspect is of particular interest to the Air Force because of the technologically advanced materials and parts required by the aerospace industry. Again, the risks involved with this activity affect the production rate. Insufficient funding will cause a reduction in the production rate, delays in delivery of finished units, or even a total production shutdown.

(vi) RISKS ASSOCIATED WITH LOGISTICS SUPPORT ANALYSIS

Logistics support analysis (LSA) is a process that ties design concepts of a system to support concepts of the system. Data resulting from LSA is provided to the logistics command and allows for the identification and planning of required equipment, manpower, technical data, supplies, and facilities to be used in support of the system. The risks involved with logistics support do not show up in the development or production phase of a program; yet, once a system is deployed, it has a direct effect on the life cycle cost (LCC) of a system. The relationship between LSA and LCC is a result of the design and supportability of a system. Therefore, a high level of preparedness, resulting from detailed logistics support analysis, will in the long run reduce the life cycle cost of a system.

(vii) RISKS ASSOCIATED WITH SYSTEMS AVAILABILITY

Systems availability can be thought of in terms of two aspects, maintainability and usability. Maintainability depends on the amount of spare parts and support equipment available to the system, while usability depends on the amount of training equipment available along with the maintainability. Although the relationship between availability, maintainability, and usability is complex, a certain minimum level of spare parts, support equipment, and training equipment is required in order to achieve and sustain a particular level of system availability. Again, the risk involved with systems availability is not realized until the systems have been deployed; however, systems availability may have a significant effect on our national defense.

The partitioned multiobjective risk method (PMRM)

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Received 16 August 1983
Revised October 1983
Communicated by A.P. Sage

This approach to risk quantification is based on the concept of conditional expectation. The resulting set of functions provides a fuller description of risk than that of the more popular expected value. Employing these risk functions in conjunction with the surrogate worth trade-off method – a multiobjective decision-making methodology – allows decision-makers to rigorously consider risk-related policy decisions without explicit expression of their utility functions or explicit knowledge of relative objective function weights. An example employing Monte Carlo techniques develops the method stepwise.

1. Literature review

1.1. The risk assessment process

A common trend in the quantification of risk functions is the use of the expected value function. This approach melds events corresponding to all degrees of loss and probability of occurrence; extreme events in particular become concealed during this amalgamation. Because there are some inherent disadvantages in using the expected value, an alternative approach is proposed here. This approach builds on the strengths of the expected value, but offers a fuller description of the distribution of risk and provides for an accounting of the political and socioeconomic aspects of risk assessment.

Risk, a focal topic in decision analysis today, has been given many definitions. The U.S. Water Resource Council [46] reserves risk for potential outcomes described by well-known probability distributions, and uncertainty for those not well-known. Lowrance [30] defines risk as the probability and severity of adverse effects. Kaplan and Garrick [27] define risk as uncertainty plus the potential for loss or damage. The discussion that follows in this paper adopts the USWRC dichotomy of risk and uncertainty and Kaplan and Garrick's definition of risk.

The risk assessment process is also debated. Lowrance [30] considers the measurement of risk to be an objective, but points out that probabilistic activity and judging risk acceptability involve active personal and societal value judgment. The Committee on Public Engineering Policy (COPEP) [8] describes a technical process where experts study alternatives and present explicit consequences, followed by a political process involving wide discussion to resolve value conflicts. Kaplan and Garrick [27] ask what losses can happen, how likely are they to happen, and what are their consequences.

Haimes [16] describes a three-phase process. Data collection, retrieval, and processing occur through active public participation. This is followed by modeling of risk and other objectives and the generation of Pareto-optimal policies [36] with trade-offs, after which sensitivity analysis is done. Finally, the analyst interacts with the decision maker(s), who use subjective value judgment to select a preferred policy in the context of the overall decision.

Gathering an adequate data base is often a substantial activity in risk assessment; diverse, long-term risk data has not yet been specifically collected. No direct data may even be available for new technologies [44]. Morgan [32], [33] identifies five data knowledge levels: good statistical evidence for the process is available; the subprocesses

North-Holland
Large Scale Systems 6 (1984) 13–38

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have good statistical evidence; no good data is available, but a similar process is well known; only professional intuition and judgment are available; and even the experts have little basis for judgment. Haimes [14,16,17] and Haimes and Hall [24] further consider data inadequacy and other modeling pitfalls.

Slack, Wallis, and Matalas [43] consider the best assumption for the distribution of a T-year flood by relating expected design loss to an assumed distribution given the actual underlying distribution. Four distributions (normal, Gumbal, log normal, and Weibul) are considered and Monte Carlo techniques are used to determine sensitivities of the expectation to variations in actual and assumed distributions, skewness, sample size, and year–flood size. The results of this analysis are given for three information levels. With no information, the normal distribution is the best assumption. Given identification of the actual distribution, the normal distribution is still the best assumption. Further identification of ranges for skewness and the relative scale, coupled with knowledge of the expected design loss, can improve on the normal assumption.

The marginal benefit of one decision versus another is important information in the decision-making process; trade-offs help guide decision-makers' choices. Useful analysis methods should make hidden trade-offs explicit (Sage and White [41]). An activity's societal benefits must balance the trade-offs of risks borne inequitably in a population (Rowe [40]). Decision-makers should consider the global circumstances of a decision (Morgan [33]).

Subjective judgment guides the choice of acceptable risk levels. Values, central to the acceptance process, are evolving, dynamic entities (COPEP [8]). Fischhoff, Lichtenstein, Slovic, Keeney and Derby [9] warn that values can be dynamic, situation dependent, and open to manipulation during the decision appraisal, noting that issues of fact and issues of value should be kept scrupulously distinct in the decision-making process. Given the interaction among various personalities and between individual and group goals, 'any successful analysis must be sensitive to the nature of the decision-making process' (Cohon, ReVelle and Palmer [7]).

1.2. General frameworks for risk assessment

COPEP [8] 'believes that risk and benefit must be regarded as a continuum, and incremental changes across the whole range must be part of the analysis'. 'There is no such thing as zero risk' (Rowe [39,40]); that is, no loss may reach a magnitude where it becomes 'unthinkable' to allow any probability of occurrence. Okrent [34] observes that society is not risk free and cannot be.

House [26] considers risk in the political decision-making process. Fischhoff et al. [9] discuss the uncertainties in assessing the precise level of very low probabilities and define three categorical approaches to acceptable risk: professional judgment, bootstrapping, and formal analysis.

Professional judgment integrates facts and technical experts' values. Bootstrapping assumes that evolutionary, adjustive processes have in the past struck a societally acceptable balance that is a useful guideline to future decisions. One approach based on the bootstrapping philosophy (Starr [44]) determines what is 'traditionally acceptable' rather than 'best'. Formal analysis applies analytic schemes from formally defined rational principles; the central question is to determine at what point risk is 'sufficiently' reduced.

1.3. Formal analysis

Formal analysis can help in clarifying the questions, making underlying assumptions explicit, anticipating consequences, and describing trade-offs and options (Lowrance, in Schwing and Albers [42]).

1.3.1. Utility theory approaches

Many formal analysis approaches are applications of utility theory (see von Neumann and Morgenstern [47] and Keeney and Raiffa [29]). Friedman and Savage [10] suggest a particular utility curve to explain some classic consumer behavior. Reutlinger [38] notes that public investment decisions require a societal utility function, but individual functions (being cardinal) cannot be mathematically aggregated. Conversely, Hax and Wiig [25] combine utility functions by weighting factors in capital investment decisions, while Keefer and Pollock [28] aggregate utility functions to perform resource allocation with multiple objectives.

Swalm [45] investigates expected value by suggesting two alternatives: receiving one million dollars, or a coin toss returning nothing for heads and three million dollars for tails. Most people will quickly choose the one million dollars, although the expected value of the coin toss is 1.5 million dollars; even a five-million-dollar chance is often not preferred, counter to some applications of decision theory where expected value is the decision criterion. Many people would prefer a guaranteed income of $2x$ to an equal chance for an annual income of x or $3x$ (Marshall [31]).

1.3.2. Other approaches

There are approaches not explicitly based on utility theory. Haimes, Loparo, Olenik and Nanda [23] developed the multiobjective statistical method (MSM), a statistical assessment of different system configurations in a context of competing objectives. Given a set of decision choices x, the expectation of each objective function $f(x)$ may be determined as follows: for each x, an expected value for $f(x)$ may be simulated; a probability is associated with each result; summing products of the expected-value/probability pairs over the range of the random variables for fixed x gives an expectation for $f(x)$. The surrogate worth trade-off (SWT) method and its extensions (Haimes and Hall [20]; Haimes [15]) are used to develop trade-offs and, through interaction with the decision-maker, a preferred solution is obtained.

Kaplan and Garrick [27] note that multiplying probability times consequences to compute risk equates low-probability, high-damage scenarios with high-probability, low-damage ones – not equivalent events. They view risk as a functional relationship of probability (or, instead, frequency of occurrence) and consequence (damage or loss) rather than the expectation of the function, and present a technique for finding that functional relationship. Howard (Haimes [16]) proposes the concept of a micromort – one one-millionth chance of death – as a means of expressing risk.

Rarig and Haimes [37] develop a dispersion index and sensitivity trade-off through a Taylor's series first-order approximation and apply them in an algorithm based on the SWT method. The uncertainty/sensitivity index method (USIM) (Haimes and Hall [21]; Haimes [16]) uses a surrogate uncertainty function to describe the sensitivity of a dominantly influential equation parameter and, in the multiobjective decision-making format of the SWT method, develops trade-offs between a business-as-usual option and a conservative, risk-averse option.

1.4. Perception of risk

Slovic, Fischhoff and Lichtenstein (Schwing and Albers [42]) and Fischhof et al. [9] have done recent work in risk perception. They feel that three heuristics are especially relevant to risk perception: availability, or judging the likelihood of rare events by the ease of recalling or imagining them; overconfidence, or underjudging the degree of risk related to oneself and presuming uncertain quantities can be judged more precisely than proves to be the case; and the desire for certainty, which causes denial of uncertainty to reduce the anxiety it can generate.

2. Mathematical foundations

The partitioned multiobjective risk method (PMRM) (Asbeck [1]) employs several concepts. The theory of random variables may be used to find an unknown marginal probability density function (marginal pdf). A conditional expectation may be defined using this marginal pdf, and both may be approximated through Monte Carlo techniques. Finally, the surrogate worth trade-off (SWT) method, a multiobjective decision-making technique, is valuable in risk-related decisions.

2.1. Random variables

Papoulis [35] describes a method for finding the unknown marginal pdf of a random variable if the process generating that random behavior is known in terms of random variables with known marginal pdfs. Consider the general problem of finding the probability rule for

$$X = g(Y_1, Y_2, \ldots, Y_n), \tag{2.1}$$

where the Y_i are random variables with known probability rules. Define a set of auxiliary random variables $X_1, X_2, \ldots, X_n$ as follows:

$$X_1 = g_1(Y_1, Y_2, \ldots, Y_n) \overset{\Delta}{=} g(Y_1, Y_2, \ldots, Y_n), \tag{2.2a}$$

$$X_i = g_i(Y_1, Y_2, \ldots, Y_n) = Y_i, \qquad i = 2, 3, \ldots, n. \tag{2.2b}$$

Furthermore, define $h(X_1, Y_2, Y_3, \ldots, Y_n)$ as the solution of equation (2.2a) for Y_1, and then substitute the identities $X_i = Y_i$, $i = 2, 3, \ldots, n$. The joint pdf of the Y_i is then:

$$f_{X_1, X_2, \ldots, X_n}(x_1, x_2, \ldots, x_n)$$

$$= \left.\frac{f_{Y_1, Y_2, \ldots, Y_n}(y_1, y_2, \ldots, y_n)}{|\det J(y_1, y_2, \ldots, y_n)|}\right|_{\substack{y_1 = h(x_1, \ldots, x_n) \\ y_i = x_i,\ i = 2, 3, \ldots, n}}, \tag{2.3}$$

where $J(\cdot)$ is the Jacobian and $\det |J(\cdot)| \neq 0$. For this problem:

$$\det J(\cdot) = \partial g_1 / \partial y_1 .$$

If it can be assumed that the Y_i are independent random variables, then:

$$f_{X_1, X_2, \ldots, X_n}(x_1, x_2, \ldots, x_n)$$

$$= f_{Y_1}(y_1) f_{Y_2}(y_2) \ldots f_{Y_n}(y_n) \left.\left|\frac{\partial g_1}{\partial y_1}\right|^{-1}\right|_{\substack{y_1 = h(x_1, \ldots, x_n) \\ y_i = x_i,\ i = 2, 3, \ldots, n}}. \tag{2.4}$$

The probability density function sought is the marginal pdf $f_{X_1}(x_1)$. This can be found by integrating the other $n - 1$ variables $x_2, x_3, \ldots, x_n$ over their limits. In general:

$$f_{X_1}(x_1) =$$

$$\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} f_{X_1, X_2, \ldots, X_n}(x_1, x_2, \ldots, x_n)\, \mathrm{d}x_2 \ldots \mathrm{d}x_n . \tag{2.5}$$

Note that if the X_i, $i = 2, 3, \ldots, n$, are constrained to intervals (e.g. uniformly distributed), the integral bounds become functions of the remaining variables which can create additional computational complexities.

2.2. Conditional expectation

Conditional expectation based on a marginal pdf may be defined as follows. Given the marginal pdf $p_X(x) = \Pr\{X = x\}$ governed by the axioms

$$p_X(x) \geq 0, \qquad -\infty < x < \infty$$

$$\int_{-\infty}^{\infty} p_X(x)\, \mathrm{d}x = 1,$$

$$P_X(x) = \int_{-\infty}^{x} p_X(y)\, \mathrm{d}y \text{ is nondecreasing}, \tag{2.6}$$

$$\Pr\{a < X < b\} = \int_a^b p_X(x)\, \mathrm{d}x,$$

and assuming $p(x) \geq 0$ for $0 < x < \infty$ and $p(x) = 0$ for $-\infty < x \leq 0$, the conditional expectation of an event $D = \{x \mid x \in [a, b]\}$, where the notation $c \in (a, b]$ means that $a < c \leq b$, is given by

$$\mathrm{E}[X \mid D] = \frac{\int_a^b x p_X(x)\, \mathrm{d}x}{\int_a^b p_X(x)\, \mathrm{d}x}. \tag{2.7}$$

2.3. Monte Carlo approximation

Repetitive computations can provide a sampling of the behavior of a random variable X. Given the functional relationship $X = g(s, Y_1, Y_2, \ldots, Y_n)$, where Y_i, $i = 1, 2, \ldots, n$, are random variables with known distributions and s is a variable related to a policy option, a model of the process may be constructed. Fixing s, successive calculations of X, using randomly drawn values for the Y_i, build a sample of X's behavior. The density distribution of this sample can be considered to be an approximation of $p_X(x)$, the probability density function for X. Define the following quantities:

$$\begin{aligned}
k &= \text{total number of simulator samples},\\
x_i &= \text{individual simulator sample values};\\
&\quad i = 1, 2, \ldots, k,\\
N &= \text{an integer}; \qquad 1 \leq N < \infty,\\
\bar{x} &= \max_{1 \leq i \leq k} x_i,\\
\underline{x} &= \min_{1 \leq i \leq k} x_i,\\
\Delta x &= (\bar{x} - \underline{x})/N,
\end{aligned} \tag{2.8}$$

$$\sigma(a, b) = \text{the number of } x_i \text{ such that } x_i \in (a, b] \text{ or, if } a = \underline{x},\ x_i \in [\underline{x}, b],$$
$$\underline{x} \leqslant a < b \leqslant \bar{x},$$
$$f_n = \sigma(\underline{x} + (n-1)\Delta x, \underline{x} + n\Delta x)\,; \qquad 1 \leqslant n \leqslant N.$$

The probability density function may be approximated by

$$p_X(x) = p(x_i) \overset{\Delta}{=} \frac{f_n}{k\Delta x}, \tag{2.9}$$

for n such that $x_i \in (\underline{x} + (n-1)\Delta x, \underline{x} + n\Delta x)$ or, when $x_i = \underline{x}$, $n = 1$. Since there are a finite number of observations, there exists a $\delta > 0$ such that for all $\Delta x < \delta$ and for all $1 \leqslant n \leqslant N$, $f_n \in \{0, 1\}$ thus, choosing $\Delta x < \delta$ results in:

$$p(x_i) \in \{0, 1/k\Delta x\}. \tag{2.10}$$

The probability distribution (also called the cumulative distribution function–cdf) may be approximated by:

$$P_X(x) \overset{\Delta}{=} \int_{-\infty}^{x} p(y)\,\mathrm{d}y \simeq \sum_{\underline{x} \leqslant x_i \leqslant x} p(x_i)\Delta x. \tag{2.11}$$

Observing that $p(x_i)\Delta x \in \{0, 1/k\}$ implies that, for $\Delta x < \delta$:

$$P_X(x) \simeq \frac{\sigma(\underline{x}, x)}{k}. \tag{2.12}$$

The conditional expectation of the event $D = \{x \mid x \in (a, b]\}$ for $\underline{x} \leqslant a < b \leqslant \bar{x}$ may be approximated (see equation (2.7)) by:

$$\mathrm{E}[X \mid D] \simeq \frac{\sum_{a < x_i \leqslant b} x_i p(x_i)\Delta x}{\sum_{a < x_i \leqslant b} p(x_i)\Delta x}. \tag{2.13}$$

Observing that $x_i p(x_i)\Delta x \in \{0, x_i/k\}$ implies that, for $\Delta x < \delta$:

$$\mathrm{E}[X \mid D] \simeq \frac{\sum_{a < x_i \leqslant b} x_i}{\sigma(a, b)}. \tag{2.14}$$

Note that in (2.13) and (2.14) the summation bounds for $a = \underline{x}$ are $\underline{x} \leqslant x_i < b$.

2.4. The surrogate worth trade-off (SWT) method

The multiple-objective optimization problem is also known as a vector optimization problem. Two approaches, the parametric and the ε-constraint (which is employed in the SWT method), are outlined here.

2.4.1. Vector optimization problems and noninferior solutions

The vector optimization problem (Brayton et al. [3]) defines a decision vector $s = (s_1, s_2, \ldots, s_n)$, an objective vector $f = (f_1, f_2, \ldots, f_m)$ with $f_i : \mathbb{R}^n \to \mathbb{R}^1$ and $f : \mathbb{R}^n \to \mathbb{R}^m$, and a set of feasible solutions $S = \{s \mid g(s) \leqslant 0\}$ with $\boldsymbol{g} = (g_1, g_2, \ldots, g_p)$, where $g_i : \mathbb{R}^n \to \mathbb{R}^1$ and $\boldsymbol{g} : \mathbb{R}^n \to \mathbb{R}^p$. The notation $f : \mathbb{R}^n \to \mathbb{R}^m$ means that the function $\boldsymbol{f}(\boldsymbol{s})$ maps values from the space of real numbers with dimension n into the space of real numbers with dimension m. Assuming the f_i have noncoincident minima, minimize them. A point $s \in S \subseteq \mathbb{R}^n$ is a noninferior (Pareto) point for a mapping $\boldsymbol{f}$ if and only if *no* change $\Delta s \in \mathbb{R}^n$ exists such that, for all $i = 1, 2, \ldots, m$:

$$f_i(s + \Delta s) \leqslant f_i(s), \tag{2.15}$$

with strict inequality for at least one function when $s + \Delta s \in S \subseteq \mathbb{R}^n$.

Consider (Fig. 1) a scalar decision variable s and two conflicting quadratic objective functions f_1 and f_2 (Haimes [14]) in the decision space, where the region N represents the noninferior solutions. Those noninferior solutions are shown in the functional (or objective) space in Fig. 2.

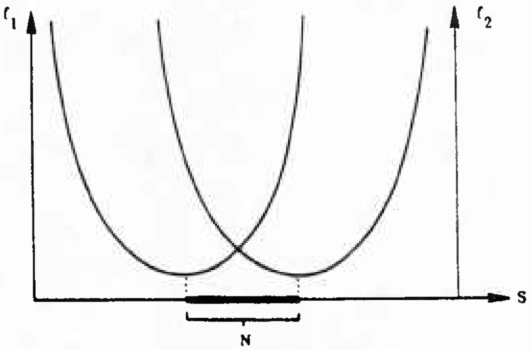


Fig. 1. Two conflicting quadratic objectives graphed in the decision space.

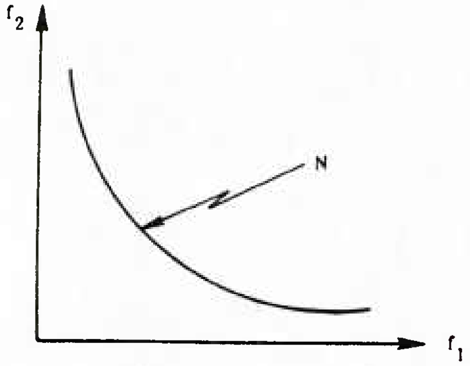


Fig. 2. The noninferior solutions from Fig. 1 graphed in the functional space.

To decrease the value of one objective, the value of (at least) one other objective must increase. This is the essential quality of noninferiority.

2.4.2. Parametric approach

The parametric approach further defines the vector optimization problem as

$$\min_{s\in S} w^{\mathrm{T}} f$$

$$\text{subject to } w^{\mathrm{T}} e = 1\,,$$

$$w_i \geq 0\,, \qquad i = 1, 2, \dots, m\,, \qquad (2.16)$$

where $w = (w_1, w_2, \dots, w_m)$ and $e = (1, \dots, 1) \in \mathbb{R}^m$. This is a well-defined minimization problem. The solution is unique when all f_i are convex; otherwise, some noninferior solutions are unobtainable. For example, Fig. 3 shows a two-objective minimization problem with a compact, nonconvex, feasible decision set in the functional space. The noninferior solutions are in bold lines. Solutions shown in the heaviest bold line (a pocket of nonconvexity) are not obtainable by the parametric approach, which finds the minimal-valued hyperplane tangent to the convex hull of the feasible set when given a $w = (w_1, w_2)$. The hyperplanes H_1 and H_2 in Fig. 3 both have slopes corresponding to the same weights w and contain noninferior solutions; however, H_1 is the

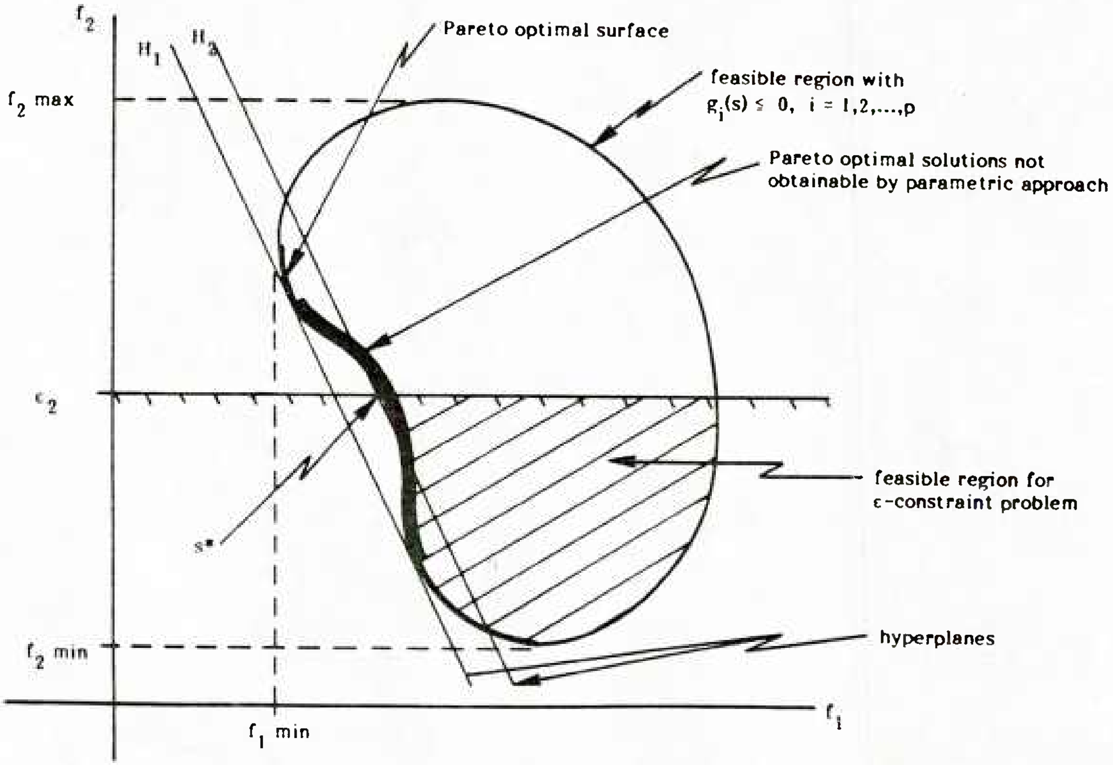

f2
H1
H2
Pareto optimal surface
f2 max
feasible region with
gi(s) ≤ 0, i = 1,2,...,p
Pareto optimal solutions not
obtainable by parametric approach
ε2
feasible region for
ε-constraint problem
s*
f2 min
hyperplanes
f1 min
f1

Fig. 3. The ε-constraint approach.

minimal hyperplane for this w, so H_2 and its associated noninferior solutions are never obtained by the parametric approach.

2.4.3. The ε-constraint approach, basis of the SWT method

The ε-constraint approach clarifies the vector optimization problem differently. Choose an $i \in \{1, 2, \ldots, m\}$ and define the problem (Haimes [12–14]):

$$\min_{s \in S} f_i(s) \qquad (2.17)$$
$$\text{subject to } f_j(s) \leqslant \varepsilon_j , \qquad j \neq i, \qquad j = 1, 2, \ldots, m ,$$

where each component of f is once continuously differentiable on S. From the Lagrangian,

$$L(s, \boldsymbol{\lambda}) = f_i(s) + \sum_{j \neq i} \lambda_{ij}(f_j(s) - \varepsilon_j) ,$$

and for each $s \in \mathbb{R}^n$ with $\lambda_{ij} > 0$ satisfying the Kuhn–Tucker conditions, it follows that $L(s) = f_i(s)$ and $\varepsilon_j = f_j(s)$; thus:

$$\frac{\partial L}{\partial \varepsilon_j} = \frac{\partial f_i}{\partial f_j} \triangleq - \lambda_{ij}(s) . \qquad (2.18)$$

The ε-constraint approach varies the ε_j parametrically to generate all needed noninferior solutions as well as their associated trade-off values, λ_{ij}. Haimes, Hall and Freedman [22] and Chankong and Haimes [5] discuss the SWT method and the ε-constraint approach, while Haimes and Chankong [19] discuss the theoretical basis for the trade-offs in terms of the local theory.

Recalling Fig. 3, ε_2 defines an artificial upper bound on the feasible set. The associated ε-constraint problem is:

$$\min_{s \in S} f_1(s)$$
$$\text{subject to } f_2(s) \leqslant \varepsilon_2 , \qquad (2.19)$$

and its solution is the noninferior point s^*. The associated strictly positive trade-off at s^* between f_1 and f_2 is given by the Lagrange multiplier λ_{12} related to the Lagrangian $L(s) = f_1(s) + \lambda_{12}(f_2(s) - \varepsilon_2)$. Chankong [4] and Chankong and Haimes [5] give conditions relating the parametric and ε-constraint problems. Haimes et al. [22] developed several algorithms for applying the ε-constraint approach. The PMRM employs the static n-objective ε-constraint (SNE) algorithm.

2.4.4. The surrogate worth function

The surrogate worth function is defined as $W_{ij} \in [-10, +10]$, $i \neq j$ and $i, j = 1, 2, \ldots, m$. For a given λ_{ij}, there are $f_i(s)$ and $f_j(s)$, $i \neq j$ and $i, j = 1, 2, \ldots, m$, associated with a particular $s \in S \subseteq \mathbb{R}^n$. The decision-makers choose $W_{ij}(>, =, <)0$ when they prefer λ_{ij} units of $f_i(s)$ (more, equally, less) than 1 unit of $f_j(s)$. Using the W_{ij} and the values of $f_i(s)$ and $\lambda_{ij}(s)$, the analyst helps the decision-maker(s) search the noninferior surface defined by $\lambda_{ij} > 0$ until all $W_{ij} = 0$. Associated with these $W_{ij} = 0$ are a set of λ^*_{ij} and f^*_i. Solving the problem

$$\min_{s \in S} f_i(s)$$
$$\text{subject to } f_j(s) \leqslant f^*_j , \qquad j \neq i \text{ and } j = 1, 2, \ldots, m . \qquad (2.20)$$

yields the preferred decision $s^* \in S \subseteq \mathbb{R}^n$.

2.4.5. Strengths of the SWT method

The vector optimization problem may be solved parametrically if the weights w_i are known; however, they usually are not known. The SWT method allows the decision-maker indirectly to discover the preferred weights by searching the noninferior surface for a preferred solution. The responsibilities in the risk assessment process are thus distributed more equitably. The analyst obtains, structures, and presents the data. The decision-makers determine the importance of the various decision factors in view of objective function values and trade-offs expressed in familiar measures.

Risk-related decisions are often made by groups. The surrogate worth trade-off method with multiple decision-makers (Hall and Haimes [24]) allows for using compromise, negotiation, and any quantifiable decision rule in the decision process.

3. The method

The PMRM involves a six-step procedure:

(1) find marginal probability density functions;

(2) partition the probability axis to provide a fuller risk description;

(3) map the probability partitions onto the damage axis;

(4) find conditional expectations;

(5) generate functional relationships between conditional expectations and policy choices; and

(6) employ the SWT method to generate Pareto optimal solutions and their associated trade-offs and to choose a preferred policy.

An overview of the process is presented in Fig. 4, while Fig. 5 describes more detailed branch points in flowchart fashion.

3.1. Find marginal probability density functions

The PMRM requires the marginal probability density functions (pdfs), $p_X(x; s_i)$, relating probability of loss to magnitude of loss for each of the policy options s_i, $i = 1, 2, \ldots, q$. The s_i are considered scalar in this discussion, although extension to the vector case should not present significant theoretical difficulties. These probability density functions may be explicitly known, obtained through random variable techniques such as those in Section 2.1, or approximated by Monte Carlo techniques, as in Section 2.3. The random variable technique, useful and inexpensive in simple problems, is exact but computationally cumbersome; the Monte Carlo approach is approximate but more broadly applicable.

From these $p_X(x; s_i)$, a set of probability distribution functions (cdfs) may be defined as:

$$P_X(x; s_i) = \int_0^x p_X(y; s_i)\,\mathrm{d}y, \qquad i = 1, 2, \ldots, q, \tag{3.1}$$

where $p_X(x; s_i) = 0$ for $x \leq 0$. Each of these cdfs is a description of the distribution of 'risk' (Kaplan and Garrick [27]) for the policy choice s_i; that is, the cdfs relate the loss x and its probability of occurrence $p_X(x; s_i)$ (Kaplan and Garrick define a relationship of loss and *frequency* of loss, rather than *probability*). One way to extract essential information is through mathematical expectation:

$$\mathrm{E}[X] = \int_{-\infty}^{\infty} x p_X(x; s_i)\,\mathrm{d}x. \tag{3.2}$$

This condensation loses information about losses at the extreme tails of the loss distribution.

3.2. Partition the probability axis

The PMRM partitions the probability axis into a set of ranges. The ultimate intention of this partitioning is to provide the decision-maker with a more complete view of the distribution of risk. One application concerns events that represent extremely large losses with a low probability of occurrence, while another is concerned with describing optimistic, middle-of-the-road, and pessimistic viewpoints. Some guidelines based on the standard normal distribution $N(0, 1)$ for choosing the partitioning values α_i, $i = 1, 2, \ldots, n+1$, on the probability axis are presented using Fig. 6. In the general literature (e.g. Section 1), catastrophic events have 10^{-5} or less probability of occurrence; this relates to events exceeding $+4\sigma$ on $N(0, 1)$. Employing the $N(0, 1)$ exceedence probability function $1 - P_X(x; s_i)$ as a heuristic (Fig. 7), it can be seen, for example, that if three ranges were needed to represent the bulk of the low-damage events, an intermediate damage range, and a range representing 'catastrophic' low probability events, the $+1\sigma$ and $+4\sigma$ partitioning values would provide an effective rule-of-thumb in the normal distribution case: the low range contains 84% of the loss events, the intermediate range contains just under 16% of the loss events, and the higher range contains about 0.0032% (or 3.2×10^{-5} probability) of the loss events. Alternatively, using $+2\sigma$ and $+4\sigma$ as the partitioning values results in 97.7%, ~2.3%, and 0.0032%% for the respective ranges.

As another example, again using the heuristic of Fig. 7, the probability axis could be partitioned into optimistic/middle-of-the-road/pessimistic ranges. This could be done by choosing the partitioning values associated with $\pm 1\sigma$ for the sample. This results in the lower 15.9% of the damage observations, the middle 68.2%, and the higher 15.9%.

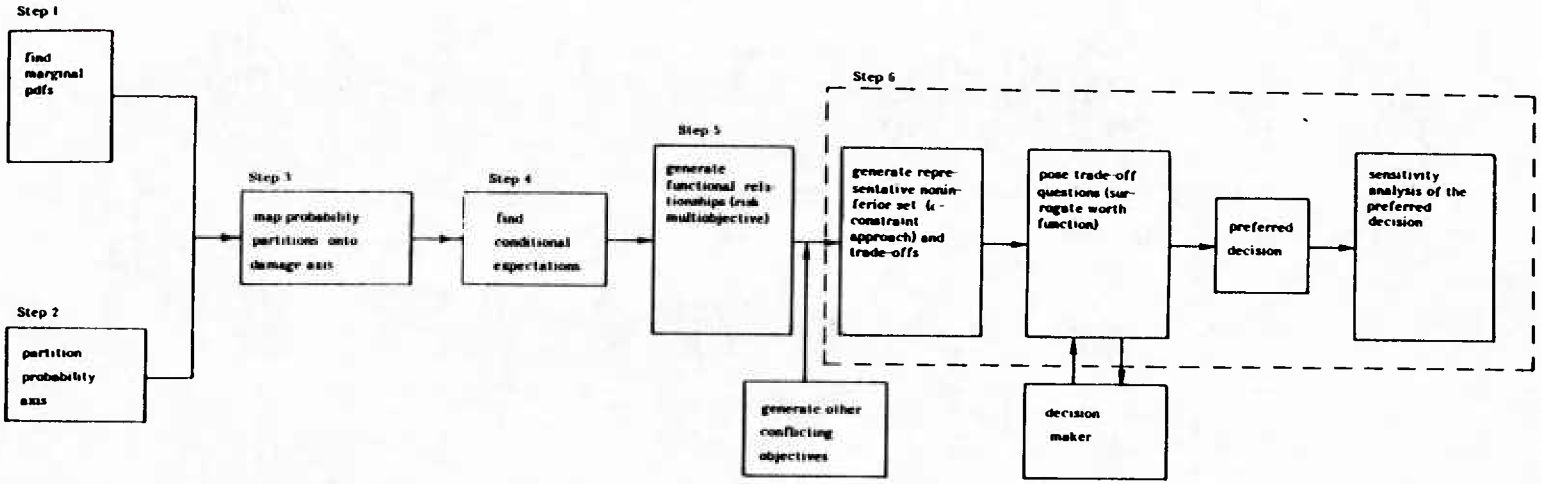

Step 1
find marginal pdfs
Step 2
partition probability axis
Step 3
map probability partitions onto damage axis
Step 4
find conditional expectations
Step 5
generate functional relationships (risk multiobjective)
generate other conflicting objectives
Step 6
generate representative noninferior set (ε - constraint approach) and trade-offs
pose trade-off questions (surrogate worth function)
decision maker
preferred decision
sensitivity analysis of the preferred decision

Fig. 4. Major steps in the PMRM.

mpdf - marginal probability density function
jpdf - joint probability density function
pdf - probability distribution function
numbers in parentheses indicate sections pertinent to that step

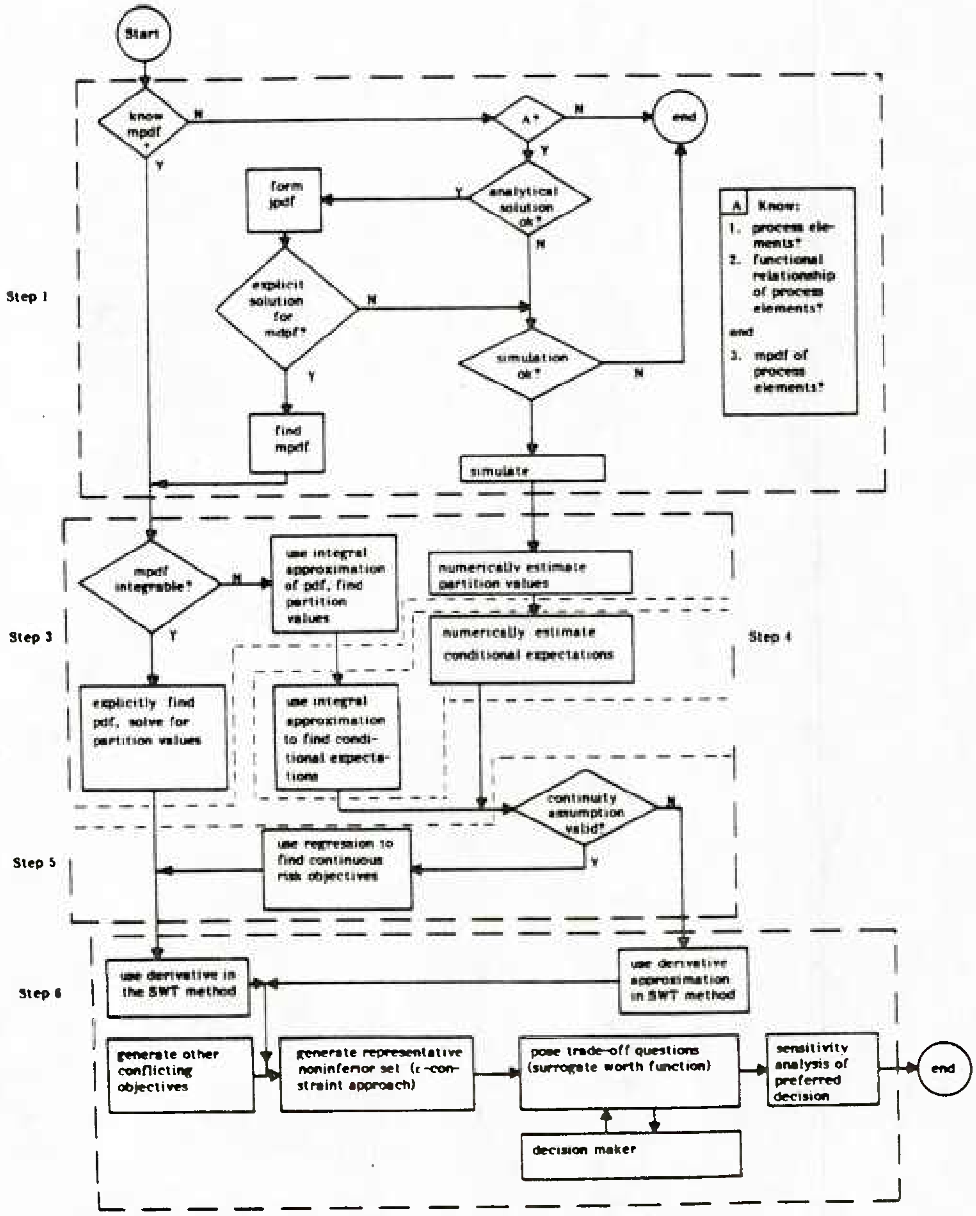

Start
know mpdf?
N
Y
A?
N
Y
end
analytical solution ok?
Y
N
form jpdf
explicit solution for mdpf?
N
Y
find mpdf
simulation ok?
N
simulate
A Know:
1. process elements?
2. functional relationship of process elements?
and
3. mpdf of process elements?
Step 1
mpdf integrable?
N
Y
use integral approximation of pdf, find partition values
numerically estimate partition values
numerically estimate conditional expectations
explicitly find pdf, solve for partition values
use integral approximation to find conditional expectations
continuity assumption valid?
N
Y
use regression to find continuous risk objectives
Step 3
Step 4
Step 5
Step 6
use derivative in the SWT method
use derivative approximation in SWT method
generate other conflicting objectives
generate representative noninferior set (ε-constraint approach)
pose trade-off questions (surrogate worth function)
sensitivity analysis of preferred decision
end
decision maker

Fig. 5. Detailed flowchart of the PMRM procedure.

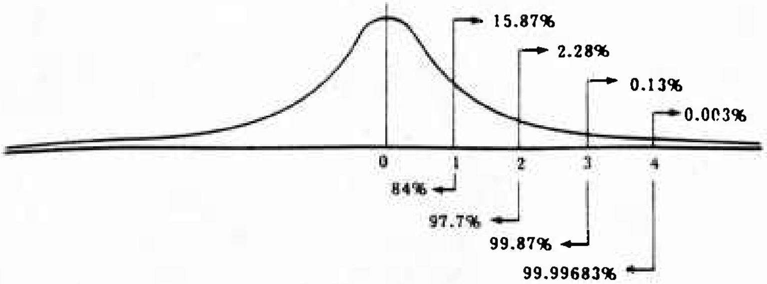


Fig. 6. Percent of observations falling above and below four σ-limits.

3.3. *Map partitions to the damage axis*

Having decided the partition values on the probability axis, these values are mapped onto the damage axis (as in Fig. 7). Solutions must be found to the following problem:

For each partition value α_i, $i = 1, 2, \ldots, n+1$, *and each policy option* s_j, $j = 1, 2, \ldots, q$, *find an* $a_{ij} > 0$ *such that* $P(a_{ij}; s_j) = \alpha_i$.

These a_{ij} are used in defining conditional expectations for the next step of the PMRM. If $P(x; s_j)$ has a closed-form expression for the inverse (that is, there exists an equation of the form $P^{-1}(\alpha_i; s_j) = a_{ij}$ for all α_i and a_{ij}), the unknown a_{ij} may be found explicitly; otherwise, those a_{ij} may be found by approximation through bisection, false position, or other line search techniques.

3.4. *Find conditional expectations*

Conditional expectations must be found for each $P(x; s_j)$, $j = 1, 2, \ldots, q$, with domains on the damage axis defined by the a_{ij}, $i = 1, 2, \ldots, n+1$ and $j = 1, 2, \ldots, q$. Let

$$\begin{aligned} D_{1j} &= [a_{1j}, a_{2j}]\,, & j &= 1, 2, \ldots, q\,, \\ D_{ij} &= (a_{ij}, a_{i+1,j}]\,, & i &= 2, 3, \ldots, n; \\ & & j &= 1, 2, \ldots, q\,. \end{aligned} \tag{3.3}$$

The expectations are computed (equation (2.7)) to be:

$$\mathrm{E}[X \mid D_{ij}] = \frac{\displaystyle\int_{a_{ij}}^{a_{i+1,j}} x p_X(x; s_j)\,\mathrm{d}x}{\displaystyle\int_{a_{ij}}^{a_{i+1,j}} p_X(x; s_j)\,\mathrm{d}x}\,,$$

$$i = 1, 2, \ldots, n\,; \qquad j = 1, 2, \ldots, q\,. \tag{3.4}$$

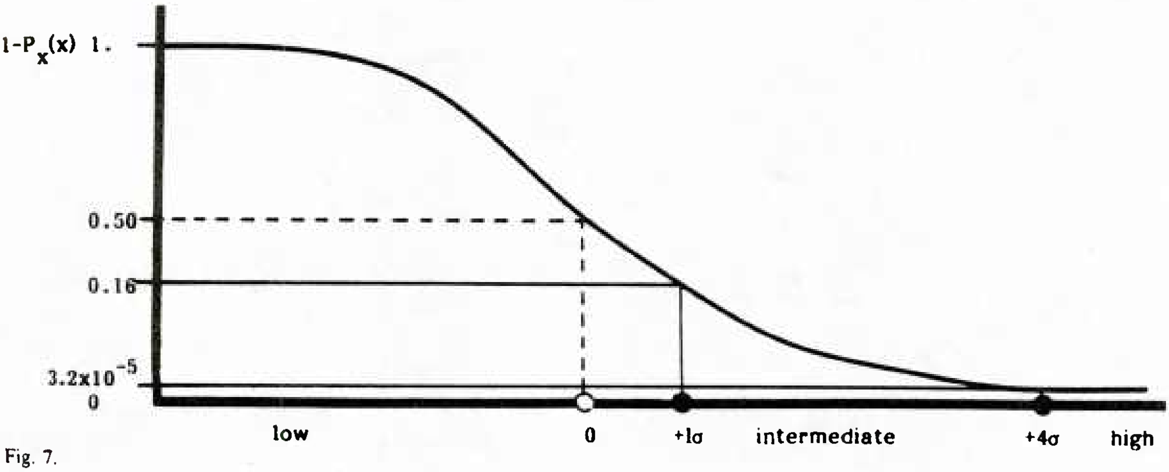


Fig. 7.

Note that the denominator above is actually

$$\int_{\alpha_{ij}}^{\alpha_{i+1,j}} p_X(x; s_j)\,\mathrm{d}x = \alpha_{i+1} - \alpha_i, \quad i = 1, 2, \ldots, n, \tag{3.5}$$

but the use of the integral denominator reduces the computational error arising from the use of approximate values for the a_i and α_i in equation (3.4).

3.5. Generate functional relationships

Given the $\mathrm{E}[X \mid D_{ij}]$, a set of risk functions $f_i(s)$, $i = 1, 2, \ldots, n$, may be found as follows. If it can be assumed that the conditional expectations for values of s between the known data points act in a continuous and a simple way, then for any region on the probability axis D_{ij}, with $i \in \{1, 2, \ldots, N\}$, regression may be used to fit a smooth curve $f_i(s)$ to the point pairs $\{s_j, \mathrm{E}[X|D_{ij}]\}$, $j = 1, 2, \ldots, q$. If the continuity assumptions cannot be made or a smooth curve cannot be found to fit the data points to the analyst's satisfaction, the data-point pairs may be used in lieu of the $f_i(s)$'s to obtain a less general result in the next step. Each $f_i(s)$ relates the damage domains associated with the partitioned regions on the probability axis to the policy variable s.

3.6. Employ the SWT method

In Section 3.5 a set of risk objectives was created that, in combination, can provide some insight into how risk is distributed over the range of losses for each decision choice. A structured technique is required for effectively employing this information and valuing each decision choice. Trade-off information for the decision-maker(s) is required; furthermore, risk is only one component of the broader context of the decision-making process. These criteria suggest the necessity of a multiple objective decision-making methodology that allows decision-makers to express their implicit values and/or those of their constituents during the decision-making process; the surrogate worth trade-off (SWT) method (Section 2.4) satisfies these needs by providing trade-offs among the several objectives.

Through the SWT method, the $f_i(s)$, $i = 1, 2, \ldots, n$, may be used in conjunction with a set of conflicting nonrisk objective functions $f_j(s)$, $j = 1, 2, \ldots m$, and a feasible decision set $S = \{s \mid g_i(s) \leq 0,\ i = 1, 2, \ldots, p\}$, as follows. Arbitrarily choosing the first nonrisk objective as the primary objective (although experience has shown that the objective measured in monetary units is the best selection as the primary objective) and for any one risk function $f_h(s)$ with $h \in \{1, 2, \ldots, n\}$, solve the problem P_h (see below) to obtain trade-offs between the risk function $f_h(s)$ and the nonrisk objectives:

$$P_h: \min_{s \in S} f_1(s)$$

$$\text{subject to}\ f_j(s) \leq \varepsilon_j, \qquad j = 2, 3, \ldots, m$$

$$f_h(s) \leq \varepsilon_h, \qquad h \in \{1, 2, \ldots, n\}.$$

In practice, the trade-offs between the m conflicting nonrisk objectives need be obtained only once, while the trade-offs related to each of the n risk objectives can be obtained by swapping one risk objective for another in P_h. This process of swapping the risk objectives one at a time is necessary because these risk functions are dependent upon each other by construction (see Section 4.4). The trade-offs provide extremely useful information in the decision-making process.

If the continuity assumption in Section 3.5 cannot be justified, the trade-offs in the SWT method may be obtained by approximation of the partial derivative; that is,

$$\lambda_{1h} = \frac{\partial f_1(s_j)}{\partial f_h(s_j)} \simeq \frac{f_1(s_j) - f_1(s_k)}{\mathrm{E}[X \mid D_{hj}, s_j] - \mathrm{E}[X \mid D_{hk}, s_k]}, \quad h = 1, 2, \ldots, n, \tag{3.7}$$

where $k = j + 1$ for an increase of s_j to s_{j+1} and $k = j - 1$ for a decrease to s_{j-1}. Gemperline [11] employed this approach with the SWT method. Although heuristically appealing, technical details of this approximation have not been confirmed.

These trade-offs allow decision-makers to see the marginal cost of a small change in an objective, given a particular level of risk assurance for each of the partitioned risk regions. A knowledge of marginal costs gives the decision-maker insights that are useful for determining acceptable risk levels. In general, trade-offs between the risk functions associated with any one loss dimension cannot be found; however, if more than one risk axis is used – say mortality, morbidity, dollars lost, etc. – trade-offs between these risks should be obtainable if the objectives are in conflict.

4. Comments and observations

4.1. On creating the risk functions

In the spirit of regarding risk as a distribution of probability and damage, the decision-maker should ideally be presented with the entire distribution of risk for each policy option. This approach quickly becomes confusing and cannot provide the marginal worth of one decision over another, nor can it show the relations between various nonrisk objectives and the risk aspects of a decision. The PMRM includes risk distribution information through the functions $f_i(s)$, $i = 1, 2, \dots, n$, that relate the conditional expectations associated with the probability axis partitions to the policy variable s (Section 3.5); this provides information across the entire domain of the damage x.

4.2. Sufficient Monte Carlo samples

The Monte Carlo sample size is dictated by the 'extremeness' of the events to be considered. In general, if events associated with $P_X(x) \geqslant t$ are of interest and a sample of r points exceeding t are necessary (for an extreme event domain estimate accurate to within some confidence bounds), then $r/(1-t)$ points must be collected. For Q policy choices, $Qr/(1-t)$ data points must be computed. For example, if events with $P_X(x) \geqslant t = 0.999$ are of interest, $r = 10$ sample points are desired for estimation accuracy, and $Q = 5$ policy options are to be considered, then $5 \times 10/(1-0.999) = 5 \times 10^4$ sample points must be computed. These five samples (each containing 10^4 sample points) can each be used as an approximation to the probability density function.

4.3. Relating conditional and unconditional expectations

A relation between the conditional (equation (2.7)) and unconditional (equation (3.2)) expectations may be found. Define the following functions:

$f_1(s)$ = a nonrisk function which serves as the primary objective function in the ε-constraint format
$f_i(s)$ = the $N-1$ conditional expectation risk functions, $i = 2, 3, 4, \dots, N$
f_{N+1} = the unconditional expectation risk function; that is, the expected-value function. (4.1)

Furthermore, let $0 = P(x_2) < P(x_3) \cdots P(x_{N+1}) = 1$ be partition values used to define the $N-1$ conditional expectation risk functions. Note that $P(x_i) = \alpha_i$ for the α_i in Sections 3.2 and 3.3, with $i = 2, 3, \dots, n+1$ and that $i \neq 1$ because the risk functions in this example begin with $f_2(\cdot)$.

Assuming that $P(x)$ is a monotonically increasing (vs. nondecreasing) function of x, it may be observed that $0 = x_2 < x_3 < \cdots < x_N < x_{N+1} = +\infty$.

Define the following constant weights:

$$\theta_i(s) = \int_{x_i}^{x_{i+1}} p(x, s)\,\mathrm{d}x\,, \qquad i = 2, 3, \dots, N. \tag{4.2}$$

Noting that $\theta_i(s)$ is constant with changing s, then

$$f_{N+1}(s) = \sum_{i=2}^{N} \theta f_i(s)\,. \tag{4.3}$$

Further effort should be made to find some similarly simple relation between the conditional and unconditional trade-offs, such that $\lambda_{N+1,1} = \psi[\lambda_{21}, \dots, \lambda N1]$.

4.4. Castastrophic losses and decision-making

Using the notation from Section 4.3, consider

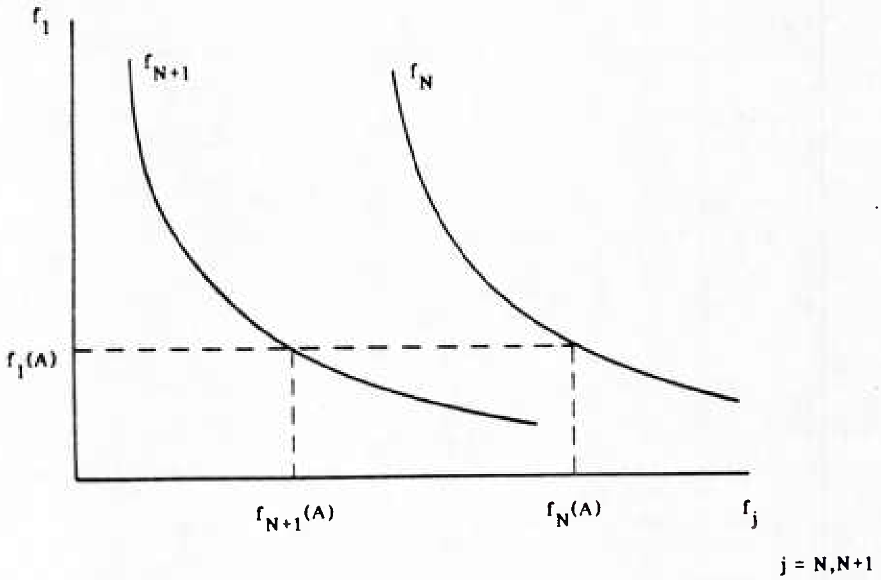


Fig. 8. f_{N+1}, the unconditional expectation, and f_N, the catastrophic conditional expectation vs. f_1, the cost objective, in the functional space.

$f_{N+1}(s)$ (the unconditional expectation), $f_N(s)$ (the conditional expectation of the catastrophic damage events), and $f_1(s)$ (the cost function). Fig. 8 plots $f_1(s)$ vs. $f_N(s)$ and $f_{N+1}(s)$. Note that $f_{N+1}(s)$ characteristically takes values less than $f_N(s)$. When decision-makers are presented with a value for $f_N(s)$ as well as $f_{N+1}(s)$, they are being reminded that besides the lesser value for $f_{N+1}(s)$ there is a nonzero probability of a major loss of $f_N(s)$: therefore, catastrophic events are considered as a component of the decision process.

For example, policy alternative $s = A$ gives the resulting values of $f_1(A)$, $f_N(A)$, and $f_{N+1}(A)$. If the business-as-usual approach is followed, $f_{N+1}(A)$ alone would be available as the risk-representing function. The nonzero probability of the significantly larger loss $f_N(A)$ would have been ignored from the decision-maker's point of view: thus, this valuable information would have been lost.

5. An example

The example that follows is based on Haimes, Asbeck and Gupta [18], a study of risk analysis for transport air pollutants done for the Office of Technology Assessment (OTA), U.S. Congress.

5.1. Problem definition

There has been much concern of late about the effects of acid rain on natural resources. The suspected mechanism involves pollutants being emitted into the atmosphere (for example by industrial smokestacks), mixing and interreacting in the atmosphere while being carried far from the emission sources, raining down on nonindustrial wild areas, and subsequently causing ecological damage such as killing fish and stunting tree growth.

A causal relationship between emission level and resource damage was hypothesized:[1]

$$r = C[(1 - B)E^A + B - T]^D/[1 - T], \qquad (5.1)$$

where

Parameters

B = background loadings

A = atm. chemistry curve shape
T = threshold loadings
C = current resource damage
D = dose/response curve shape

Variables
r = resource damage
E = pollutant emission level.

Resource damage is restricted to $r \geq 0$. Various levels of uncertainty are associated with the above five parameters, but they are assumed to inhabit known ranges. Based on Slack et al. [43] all five parameters are assumed to be normally distributed, independent random variables with the statistics as shown in Table 1. Each mean is the median of the parameter's range, which is assumed to encompass two standard deviations. Thus, the unknown random variable is the resource damage given as a function of a known emission level and probabilistic parameters. Pollutant emission levels of 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 are considered. The emission level $E = 1.0$ represents current emissions and $E = 0.5$ represents 50% of current emission levels. The PMRM is next developed and demonstrated step by step.

5.2. *Find marginal probability density functions*

5.2.1. *Random variable technique*

Define

$$x_1 = g_1(A, B, C, D, E, T) = r ,$$

Table 1

Parameter (random variable)	Mean (μ)	Std. deviation (σ)	Coeff. of variation (σ/μ)
A	0.8	0.15	0.187
B	0.1	0.05	0.5
C	1.0	0.5	0.5
D	1.0	0.25	0.25
T	0.25	0.125	0.5

$$\begin{aligned} x_2 &= g_2(A, B, C, D, E, T) = A , \\ x_3 &= g_3(A, B, C, D, E, T) = B , \\ x_4 &= g_4(A, B, C, D, E, T) = D , \\ x_5 &= g_5(A, B, C, D, E, T) = T . \end{aligned} \tag{5.2}$$

The Jacobian factor for this problem (where C acts as y_1) is:

$$|\det J(\cdot)| = \left|\frac{\partial g_1}{\partial C}\right| = \left|\frac{\partial r}{\partial C}\right|$$

$$= \left|\frac{[(1-B)E^A + B - T]^D}{[1-T]}\right| \neq 0 . \tag{5.3}$$

Solving for C in terms of the x_i gives:

$$C = x_1(1-x_5)[(1-x_3)E^{x_2} + x_3 - x_5]^{-x_4} \triangleq h(\underline{x}, E) . \tag{5.4}$$

The marginal probability density functions of the five parameters are of the form:

$$f_y(y) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^2\right] . \tag{5.5}$$

Since the five random variables are assumed to be independent, the joint density of X_1, X_2, X_3, X_4, and X_5 is:

$$f_{X_1,X_2,X_3,X_4,X_5}(x_1, x_2, x_3, x_4, x_5, E)$$

$$= \frac{640}{\pi^2}\sqrt{\frac{2}{\pi}}\, e^{-K(\underline{x}, E)}|(1-x_5)[(1-x_3)E^{x_2} + x_3 - x_5]^{-x_4}| , \tag{5.6}$$

where

$$\begin{aligned} K(\underline{x}, E) = {} & \tfrac{10}{3}(x_2 - 0.8)^2 + 10(x_3 - 0.1)^2 \\ & + [x_1(1-x_5)[(1-x_3)E^{x_2} + x_3 - x_5]^{-x_4} - 1]^2 \\ & + 2(x_4 - 1)^2 + 4(x_5 - 0.25)^2 . \end{aligned} \tag{5.7}$$

The marginal density function for X_1 is:

---

[1] Dr. Robert Friedman, Office of Technology Assessment, U.S. Congress.

$$f_{X_1}(x_1, E) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f_{X_1,X_2,X_3,X_4,X_5} \times (x_1, x_2, x_3, x_4, x_5, E)\, \mathrm{d}x_2\, \mathrm{d}x_3\, \mathrm{d}x_4\, \mathrm{d}x_5 . \tag{5.8}$$

This quantity is not explicitly integrable because of the form of $K(\underline{x}, E)$. Given the proper computer algorithms for approximating multiple integrals, this result could be employed effectively in the PMRM mathematics to obtain numerical approximations of the expectation for specific values of E. No such computational tools were readily available, so this approach was abandoned.

5.2.2. *Monte Carlo approximation*

In this approach, 9000 calculations of resource damage were made for each of the six emission levels $E = 0.5$ through $E = 1.0$ (see Section 2.3). The random parameters were assumed to be independent and computations taking values less than zero were assigned the value zero. The Box–Muller transform (Box and Muller [2]) was used to generate normally distributed deviates. The samples were then ordered from least to greatest. Fig. 9 shows histograms for the two extreme cases ($E = 0.5$, $E = 1.0$) created using resource damage increments of 0.02 and normalizing the occurrences by the sample size (9000). About 2.5% of the observations were zeros.

5.3. *Partitioning the probability axis*

For the purposes of example, both the extreme event and pessimistic/optimistic approaches to

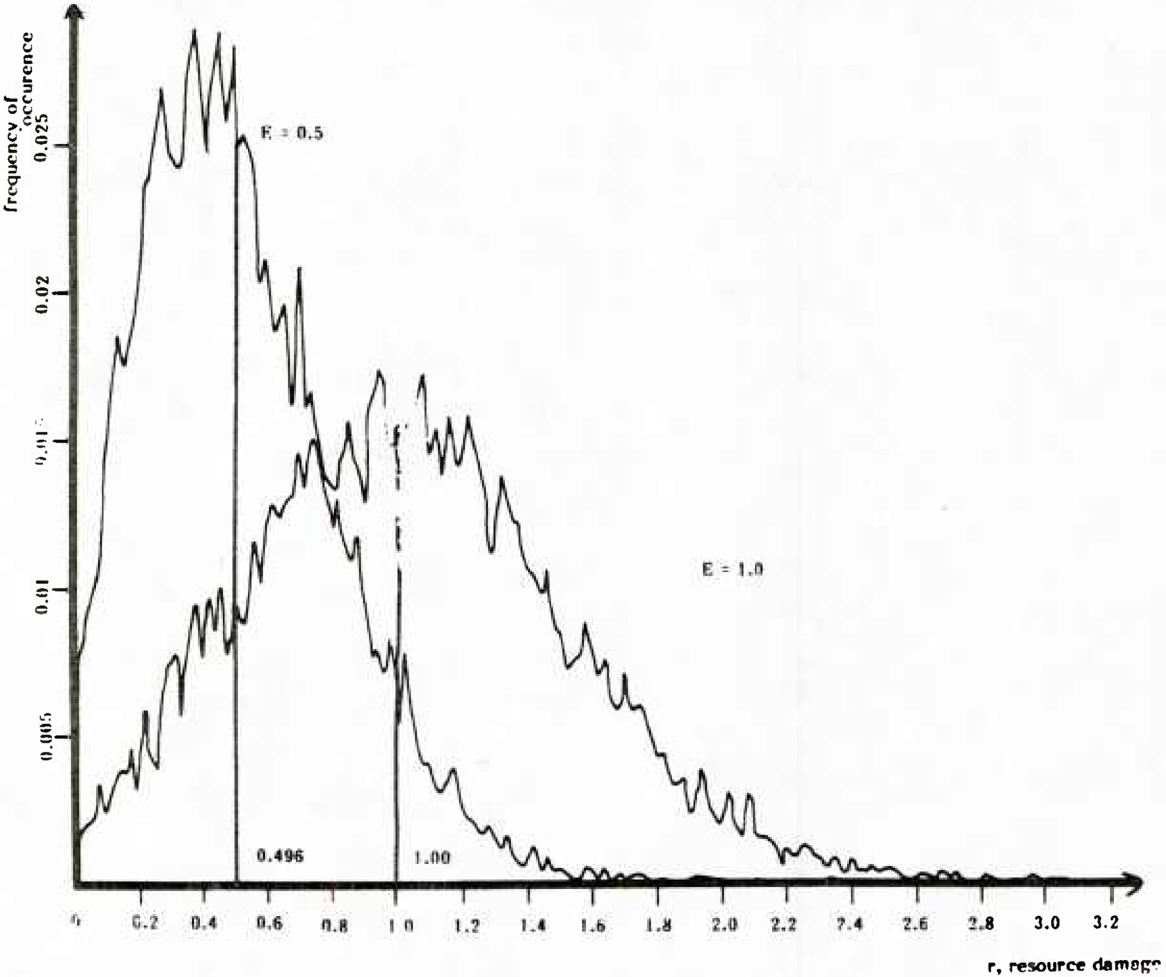


Fig. 9.

partitioning the probability axis (Section 3.2) are employed. Owing to the limited number of sample points, the extreme event partition will use 0.9 and 0.995, which relate closely to the normal distribution heuristic's values of $+1\sigma$ and $+3\sigma$. The pessimistic/optimistic values were 0.159 and 0.841 (see Section 3.2).

5.4. Map partitions to the damage axis

In employing the repetitive computation approach, the probability axis partitions did not need to be mapped onto the damage axis in the strict sense of Section 3.3. The ordered sample values were cumulatively summed and normalized onto the range [0, 1]. Fig. 10 shows histograms for the two extreme cases (E = 0.5, E = 1.0) determined as in Fig. 9. The positions of the entries most closely matching each of the partition values were determined for use in the next step.

5.5. Find conditional expectations

For notational convenience, call the lower-damage events domain I, the intermediate events domain II, and the larger-damage events domain III. Since the samples were ordered from least to greatest, the conditional expectations were computed by summing all samples between entries corresponding to the partition values and then normalizing the sum by the number of entries included (see equation (2.14)). The unconditional expectations were similarly com-

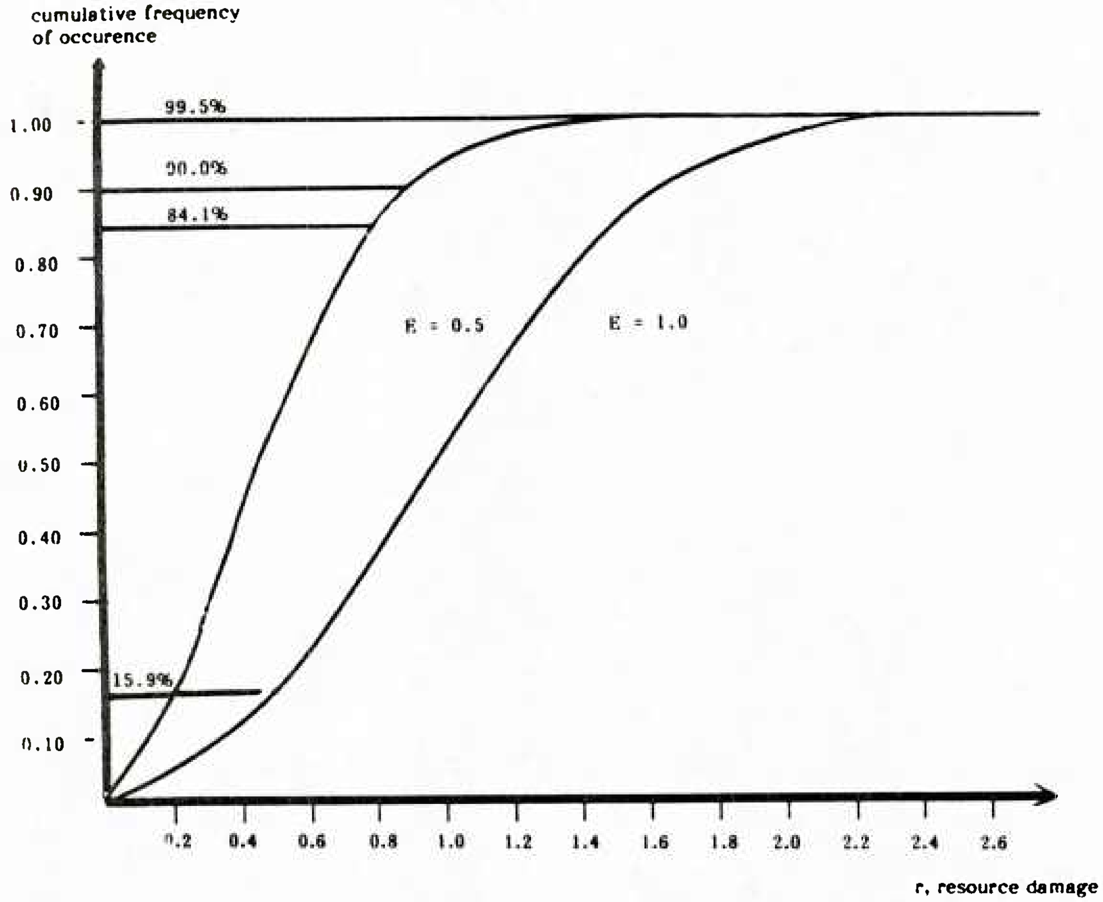


Fig. 10.

puted by summing all the samples and normalizing by the sample size (9000). The results of these computations are given in Tables 2 and 3 for the extreme event and pessimistic/optimistic partitions, respectively; the trade-offs are described in Section 5.7. The conditional and unconditional expectations are plotted against the emission levels in Figs. 11 and 12. The points defining $f_4(E)$ in Fig. 11 are probably erratic due to the small sample size (11–17 observations) per point.

5.6. *Generate functional relationships*

Since the emission level is a continuous variable with $E \in [0, +\infty)$, the continuity assumption (see Section 3.5) can be justified for linear relationships except for $f_4(x)$ in Fig. 11. Table 4 presents coefficients of regression for relationships of the form:

$$f_j(E) = a + bE, \qquad j = 2, 3, 4, 5, \tag{5.9}$$

Table 2
Extreme event partition

Emission level (E)	% Reduction (R)	Additional cost ($\$10^9$) ($f_1(E)$)	Domain I			Domain II			Domain III			Unpartitioned (unconditional)		
			Expected damage ($f_2(E)$)	Trade-off λ_{12}		Expected damage ($f_3(E)$)	Trade-off λ_{13}		Expected damage ($f_4(E)$)	Trade-off λ_{14}		Expected damage ($f_5(E)$)	Trade-off λ_{15}	
				Continuous function	Discrete estimate		Continuous function	Discrete estimate		Continuous function	Discrete estimate		Continuous function	Discrete estimate
1.0	0	0	0.947	1.80	1.56	2.09	1.08	0.704	2.73	1.26	0.941	1.00	1.72	1.47
0.9	10	0.15	0.871	3.22	5.22	1.88	1.93	2.99	2.57	2.25	1.83	0.900	3.08	4.98
0.8	20	0.60	0.765	5.76	9.22	1.73	3.44	5.25	2.32	4.02	4.65	0.810	5.50	8.78
0.7	30	1.5	0.667	10.3	12.3	1.56	6.15	9.92	2.13	7.19	−8.60	0.708	9.82	11.8
0.6	40	2.7	0.569	18.4	19.6	1.44	11.0	12.3	2.27	12.9	7.25	0.606	17.6	18.6
0.5	50	4.8	0.464	32.9	L+	1.27	19.7	L+	1.99	23.0	L+	0.496	31.4	L+

Table 3
Pessimistic/optimistic partition

Emission level (E)	% Reduction (R)	Additional cost ($\$10^9$) ($f_1(E)$)	Domain I			Domain II			Domain III			(Unpartitioned (unconditional)		
			Expected damage ($f_2(E)$)	Trade-off λ_{12}		Expected damage ($f_3(E)$)	Trade-off λ_{13}		Expected damage ($f_4(E)$)	Trade-off λ_{14}		Expected damage ($f_5(E)$)	Trade-off λ_{15}	
				Continuous function	Discrete estimate		Continuous function	Discrete estimate		Continuous function	Discrete estimate		Continuous function	Discrete estimate
1.0	0	0	0.464	3.38	3.09	1.19	1.52	1.26	1.98	1.10	0.775	1.00	1.72	1.47
0.9(B)	10	0.15	0.416	6.03	10.4	1.07	2.72	4.21	1.79	1.97	2.96	0.900	3.08	4.98
0.8	20	0.60	0.372	10.8	17.7	0.959	4.85	7.56	1.64	3.53	5.48	0.810	5.50	8.78
0.7	30	1.5	0.322	19.3	21.2	0.840	8.68	11.0	1.47	6.31	9.46	0.708	9.82	11.8
0.6(A)	40	2.7	0.265	34.5	34.7	0.731	15.5	17.4	1.35	11.3	12.8	0.606	17.6	18.6
0.5	50	4.8	0.206	61.6	L+	0.614	27.7	L+	1.19	20.2	L+	0.496	31.4	L+

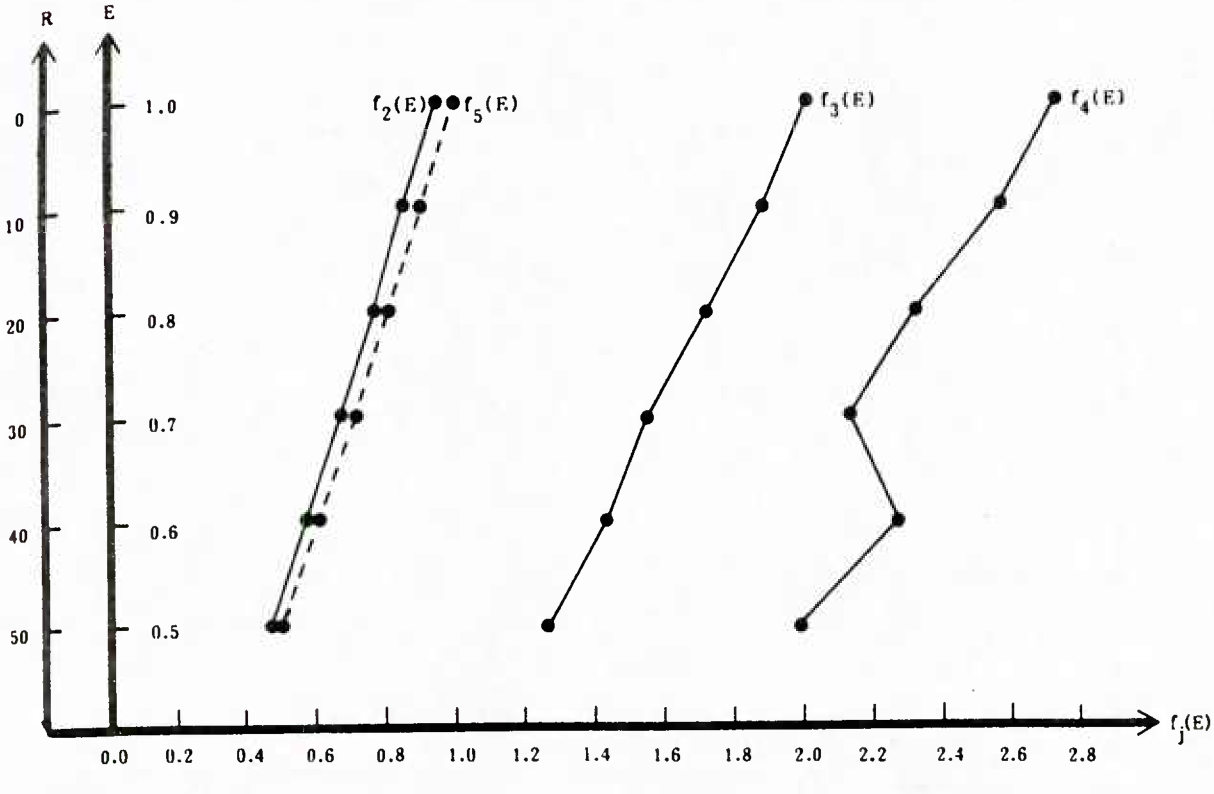


Fig. 11. Extreme event conditional expectations.

where

a = intercept on damage axis.
b = slope of line (damage per unit of emissions).

$$R^2 = \frac{\Sigma\,(aE + b - \bar{f}_j)^2}{\Sigma\,(f_j(E) - \bar{f}_j)^2} = \text{goodness of fit}\,, \qquad j = 2, 3, 4, 5\,.$$

Table 4
Coefficients of regression

Curve	a	b	c	R^2
Extreme event:				
domain I	0.959	−0.00891	–	0.999
domain II	1.60	0.456	–	0.995
domain III	1.37	1.30	–	0.873
Pessimistic/optimistic:				
domain I	0.512	−0.0433	–	0.997
domain II	1.14	0.0456	–	1.00
domain III	1.56	0.397	–	0.997
Cost	5.81	0.298	0.344	1.00

$$\bar{f}_j = \tfrac{1}{6} \sum_{\forall E} f_j(E) = \text{average value of } f_j(E)\,, \qquad j = 2, 3, 4, 5\,.$$

The cost coefficients are discussed in Section 5.7.1. As expected, the fits are quite good except for that of extreme event domain III, $f_4(E)$.

5.7. *Employ the SWT method*

To determine acceptable risk levels in the context of the overall decision circumstances, functional relationships describing other decision factors are required. A cost function is developed and trade-off related to the linear relationships from Section 5.6 are found; discrete trade-off approximations are also explored.

5.7.1. *The cost function*

The cost of sulphur dioxide (SO_2) control is given in Fig. 13. This analysis employs the

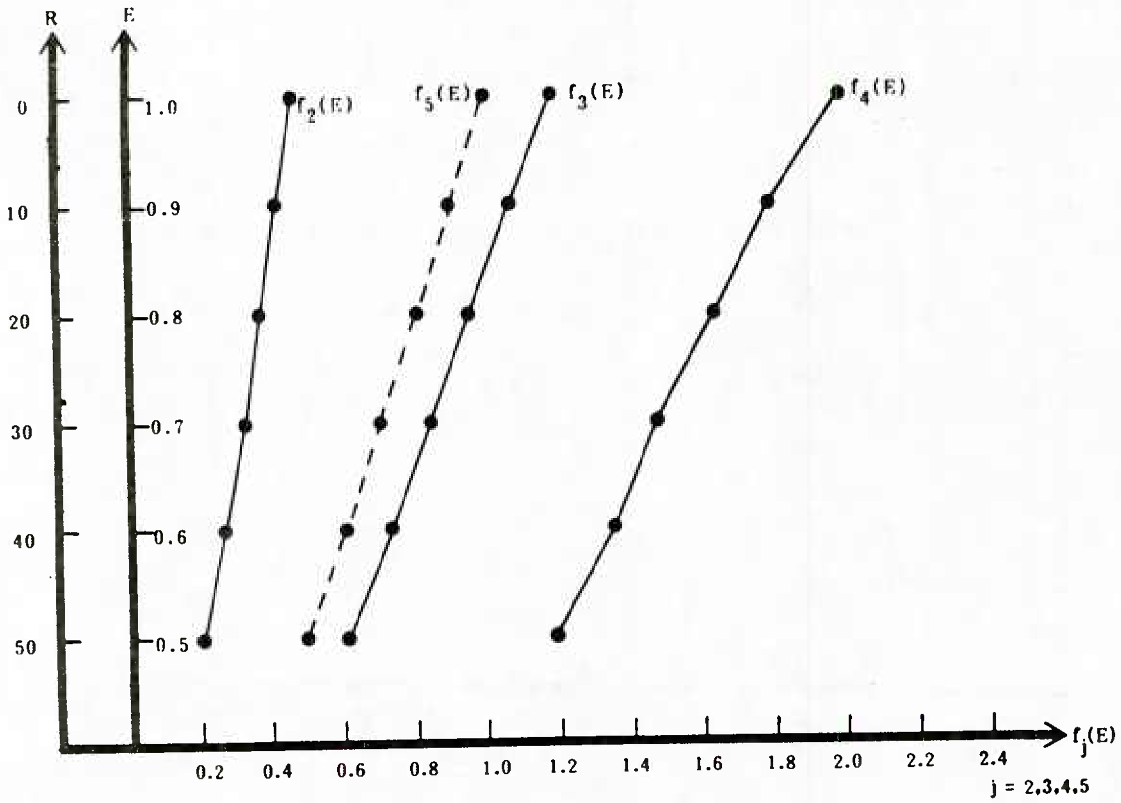


Fig. 12. Pessimist/optimist conditional expectations.

median OTA Cap cost estimates between the 'plant cap', which assumes any plant's emissions do not exceed the specified limit, and the least-cost 'state cap', where required 'plant cap' reductions are achieved through intrastate trading. The base (current) level of SO_2 emissions is taken to be 22.5 million tons/year; hence $E = 0.5$ corresponds to a reduction of SO_2 emissions to 11.25 million tons/year. Median costs and emission levels for each of the eight Cap ranges 1.0 lb through 4.0 lb are given in Table 5.

Given that the curve in Fig. 13 is approximately exponential, coefficients of regression for a relationship of the form

$$f_1(E) = b\, e^{a(1-E)} - c \tag{5.10}$$

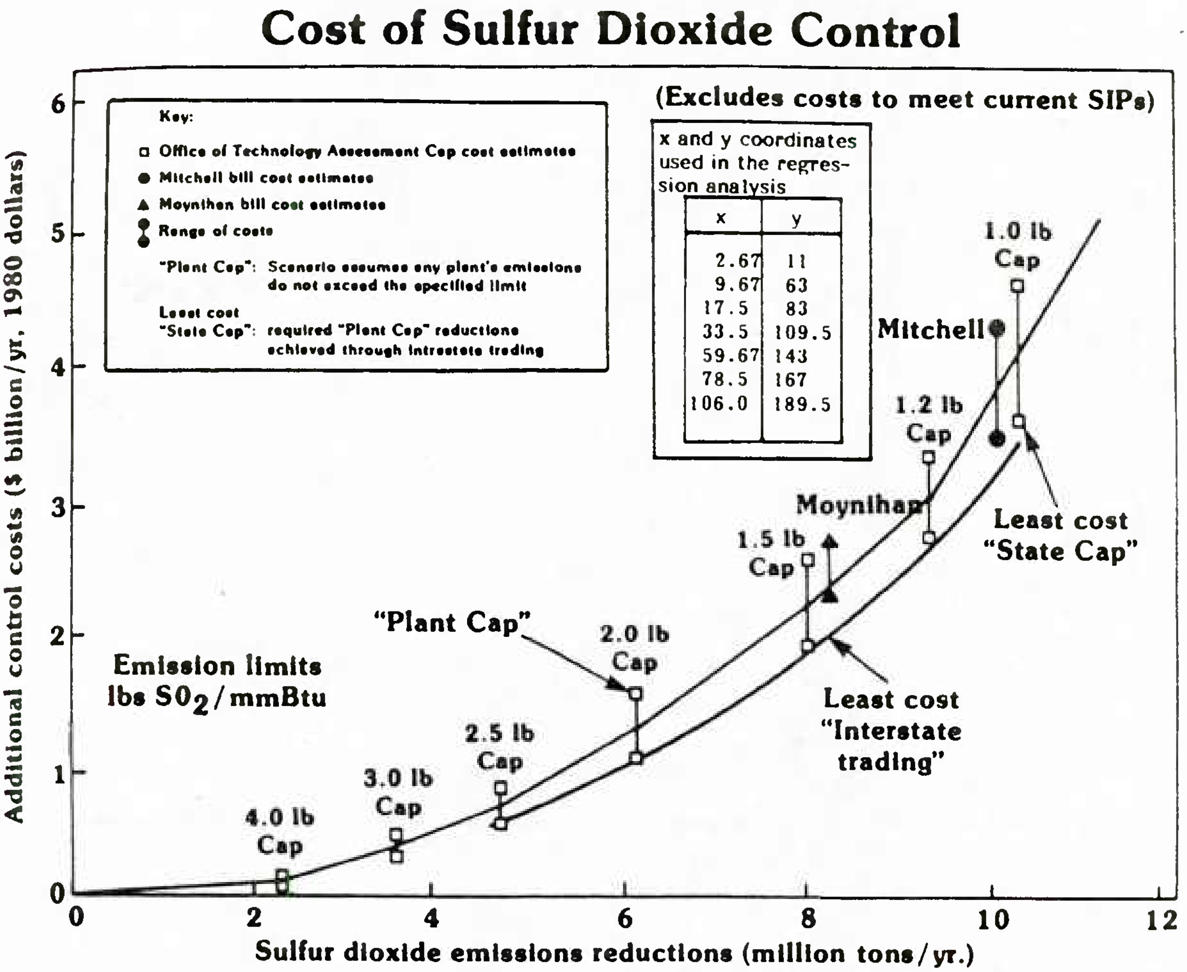
are shown in Table 4. The conditional and unconditional expectations versus additional cost of reduction for the six emission levels $E = 0.5$ through $E = 1.0$ are plotted in Figs. 14 and 15 for the extreme event and pessimistic/optimistic partitions, respectively.

Table 5
Cost data

Emission level (E)	Additional cost ($\$10^9$)
1.000	0.000
0.8982	0.09780
0.8436	0.3542
0.7939	0.6410
0.7281	1.227
0.6449	2.112
0.5854	2.875
0.5431	3.883

5.7.2. Find continuous function trade-offs

Given a cost function (see equation (5.10)) of the form $f_1(E) = B\, e^{a(1-E)} - c$ and risk functions (see equation (5.9)) of the form $f_j(E) = rE + s$, $j = 2, 3, 4, 5$, trade-offs may be obtained for



x and y coordinates used in the regression analysis

x	y
2.67	11
9.67	63
17.5	83
33.5	109.5
59.67	143
78.5	167
106.0	189.5

SOURCE: Office of Technology Assessment, 1982.

Fig. 13.

noninferior points on the Pareto-optimal frontier (see Section 2.4.3). Since E is a scalar policy variable, an explicit equation describing the trade-offs may be found as follows. Solving equation (5.9) for E and substituting into equation (5.10) gives:

$$f_1 = b \exp\left[a - \frac{a}{r}(f_j - s)\right] - c, \qquad j = 2, 3, 4, 5. \tag{5.11}$$

In this case,

$$\lambda_{1j} = -\left.\frac{\mathrm{d}f_1}{\mathrm{d}f_j}\right|_{f_j = rE+s} = \frac{ab}{r} \mathrm{e}^{a(1-E)}, \qquad j = 2, 3, 4, 5. \tag{5.12}$$

Tables 2 and 3 list the trade-offs associated with each emission level, range, and partitioning scheme. Observe that $\lambda_{ij} > 0$ for all $E \in (-\infty, \infty)$; thus, nonzero trade-offs for $E = 1$ are to be expected.

5.7.3. Find discrete trade-off estimates

The trade-offs may also be estimated using

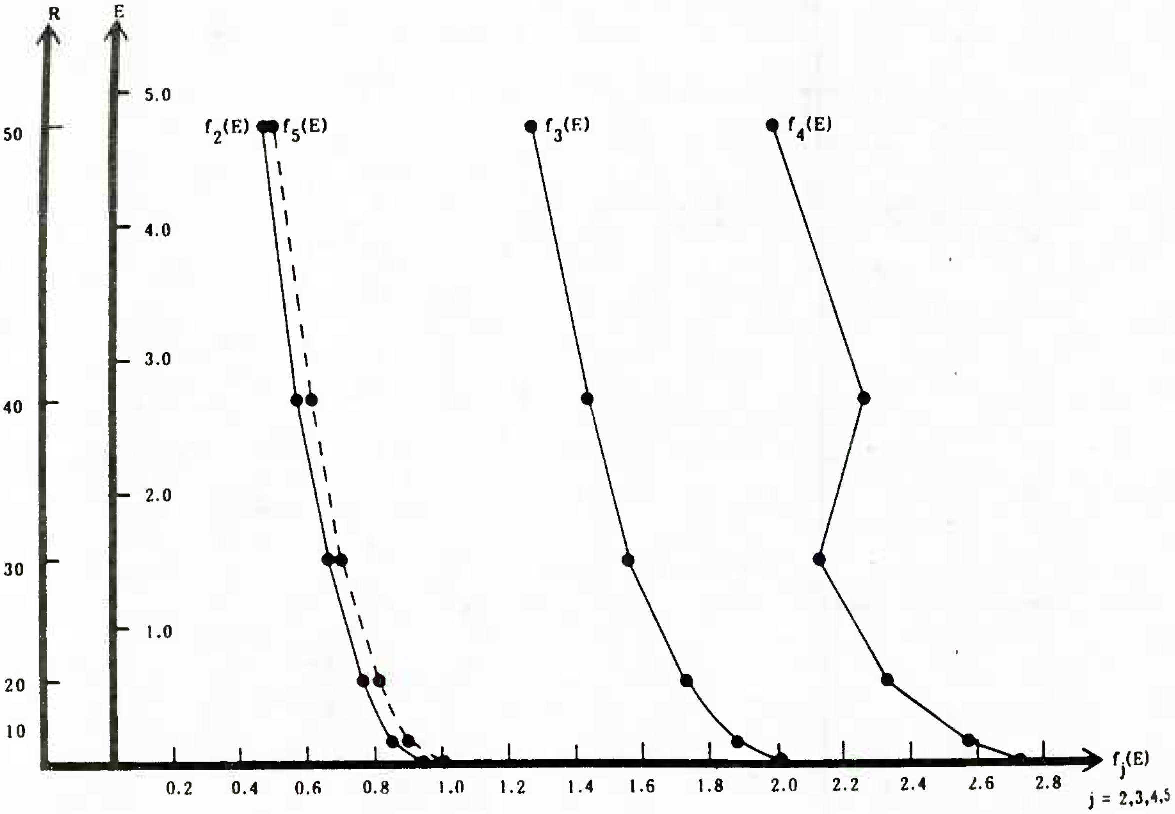


Fig. 14. Extreme event functional space.

equation (3.7). Tables 2 and 3 give the trade-offs for a decrease of the emission level to the next smaller value. The notation $L+$ indicates a large positive number.

5.8. *Interpretation of results*

For the extreme-event partitioning, the decision-makers are reminded that besides the lesser damage levels presented by $f_5(E)$ (the unconditional expectation), there is a low, albeit nonzero, probability of the major damage level presented by $f_4(x)$ (higher damages, domain III). Also, reducing E causes the largest magnitude of reduction in domain III resource damages. This information is not available from the unconditional expectation alone.

Alternatively, through the pessimistic/optimistic partitioning, optimistic decision-makers would tend to disregard $f_4(E)$ (domain III); thus they would spend less funds for emission reduction by making their expenditure just sufficient to lower $f_2(E)$ to an acceptable level. Conversely, pessimistic decision-makers would more seriously consider the impact of $f_4(E)$ and spend more funds for emission reduction to lower $f_4(E)$ to an acceptable level. Note that the cost would be manyfold higher to reduce $f_4(E)$ to a particular damage level than to reduce $f_2(E)$ to that same level.

Consider policies A and B in Fig. 15 and Table 3. Policy A represents a relatively high-cost/low-resource-damage option with a respectively large trade-off: \$34.5 × 10^9/damage unit at a reduction level of 40% with an additional cost of $f_1(x) =$ \$2.7 × 10^9/year. For this policy, the expected resource damage is $f_2(x) = 0.265$. The significance of this relatively high trade-off is that a small increase in the level of resource damage results in a relatively large reduction in the cost. Policy

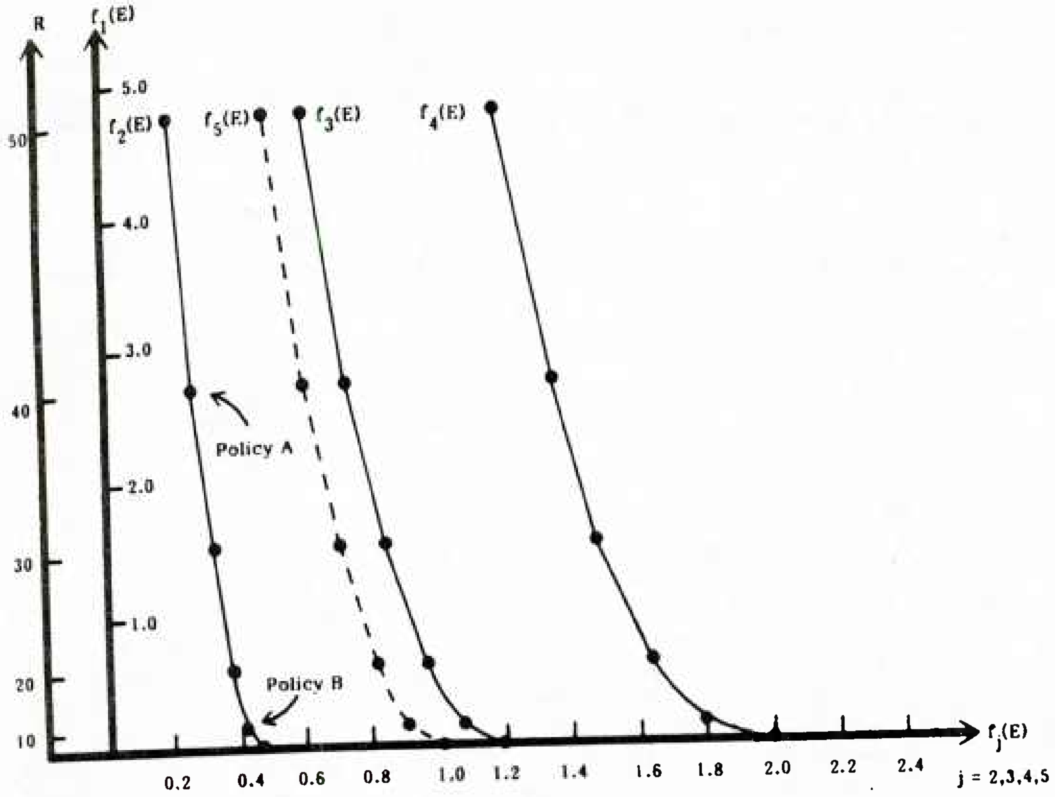


Fig. 15. Pessimist/optimist functional space.

B, on the other hand, is an example of a relatively low-cost/high-resource-damage policy exhibiting a relatively low trade-off value. For this 10% reduction of emissions, the additional cost is $f_1(x) = \$0.15 \times 10^9$/year, the expected resource damage is $f_2(x) = 0.416$, and the trade-off is a low $\$6.03 \times 10^9$/damage unit. This means that at a relatively lower cost, the expected resource damage can be markedly decreased.

Further examination of Figs. 14 and 15 indicates that initial reduction in expected damage can be achieved to quite a significant degree with little additional cost. Further spending has the most dramatic effect on the reduction of domain III damages, although the marginal returns for dollars spent are less.

Because of the linear nature of the resource damage versus emission-level relationship, the damage distribution is nearly a truncated Gaussian with little discernible skew. Had a more distinctly skewed distribution been obtained, some advantages of the PMRM might have become more obvious. The resulting risk functions were linear, as might be anticipated from the linear model; however, nonlinear models may not yield risk functions of similar nonlinear form.

In brief, this example quantified the risk objectives, provided a multiobjective framework for risk decisions in a broader context, obtained trade-offs between risk and other objectives, and thereby accommodated decision-making with explicit and quantitative consideration of risk.

6. Evaluation of the method and extensions

6.1. *Evaluation of the PMRM*

Fischhoff et al. [9] suggested seven criteria against which a risk-related decision-making methodology might be measured: comprehensiveness; logical soundness; practicality in relation to real problems, people, and resource constraints; openness to evaluation; political acceptability; compatibility with existing institutions; and conduciveness to learning for future risk decisions.

6.1.1. *Attributes*

In view of these seven criteria, the following observations can be made. An increase in the comprehensiveness and practicality of the analysis has been brought about by presenting information about the distribution of risk in a multiple-objective format with other objective functions, allowing risk to be viewed in perspective to other important criteria. The PMRM proceeds in a structured and logical manner. Explicit steps to create the risk functions and the trade-offs provide an openness to later evaluation. Transforming the risk problem into a multiple-objective problem allows the decision-maker to consider the political acceptability and institutional compatibility of various alternatives through multiobjective decision-making techniques such as the surrogate worth trade-off (SWT) method. Finally, the structured format allows each well-documented study to be a learning experience for improving the method for future analyses.

Beyond the seven evaluation criteria, the PMRM provides some additional strong points. Proper development of the risk multiobjective separates information about catastrophic (primarily low probability) events and low damage (primarily high probability) events, thereby circumventing a point of contention with the traditional expected value; thus, more information is available to the decision-maker about the distribution of risk. Employing the SWT method further strengthens the PMRM by avoiding the need to explicitly assess each decision maker's utility function(s).

6.1.2. *Shortcomings*

This section describes some of the shortcomings of mathematical decision-making systems in general and those specific to the PMRM.

61.2.1. Shortcomings indigenous to mathematical decision-making systems. Several difficulties are shared by all mathematical decision-making systems. The comprehensiveness of the analysis is formulation dependent; that is, broad and clear formulation, care in the actual decision-making, and a diligent and thorough sensitivity analysis provide for the soundest results. Practicality in terms of real people, problems, and resource constraints requires the use of robust, proven mathematical models of the risks, other objectives, and constraints. For a study to provide the opportunity of learning for future decisions, documentation of that study must be as complete and thorough as possible. Finally, the alternatives included in any analysis must be structured in such a way that compatibility with existing institutions is kept in mind.

6.1.2.2. PMRM shortcomings. There are some specific shortcomings indigenous to the PMRM itself. The decision-makers' utility function(s) are not made explicit during the procedure, so the basis for the decision retains some subjectivity; however, explicit utility functions are subject to some question in any analysis. The basis by which the probability range is partitioned could be strengthened. The interpretation of the risk functions could be more complete. Although there is no reason to doubt their solvability, the PMRM has yet to be applied to problems involving multidimensional decision and/or risk vectors. Partitioning on the damage axis rather than the probability axis has been suggested, but the efficacy and practical application of this option has yet to be demonstrated.

The simulator approach (Section 2.3) requires a large amount of (computer) calculation and, therefore, requires either easily solvable models for the risky–loss variables and/or computer packages for solution approximations of multiple integrals. On the brighter side, a micro- or minicomputer with hard disk storage capacity should provide adequate computer capacity for many problems.

6.2. *Extensions*

The PMRM at present offers exciting and widespread potential use in risk-related decision-making problems, and several suggestions come to mind. More studies employing the PMRM should be done, particularly examples involving multidimensional decision and/or damage vectors and partitioning on the damage (rather than the probability) axis. These studies could also be used in refining the interpretation of the risk functions. Development of a more theoretical basis for assigning the partitioning ranges could provide for a better communication of the distribution of risk for a given alternative. Other theoretical investigation intended to find an explicit relationship between risk function tradeoffs similar to the relation among risk functions found in Section 4.3 could be quite useful. As may be recalled from Section 1, Kaplan and Garrick [27] suggested a frequency analog to the probability distribution function employed by the PMRM. Further strengthening of the theoretical basis for their work could lead to the development of the PMRM using the 'frequency distribution function', which, in turn, could prove quite useful in the policy-making process.

Acknowledgments

The authors appreciate the contributions to this paper made by Robert Friedman, Vijay Gupta, Marc Buchner, Howard Chizeck and Mark Leach. Partial support has been provided by the National Science Foundation, Grant No. ENG79-03605, under the project title 'The Integration of the Hierarchical and Multiobjective Approaches', and by the U.S. Department of Energy, Contract No. DEACO-180RA50256, under the project title, 'Industry Functional Modeling'.

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APPENDIX E

THE SURROGATE WORTH TRADE-OFF (SWT) METHOD AND ITS EXTENSIONS

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Abstract

This paper briefly summarizes selected published results on the Surrogate Worth Trade-off (SWT) Method--a method for solving multiple objective optimization problems--and its extensions. The development of the SWT method is briefly discussed. Theoretical basis for the Kuhn-Tucker multipliers and trade-off functions associated with Pareto optimal solutions is presented. The SWT method is then extended to handling multiple decision-makers. The Multiobjective Statistical Method (MSM), and the analysis of risk and sensitivity in a multiobjective optimization framework using the SWT method are discussed also. A case study in water resources planning with several noncommensurable objective functions is summarized. Finally, special attributes of the SWT method are presented. Because of the very limited scope of this paper, no attempt has been made to relate the SWT method to other multiobjective optimization methods.

Published in "Multiple Criteria Decision Making Theory
and Application, Prodeedings, Hagen/Königswinter,
West Germany, 1979. Edited by G. Fandel and T. Gal
Springer-Verlag Berlin Heidelberg New York

subject to $f_j(\underline{x}) \le \varepsilon_j\ , \quad j \ne i$ (2)

$j = 1,2,\ldots,n; \quad \underline{x} \in X$

where

$\bar{f}_j = \min f_j(\underline{x})\ , \quad \underline{x} \in X, \quad j = 1,2,\ldots,n$ (3)

$\varepsilon_j,\ j \ne i,\ j = 1,2,\ldots,n$ are maximum tolerable levels such as $\varepsilon_j = \bar{f}_j + \bar{\varepsilon}_j$, and $\bar{\varepsilon}_j > 0$.

The equivalence between problems (1) and (2) is proved in the equivalence theorem by Haimes, Lasdon and Wismer [1971]. The levels of satisfactory ε_j can be varied parametrically to evaluate the impact on the single objective function $f_i(\underline{x})$. Of course, the ith objective, $f_i(\underline{x})$, can be replaced by the jth objective $f_j(\underline{x})$, and the solution procedure repeated. The ε-constraint aporoach facilitates the generation of noninferior solutions as well as the trade-off functions, as will be discussed later.

By considering one objective function as primary and all others at minimum satisfying levels as constraints, the Lagrange multipliers related to the (n-1) objectives as constraints will be zero or nonzero. If nonzero, that particular constraint does limit the optimum. It will be shown that nonzero Lagrange multipliers correspond to the noninferior set of solutions. Furthermore, the set of nonzero Lagrange multipliers represents the set of trade-off ratios between the principal objective and each of the constraining objectives, respectively. Clearly, these Lagrange multipliers are functions of the optimal level attained by the principal objective function, as well as the level of all other objectives satisfied as equality (binding) constraints. Consequently, these Lagrange multipliers form a matrix of trade-off functions.

The question of the worth ratios still remains after the matrix of trade-off functions has been computed. The worth ratios are essentially achieved via an interaction with the decision-maker. However, since the worth ratio need only represent relative worth, not the absolute level of worth of the objectives, any surrogate ratio which varies monotonically with the correct one will suffice.

1.3 The Trade-off Function

The following development shows that the trade-off functions can be found from the values of the dual variables associated with the constraints in a reformulated problem. Reformulate problem (1) as follows:

$$\min_{\underline{x}} f_1(\underline{x}) \quad \text{subject to } \underline{x} \in X, \quad f_j(\underline{x}) \le \varepsilon_j, \qquad j = 2,3,\ldots,n \tag{4}$$

where $\varepsilon_j = \bar{f}_j + \bar{\varepsilon}_j$, $\bar{\varepsilon}_j > 0$, $j = 2,3,\ldots,n$, $\bar{f}_j$ were defined in Eq. (3) and $\bar{\varepsilon}_j$ will be varied parametrically in the process of constructing the trade-off function.

Form the generalized Lagrangian, L, to the system (4):

$$L = f_1(\underline{x}) + \sum_{j=2}^{n} \lambda_{1j}[f_j(\underline{x}) - \varepsilon_j] \tag{5}$$

where λ_{1j}, j = 2,3,...,n, are generalized Lagrange multipliers. The subscript 1j in λ denotes that λ is the Lagrange multiplier associated (in the ε-constraint vector optimization problem) with the jth constraint, where the objective function is $f_1(\underline{x})$. λ_{1j} will be subsequently generalized to associate with the ith objective function and the jth constraint, λ_{ij}. Denote by $\hat{X}$ the set of all x_i, i = 1,2,...,N, and by Ω the set of all λ_{1j}, j = 2,3,...,n, that satisfy the Kuhn-Tucker condition for problem (5). The conditions of interest to our analysis are

$$\lambda_{1j}[f_j(\underline{x}) - \varepsilon_j] = 0; \qquad \lambda_{1j} \geq 0; \qquad j = 2,3,\ldots,n \tag{6}$$

Note that if $f_j(\underline{x}) < \varepsilon_j$ for any j = 2,3,...,n (i.e., the constraint is not binding), then the corresponding optimal Lagrange multiplier $\lambda_{1j} = 0$.

The value of λ_{1j}, j = 2,3,...,n, corresponding to the binding constraints, is of special interest since it indicates the marginal benefit (cost) of the objective function $f_1(x)$ due to an additional unit of ε_j. From Eq. (5), assuming that the solution is optimal, the following results can be derived[4]:

$$\lambda_{1j}(\varepsilon_j) = -\frac{\partial L}{\partial \varepsilon_j} \qquad j = 2,3,\ldots,n \tag{7}$$

Note, however, that for $\underline{x}\in\hat{X}$, $\lambda_{1j}\in\Omega$ for all j

$$f_1(\underline{x}) = L \tag{8}$$

Thus,

$$\lambda_{1j}(\varepsilon_j) = -\frac{\partial f_1(\cdot)}{\partial \varepsilon_j} \qquad j = 2,3,\ldots,n \tag{9}$$

In the derivation of the trade-off functions in the SWT method, only those $\lambda_{ij} > 0$ corresponding to $f_j(x) = \varepsilon_j$ are of interest (since they correspond to the noninferior solution). Thus, for $f_j(\underline{x}) = \varepsilon_j$, Eq. (9) can be replaced by Eq. (10):

$$\lambda_{1j}(\varepsilon_j) = -\frac{\partial f_1(\cdot)}{\partial f_j(\cdot)} \tag{10}$$

Clearly, Eq. (10) can be generalized where the index of performance is the ith objective function of the system (1) rather than the first one. In this case, the index i should replace the index 1 in λ_{1j}, yielding λ_{ij}. Accordingly, ence band is assumed to exist within the neighborhood of λ^*_{ij}. Additional questions to the DM can be asked in the neighborhood of λ^*_{ij} to improve the accuracy of λ^*_{ij} and the band of indifference.

There are three ways of specifying a noninferior solution via the surrogate worth function:

1. by the values of its decision variables, $x_1,\ldots,x_N$
2. by the trade-off functions $\lambda_{i1},\ldots,\lambda_{in}$
3. by its objective function values $f_1,\ldots,f_n$

Hence, we can have $W_{ij}(x_1,\ldots,x_N)$ or $W_{ij}(\lambda_{i1},\ldots,\lambda_{in})$ or $W_{ij}(f_1,\ldots,f_n)$. The first is generally ruled out by the inefficiencies of decision space manipulations. The second may suffer from problems when discontinuities or nonconvexities occur in the functional space, but can be used in other problems. The third, or objective function space, approach appears to be best.

As an example of how the method works, consider a three-objective problem. Several noninferior points, $(f_2,f_3)_0,\ldots,(f_2,f_3)_k$, and their trade-offs, $(\lambda_{12},\lambda_{13})_0,\ldots,(\lambda_{12},\lambda_{13})_k$, are determined, e.g., via the ε-constraint method. The decision-maker is then questioned to get values $W_{12}(f_2,f_3)_0,\ldots,W_{13}(f_2,f_3)_k$ and $W_{13}(f_2,f_3)_0,\ldots,W_{13}(f_2,f_3)_k$. (It can be shown that the other W_{ij} need not be determined.) Now, since generally none of these will be zero, we must determine more noninferior solutions and their trade-offs than before, and ask more questions of the DM until we find an $(f_2,f_3)^*$ so that $W_{12}(f_2,f_3)^*$ and $W_{13}(f_2,f_3)^*$ both equal zero.

Since the worth is only evaluated at known noninferior points, it is guaranteed that $(f_2,f_3)^*$ will give rise to a feasible solution when put into the overall mathematical model. The same guarantee holds when $W_{i1}(\lambda_{i1},\ldots,\lambda_{in})$ is used.

What happens if there can not be found a pair of $(f_2,f_3)^*$ whose worth functions are both zero? In that case, we can take the one whose worth functions are closest to zero as an approximate preferred solution. Note that the noninferior solutions whose surrogate worth functions are all zero are the maximum utility solutions. The noninferior solution whose worth functions are closest to zero will be the one closest to the maximum utility solution.

There is a close relation between the surrogate worth function, W_{ij}, and the partial derivatives of the utility function.

In multiobjective analysis it is assumed implicitly that the decision-maker maximizes his utility, which is a monotonic decreasing function of the various objective functions.

The relationship between the surrogate worth function and the utility function is presented elsewhere.[8]

Finally, one may question whether an interaction with the DM in the function space should always yield a $W_{12}(\lambda_{12}) = 0$, i.e., an indifference solution. Two cases may be identified here.

1. The DM's response is always on one side of the W_{12} scale for all λ_{12} corresponding to the Pareto optimum solutions. That is to say, the DM's answers are either all on the positive or all on the negative scale of W_{12}. This really means that the DM is always willing to improve--say objective 1--at the expense of degrading objective 2 in the entire Pareto optimal space. This case, while it may actually happen, is of no particular interest here, since it reduces the multiobjective problem to a single-objective optimization problem.

2. Should the DM's response in the function space be on the positive scale of W_{12} for some values of λ_{12}, and negative for other sets of values of λ_{12}, then (assuming consistency in the DM response and continuity in λ_{12}), it can be guaranteed that a value of $W_{12} = 0$ exists which corresponds to an indifference solution with λ^*_{12}, i.e. $W_{12}(\lambda^*_{12}) = 0$.

1.5 Transformation to the Decision Space

Once the indifference bands have been determined for λ^*_{ij}, the next and final step in the SWT method is to determine an $\underline{x}^*$ that corresponds to all λ^*_{ij}. To each λ^*_{ij} determined from the surrogate worth function via the interaction with the decision-maker there corresponds $f^*_j(\underline{x})$, $j = 1,2,\ldots,n$, $j \neq i$. These $f^*_j(\underline{x})$ are the values of the functions $f_j(\underline{x})$ at the equality constraints ε_j so that $\lambda^*_{ij}[f^*_j(\underline{x}) - \varepsilon_j] = 0$. Accordingly, the optimal vector of decisions, $\underline{x}^*$, can be obtained by simply solving the following optimization problem:

$$\min_{\underline{x} \in X} f_i(\underline{x}) \text{ subject to } f_j(\underline{x}) \leq f^*_j(\underline{x}) \qquad j = 1,2,\ldots,n;\ j \neq i \qquad (14)$$

The system Eq. (14) is a common optimization problem with a single objective function. The solution of Eq. (14) yields the desired $\underline{x}^*$ for the total vector optimization problem posed by Eq. (1).

The consistency of the DM should not always be assumed. The DM may show nonrational behavior or provide misinformation at times. The SWT method safeguards against this by crosschecking the resulting λ^*_{ij}. It has been shown elsewhere that one set of $\lambda_{11},\ldots,\lambda_{1n}$ will suffice for solving the multiobjective problem posed previously.[9] It is always possible, however, to generate, for example, λ^*_{12}, λ^*_{23}, and λ^*_{13} (via an interaction with the DM), and to check that indeed the following relation holds: $\lambda^*_{13} = \lambda^*_{12}\lambda^*_{23}$ (i.e., satisfies the general relationship $\lambda_{ij} = \lambda_{ik}\lambda_{kj}$, for $i \neq j$, $\lambda_{ij} > 0$; $i,j = 1,2,\ldots,n$).

Theorem 1: Given the multiobjective problem (1) referred to as Problem 1, then for the feasible set of λ^*_{ij}, there exists a corresponding feasible set of desicions $\underline{x}^*$.

Proof: Rewrite Problem 1 as follows:

$$\min_{\underline{x} \in X} f_i(\underline{x}) = \sum_{j \neq i} \lambda^*_{ij} f_j(\underline{x})$$

If all $f_k(\underline{x})$, $k = 1,2,\ldots,n$, are continuous and the solution set X is compact, then this problem must have a solution (by Weierstrass' Theorem).[10]

These assumptions are very mild. Compactness of X can be guaranteed by imposing finite upper and lower bounds on each component of the decision vector $\underline{x}$, assuming the constraint functions $g_i(\underline{x})$ are continuous. Continuity assumption of all $f_j(\underline{x})$ and $g_i(\underline{x})$ (as defined in Eq. 1) is common in mathematical programming.

Let $\underline{x}^*$ be a solution for a given λ^*_{ij}. Then λ^*_{ij}'s are the optimal trade-off values (Lagrange multipliers) for the problem:

$$\min_{\underline{x} \in X} f_i(\underline{x}) \text{ subject to the constraints } f_j(\underline{x}) \leq f_j(\underline{x}^*) \equiv \varepsilon_j$$

$$j = 1,2,\ldots,n; \; i \neq j$$

Thus, $\underline{x}^*$ is in X and λ^*_{ij}'s are the desired Lagrange multipliers.

The feasibility of a solution $\underline{x}^*$ corresponding to λ^*_{ij} can also be shown on the basis of the Lambda Theorem by Everett.[11]

It is helpful to summarize the three major steps in the SWT method. These are:

Step 1. Identify and generate noninferior (Pareto optimum) solutions, along with the trade-off functions, λ_{ij}, between any two objectives functions $f_i(\underline{x})$ and $f_j(\underline{x})$, $i \neq j$. It can be shown that under certain mild conditions, one set of (n-1) trade-off functions, $\lambda_{12},\ldots,\lambda_{1n}$, will suffice to generate all other λ_{ij}, $i \neq j,i$; $j = 1,2,\ldots,n$.

Step 2. Interact with the DM to assess the indifference band where the surrogate worth function $W_{ij}(\lambda^*_{ij}) = 0$. It was shown that under certain mild conditions W_{ij} depends only on λ_{ij}.

Step 3. Determine the optimal decision set, $\underline{x}^*$, using the optimal trade-off values λ^*_{ij}.

2. Trade-Off Interpretation of Kuhn-Tucker Multipliers

For convenience, we redefine problems (1) - (3) in this section.[12] Let

$$X \underline{\Delta} \{\underline{x} \mid \underline{x} \in R^N,\ g_i(\underline{x}) \le 0,\ i = 1,\ldots,m\}$$

where g_i is a continuously differentiable real-valued function defined on R^N. Define $P_k(\varepsilon)$ as:

$$\left.\begin{array}{l} \min f_k(\underline{x}) \text{ subject to } f_j(\underline{x}) \le \varepsilon_j,\ j = 1,\ldots,n,\ j \ne k \\ g_i(\underline{x}) \le 0,\ i = 1,\ldots,m, \text{ and } x \in R^N \end{array}\right\} P_k(\varepsilon)$$

Let $\underline{x}^*$ solve $P_k(\varepsilon)$ with λ^*_{kj}, $j = 1,\ldots,n$, $j \ne k$ and μ^*_i, $i = 1,\ldots,m$ as the optimal Kuhn-Tucker multipliers associated with f_j's and g_i's constraints, respectively. (Note: λ^*_{kj} and μ^*_i are the optimal Kuhn-Tucker multipliers of $P_k(\varepsilon)$ if $(\underline{x}^*,\lambda^*_{k1},\ldots,\lambda^*_{kk-1},\lambda^*_{kk+1},\ldots,\lambda^*_n,\mu^*_1,\ldots,\mu^*_m)$ satisfies the Kuhn-Tucker conditions for optimality for $P_k(\varepsilon)$.)

The key concept underlying relationships between Kuhn-Tucker multipliers λ^*_{kj} and trade-offs between f_k and f_j at $\underline{x}^*$ is the sensitivity interpretation of the multipliers. For convenience, we shall restate Luenberger's Sensitivity Theorem using notations suitable for our discussions.[13]

Sensitivity Theorem

Given $\varepsilon^0 \in Y_k$, let $\underline{x}^*$ solve $P_k(\varepsilon^0)$ with λ^*_{kj}, $j \ne k$, being the corresponding Kuhn-Tucker multipliers associated with the constraints $f_j(\underline{x}) \le \varepsilon^0_j$, $j \ne k$. If

i) $\underline{x}^*$ is a regular point of the constraint of $P_k(\varepsilon^0)$

ii) the second-order sufficiency conditions are satisfied at $\underline{x}^*$, and

iii) there are no degenerate constraints at $\underline{x}^*$, then

$$\lambda^*_{kj} = -\partial f_k(\underline{x}^*)/\partial \varepsilon_j \text{ for all } j \ne k.$$

Corollary 1

If $\underline{x}^*$ solves $P_k(\varepsilon^0)$ and satisfies (i), (ii), and (iii), then there exists a neighborhood $N(\varepsilon^0)$ of ε^0 so that, for all $\varepsilon \in N(\varepsilon^0)$, $\underline{x}(\varepsilon)$, which uniquely solves $P_k(\varepsilon)$, locally exists, and is continuously differentiable function of ε with $\underline{x}(\varepsilon^0) = \underline{x}^*$.

Corollary 2

With all the hypotheses of the sensitivity theorem satisfied, there exists a neighborhood $N(\varepsilon^0)$ of ε^0 so that for each j such that $\lambda^*_{kj} > 0$, $f_j(\underline{x}(\varepsilon)) = \varepsilon_j$ for all $\varepsilon \in N(\varepsilon^0)$.

The results in the above two corollaries arise naturally from the proof of the sensitivity theorem which, in turn, relies heavily on the implicit function theorem. It should be stressed here that conditions (i), (ii), and (iii) required for the sensitivity interpretation of Kuhn-Tucker multipliers above are merely sufficient conditions.[14]

3. The SWT Method With Multiple Decision-Makers

Often systems, which are best modeled by multiple objective functions, are also characterized by more than one decision-maker (DM). Most public policy issues, for example, lend themselves to multiple objectives and multiple DMs. A hierarchy of DMs often exists within an agency or corporation, and preferred noninferior solutions are transferred from one level of the hierarchy to another. The SWT method is very well suited to incorporate multiple DMs and their corresponding preferences.[15]

In the case study discussed in section 6, for example, the Planning Board of the Maumee River Basin consists of eight members from federal, state, and regional agencies. The Board is in charge of developing a basin-wide comprehensive plan that is responsive to environmental, economic, social, legal, political, and institutional needs. However, each member of the Board, as a decision-maker, exercises his mandate to be responsive simultaneously to his professional judgment, his agency's stand, and the public preferences as voiced by various public hearings and other media. Clearly, in applying the Surrogate Worth Trade-off method, different indifference bands may result by interacting with each Planning Board member. The key question is how would the SWT method be modified to handle this situation.

Three major cases of multiobjective optimization problems with multiple decision-makers have been discussed in the literature.[16] These are the direct group decision-making systems, the representative decision-making systems, and the political decision simulations. These three classifications will not be discussed here, but rather a more general case will be assumed here for simplicity.

Consider the multiobjective optimization problem posed by Eq. (1), where an interaction with the DMs for assessing the corresponding trade-offs and preferences that lead to $W_{ij} = 0$ takes place. Two cases will be identified here--the ideal and the probable.

The Ideal Case: In assessing the trade-offs and preferences with the DMs it is assumed in the ideal case that the indifference bands generated by all the DMs for all W_{ij}, $i \neq j$, $i,j = 2,\ldots,n$, have a common indifference band, Δ, as depicted in Fig. 2. This situation is unlikely to happen; however, it provides a medium for understanding the probable case. All the indifference bands in Fig. 2 correspond, of course, to $W_{ij} = 0$; however, they are plotted at different levels on the W_{ij} scale in order to distinguish among the indifference bands of the various DMs.

The Probable Case: In the probable case, no common indifference band can be found for all the DMs. This case is depicted in Fig. 3. The Surrogate Worth Trade-off method provides an explicit and quantitative mechanism in simulating the decision-makers' preferences with respect to the trade-offs between any two objective functions. Identifying the differences in the DMs' preferences is a first step in closing these gaps through the inevitable process of negotiation and compromise. These negotiations may take different forms and are expected to lead to an agreeable decision (depending on the rules of the game whether a simple majority, absolute majority, consensus, or other is needed for an agreed-upon decision).

4. Multiobjective Statistical Method (MSM)

The Multiobjective Statistical Method (MSM) has been developed to integrate statistical attributes with multiobjective optimization methodologies, such as the SWT method.[17]

Outlines of the MSM are presented herein:

Let $\underline{x}$ denote a vector of decision variables and $\underline{f}(\underline{y})$ a vector of noncommensurable objective functions with $\underline{y}$ the state vector of the system being analyzed. The state vector $\underline{y}$ is given by $\underline{y} = \underline{y}(\underline{x};\underline{r})$ where $\underline{r}$ is a vector of random variables modelling the uncertainties in the system. Let

$$\underline{r} = (r_1, r_2, \dots, r_n)$$

where each of the r_i, $i = 1,2,\dots,n$ are real-valued random variables satisfying

$$\underline{r}_i \le r_i \le \bar{r}_i, \; i = 1,2,\dots,n.$$

Let

$$A_{ij}, \; j = 1,2,\dots,J_i$$

be a collection of subsets of $[\underline{r}_i, \bar{r}_i]$ with probabilities $P(A_{ij})$, $i = 1,2,\dots,n$ to be used for a given study. Define the n-fold probabilities

$$p_m = P(A_{1j_1} A_{2j_2} \cdots A_{nj_n})$$

where $1 \le j_i \le J_i$; $i = 1,2,\dots,n$ and m is an index variable from the set

$$\{1,2,\dots,M\}, \qquad M = \prod_{i=1}^{n} J_i .$$

Here, p_m is the probability that

$$r_1 \epsilon A_{1j_1}, \; r_2 \epsilon A_{2j_2}, \dots, r_n \epsilon A_{nj_n} .$$

The planning of the system is formulated as the multiobjective optimization problem

$$\min_{\underline{x} \in X} \underline{f}(\underline{y}) \qquad \begin{bmatrix} f_1(\underline{y}) \\ \cdot \\ \cdot \\ \cdot \\ f_L(\underline{y}) \end{bmatrix}$$

$$\text{s.t. } G(\underline{x}) \leq 0$$

where $y = \underline{y}(\underline{x};\underline{r})$ is a vector of random variables.

For $\hat{\underline{x}} \in X$, determine $y_m(\hat{\underline{x}},\underline{r}_m)$, where $\underline{r}_m$ is the vector of random variables with probability p_m for $m = 1,2,\ldots,M$. The most convenient way to define the sets A_{ij} is by discretizing the intervals $[\underline{r}_i,\bar{r}_i]$ into J_i subintervals such that

$$\Delta r_i = \frac{\underline{r}_i - \bar{r}_i}{J_i} \quad \text{and} \quad A_{ij} = (\underline{r}_i + (j-1)\Delta r_i, j\Delta r_i].$$

The components of $\underline{r}_m$ are taken to be the midpoints of the appropriate subintervals of $[\underline{r}_i,\bar{r}_i]$ dictated by the index variable m.

To account for the random nature of the state vector $\underline{y}$ in the optimization problem, define the quantities $f_\ell(\underline{y}) = E\{f_\ell(\underline{y})\}$ where $\ell = 1,2,\ldots,L$ and $E\{\cdot\}$ denotes expectation. Then

$$\tilde{f}_\ell(\hat{\underline{y}}) = \tilde{f}_\ell(\underline{y}(\hat{\underline{x}})) = \sum_{k=1}^{M} f_\ell(y(\hat{\underline{x}};r_m))p_m$$

where $\hat{\underline{x}} \in X$ represents a fixed set of decisions.

In order to proceed with the optimization problem, it is necessary to obtain a functional relationship which maps $\underline{x}$ into $\tilde{f}_\ell(\underline{x})$ for each objective function, $\ell = 1,2,\ldots,L$. One possible method is to obtain a collection of ordered pairs $\{\hat{\underline{x}},\tilde{f}_\ell(\hat{\underline{x}})\}$ and use a curve-fitting technique to determine the functional relationships $\tilde{f}_\ell(\cdot)$, for each ℓ.

The problem has now been reduced to

$$\min_{\underline{x} \in X} \underline{\tilde{f}}(\underline{x})$$

$$\text{s.t. } G(\underline{x}) \leq 0$$

which is a deterministic multiobjective optimization problem and can be solved by standard procedures, such as, the Surrogate Worth Trade-off (SWT) method to determine the "optimal" decision vector $\underline{x}^*$.

5. Risk and Sensitivity As Multiple Objective Functions

At present, most mathematical models treat important system characteristics such as risk, uncertainty, sensitivity, stability, responsivity, irreversibility, etc., either by means of system constraints or by artificially imbedding them in the overall index of performance.[18] The systems analyst (the modeler) assumes both the role of the professional analyst and the decision-maker by explicitly or implicitly assigning weights to these and other noncommensurate system characteristics, thus commensurating them into the performance index (the mathematical model's objective function). Obviously, this process is questionable even where the analyst is the decision-maker. When he is not, the result will seldom be the decision-maker's optimum.

It is argued elsewhere that the above system characteristics can and should be quantified and included in the mathematical models as separate objective functions.[19] These should then be optimized along with the original model's objective function (index of performance), to allow the decision-maker(s) to select a preferred policy (solution) from within the Pareto optimal set. Any procedure short of recognizing these characteristics as objective functions in their own right essentially compromises the modeling process.

In previous work a number of questions associated with risk and uncertainty have been tentatively explored to stimulate further analysis and research into the quantifications of these factors for use in multiobjective optimization analysis.[20] A great many problems exist in water resources systems and other civil systems involving resources in which avoidance of risk and uncertainty is often in fact the dominating objective. If suitable quantitative measures of these objectives can be formulated, then the Surrogate Worth Trade-off method or other multiobjective optimization methodologies can determine the optimal, or at least superior, combinations of risk and various forms of return.

This somewhat preliminary analysis and discussion indicates that quantitative measures of risk can be defined and utilized as objectives to be optimized in a multiobjective control. In some instances even uncertainty (no probability distribution data) can be treated adequately.

An indication, however, is not an accomplished fact and much insight and analysis will be required to quantify the major risk factors involved in common water resources systems well enough to include them in multiobjective decision analysis.

The proposed consideration of risk in a multiobjective framework might be used systematically to[21]:

(i) Assist planners, professionals and decision-makers involved in resources planning and management in general and in water and related land resources in particular.

(ii) Quantify and display the trade-offs involved in reducing risk, sensitivity, irreversibility and other systems characteristics (viewed as systems objectives) along with reducing cost or other performance indices, where all these objectives are kept in their noncommensurable units.

(iii) Insure comprehensive consideration of economic issues, social well-being, health hazards, environmental issues, irreversible impacts, and other costs and benefits regardless of commensurability through the use of the multiobjective approach.

(iv) Reduce the uncertainty surrounding resources planning and development in general, and water and land resource development and management decisions in particular, by the development of more realistic systems models, and accurately displaying the probable consequences of the decisions and policies followed.

6. Maumee Study: Case Study for Multiobjective Optimization

The Maumee study addresses itself to the systematic evaluation and formulation of a planning and management framework for solving the critical problems of water and land resources in the Maumee River Basin. The planning process has been carried out in complete cooperation with the Maumee River Basin Level-B Planning Board. Results and findings of this study are utilized in the Level-B planning effort, and in formulating the recommended plan for the Basin.[22]

While a great many studies related to water and land resources planning were conducted in the past, only a handful have been sufficiently comprehensive in nature to integrate all the inherently complex, and interacting components in a multiobjective framework. The problems of land and water resources of the Maumee Basin, in particular, serve to emphasize the need for such an integration--if the consequences in the future are to be adequately considered and planned for.

To facilitate the process of comprehensive planning in the Maumee Basin, a hierarchical-multiobjective modelling and optimization structure was developed; and, based on this structure, a computer program was developed to generate alternative plans, and the associated trade-offs using the Surrogate Worth Trade-off methodology. The seven major considerations regarding land and water resource management in the Basin--water quality, water supply, protection of agricultural land, sedimentation, flooding, outdoor recreation, and fish and wildlife--have been converted to a set of specified objectives for multiobjective analysis.

Linear models were developed for each of these objectives. Using these models, the level of objectives among the various components have been generated for a range of feasible alternative solutions: minimum economic development, minimum environmental quality, economic development and environmental quality alternatives used were the alternatives developed by the Maumee Planning Board and presented by The Great Lakes Basin Commission at public forums held January, 1976.

Trade-off values were determined for each of these alternative scenarios. For example, under environmental quality, planning subarea 1, the worth of reducing an additional ton of sheet erosion on agricultural land is $3.4, given a 45% reduction of the projected sheet erosion in the year 1990 has already been achieved. These trade-off values with their respective level of achieved objectives are presented by planning subarea for each component and each alternative scenario in Table 1.

Planning Board members were then asked to specify their range of indifference with regard to economic development (cost) and environmental quality (unit of objective achievement) trade-offs. The overlapping range of indifferences obtained represents the optimal solution area along the trade-off curve, i.e. the consensus.

The range of consensus by component can serve as one of the guidelines for formulation of the Selected Plan. In this case, the Selected Plan used, which was the one arrived at by the Maumee Planning Board and Citizen's Advisory Committee, coincides with the overlapping range of indifferences obtained by the SWT method. Trade-offs and percentage level reduction in gross needs corresponding to this plan were subsequently generated, and are also shown in Table 1.

The trade-offs can also be evaluated by a comparison of planning subareas. The five planning subareas in the Maumee River Basin have different hydrology, geography, economic characteristics, population density, and other features. Consequently, the overall Basinwide objective would be best achieved by capitalizing on these local and subarea attributes. For example, under the Selected Plan, a reduction in sheet erosion of agricultural land would be achieved at 45 percent of the 1990 projected gross erosion for both PSAs 1 and 3. Yet the marginal cost values of reducing an additional ton of sheet erosion are $3.40 per ton, and $8.20 per ton for PSAs 1 and 3, respectively. These marginal cost values are the trade-offs generated by the Surrogate Worth Trade-off method as given in Table 1. In other words, in the recommended plan of sheet erosion reduction, an additional reduction of sheet erosion in PSA 1 would cost less than half of that of PSA 3. Therefore, from a Basinwide point of view, simple economics dictates that an additional sheet erosion reduction in PSA 1 should be pursued at the expense of a lower reduction in PSA 3 while still maintaining the total net reduction. However, the institutional arrangements are not available for that purpose. Today, there is no system of incentives, rebates, taxation, or other mechanisms that induces the various sectors of the public in the Basin to be responsive to the ecological, hydrological, or environmental needs beyond the level of compliance with the law. Other examples that could be mentioned are ground water management (pumping and recharge) and waste-water treatment (level of treatment and effluent discharge in a specific reach).

7. Summary

The Surrogate Worth Trade-off (SWT) method can be used to analyze and optimize multiobjective optimization problems. A brief summary of the SWT method is presented here.[23]

1. The SWT method is capable of generating all needed noninferior solutions to a vector optimization problem.

2. The method generates the trade-offs between any two objective functions on the basis of duality theory in nonlinear programming. The trade-off function between the ith and jth objective functions, λ_{ij}, is explicitly evaluated and is equivalent to $-\partial f_i/\partial f_j$.

3. The decision-maker interacts with the systems analyst and the mathematical model at a general and very moderate level. This interaction is accomplished by the generation of the Surrogate Worth functions, which relate the decision-maker's preferences to the noninferior solutions through the trade-off functions. These preferences are constructed in objective function space (more familiar and meaningful to the decision-makers) and only then transferred to the decision space. This aspect is particularly important, since the dimensionality of the objective function space is often smaller than that of the decision space. The preferences yield to an indifference band, where the decision-maker is indifferent to any further trade-off among the objectives.

4. The SWT method provides for the quantitative analysis of noncommensurable objective functions.

5. The method is very well suited for the analysis and optimization of multiobjective functions with multiple decision-makers.[24]

6. The method possesses an appreciable computational efficiency, and has some advantages over other existing methods, when the number of objective functions is three or more.[25]

7. The method is applicable to both static (mathematical programming) and dynamic (optimal control) vector optimization problems.[26]

8. The method has been extended to incorporate an interactive mode between the analyst and the DMs--Interactive Surrogate Worth Trade-Off (ISWT) method.[27]

9. The method has been extended to incorporate statistical data--Multiobjective Statistical Method (MSM).[28]

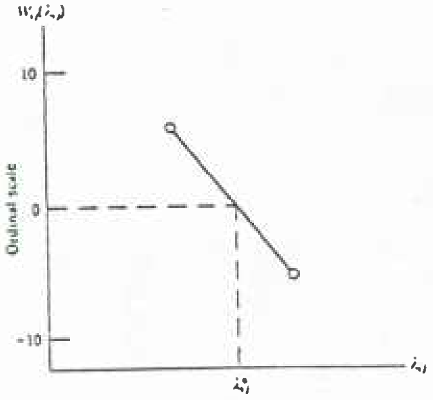

Figure 1. Determination of the indifference band at λ^*_{ij}.

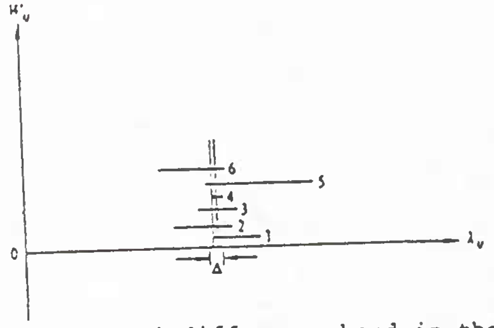

Figure 2. Common indifference band in the ideal case.

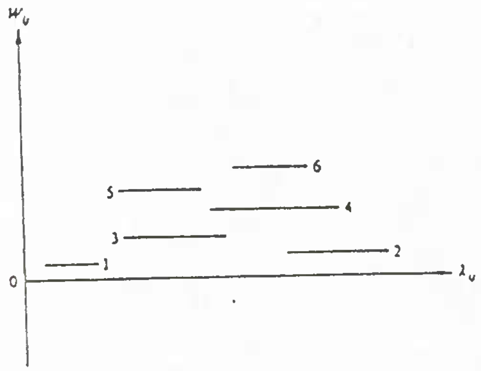

Figure 3. Indifference bands in the probable case.

Table 1. Levels of Objectives in Percentage of Project Gross Needs for the year 1990, the Associated Trade-offs, and land Management Costs.

		BQ		MIN BQ		MIN ED		ED		SELECTED PLAN	
OBJECTIVE	PSA	PERCENT LEVEL	TRADE-OFF	PERCENT LEVEL	TRADE-OFF	PERCENT LEVEL	TRADE-OFF	PERCENT LEVEL	TRADE-OFF	PERCENT LEVEL	TRADE-OFF
Reduction in Sheet Erosion (Ag. Land) (tons/yr.)	1	45	3.4	28	3.1	11	2.8	17	2.8	45	3.4
	2	37	4.6	30	4.5	29	4.5	34	4.5	38	4.6
	3	46	8.2	31	8.2	26	8.2	19	8.2	45	8.2
	4	57	5.4	28	5.4	1.1 Increase	5.4	14	5.4	57	5.4
	5	19	7.3	18	6.9	18	6.5	18	6.5	16	6.9
Recreation (recreation days)	1	13	1.3	15	1.3	17	1.3	18	1.3	15	1.3
	2	27	2.6	28	2.6	29	2.6	30	2.6	28	2.6
	3	18	3.2	19	3.2	20	3.2	20	3.2	20	3.2
	4	27	3.3	28	3.3	28	3.3	29	3.3	28	3.3
	5	19	3.2	19	3.3	19	3.3	20	3.4	19	3.3
Wildlife (user days)	1	74	3.0	66	3.0	52	2.9	33	2.9	35	2.9
	2	64	2.5	64	2.5	65	2.5	65	7.5	66	2.5
	3	134	2.3	144	2.5	154	2.5	158	2.5	162	2.5
	4	87	2.4	84	2.4	77	2.5	68	2.5	70	2.5
	5	20	3.0	20	1.7	18	1.7	16	0.9	17	1.7
Flood Plain Acquisition (acres)	1	7.0	67	12	67	23	67	37	67	15	67
	2	5.0	49	11	49	21	49	42	49	16	49
	3	8.0	49	12	49	25	49	38	49	16	49
	4	5.0	49	12	49	21	49	35	49	20	49
	5	3.0	51	10	60	20	60	30	70	19	60
Total Land Management Cost ($)	1	22,949,000		22,903,000		22,867,000		22,893,000		22,908,000	
	2	35,048,000		33,681,000		30,461,000		34,107,000		34,219,000	
	3	38,555,000		38,306,000		38,035,000		38,026,000		38,407,000	
	4	54,003,000		53,807,000		52,738,000		53,219,000		53,926,000	
	5	11,670,000		11,690,000		11,758,000		11,912,000		11,638,000	

Footnotes

1. The generic term "decision-maker" connotes here one or more decision-makers (see section 3). This review of the SWT method is based on the work by Haimes and Hall (1974), Haimes, Hall and Freedman (1975), Hall and Haimes (1976), and Haimes (1977).

2. See Haimes and Hall (1974).

3. The ϵ-constraint approach is discussed by Haimes (1970), Haimes, Lasdon and Wismer (1971), and Haimes (1975).

4. See Luenberger (1973) and Haimes (1977).

5. See Everett (1963) and Haimes, Hall, and Freedman (1975).

6. See Haimes, Hall, and Freedman (1975). In addition, several variational approaches for the determination of $\lambda_{ij}(\cdot)$ are discussed in the above book.

7. See, for example, Raiffa (1968), Marschak (1955), Fishburn (1970), etc.

8. See Kaplan (1975), Passy and Haimes (1975), and Haimes (1977).

9. See Haimes, Hall, and Freedman (1975).

10. See, for example, Luenberger (1973).

11. See Everett (1963).

12. This section is based on the paper by Haimes and Chankong (1979). The reader is also referred to Chankong (1977).

13. See Luenberger (1973), page 236.

14. Proof of these corollaries can be found in Chankong (1977), and Haimes and Chankong (1979).

15. A detailed discussion on the SWT method with multiple decision-makers can be found in Hall and Haimes (1976), and Haimes (1977).

16. See Hall and Haimes (1976), and Haimes (1977).

17. See Haimes (1978), and Haimes, Loparo, Olenik, and Nanda (1979).

18. See Haimes, Hall, and Freedman (1975), Haimes and Hall (1977), and Haimes (1977).

19. See Haimes and Hall (1977) and Olenik and Haimes (1979).

20. See Haimes and Hall (1977).

21. See Haimes and Hall (1977).

22. See, for example, Haimes, Das and Sung (1977,1979), Haimes (1977), and Das and Haimes (1979).

23. See, for example, Haimes (1977).

24. See Hall and Haimes (1976).

25. See Cohon and Marks (1975).

26. See Haimes, Hall, and Freedman (1975).

27. See Chankong (1977), and Chankong and Haimes (1978).

28. See Haimes, Loparo, Olenik, and Nanda (1979).

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