PROCEDURES FOR ASSESSING THE VALUE OF COMMAND AND CONTROL CAPABILITIES

DECISIONS AND DESIGNS INCORPORATED

(12)

Michael F. O'Connor

ADVANCED DECISION TECHNOLOGY PROGRAM

CYBERNETICS TECHNOLOGY OFFICE
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
Office of Naval Research • Engineering Psychology Programs

The objective of the Advanced Decision Technology Program is to develop and transfer to users in the Department of Defense advanced management technologies for decision making. These technologies are based upon research in the areas of decision analysis, the behavioral sciences and interactive computer graphics. The program is sponsored by the Cybernetics Technology Office of the Defense *Advanced Research Projects Agency and* technical progress is monitored by the Office of Naval Research – Engineering Psychology Programs. Participants in the program are:

Decisions and Designs, Incorporated
Harvard University
Perceptronics, Incorporated
Stanford University
The University of Southern California

Inquiries and comments with regard to this report should be addressed to:

Dr. Martin A. Tolcott
Director, Engineering Psychology Programs
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

or

LT COL Roy M. Gulick, USMC
Cybernetics Technology Office
Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, Virginia 22209

TECHNICAL REPORT 77-4

PROCEDURES FOR ASSESSING THE VALUE OF COMMAND AND CONTROL CAPABILITIES

by

Michael F. O'Connor

Sponsored by

Defense Advanced Research Projects Agency
ARPA Order No. 3052

July 1977

DECISIONS and DESIGNS, INC.
Suite 600, 8400 Westpark Drive
McLean, Virginia 22101
(703) 821-2828

SUMMARY

In 1977, nearly seven percent of the Department of Defense Budget was allocated to the area of intelligence and communications. The command and control (C^2) function, an integral part of intelligence and communications, provides the structure which enables the National Command Authority (NCA) the President and Secretary of Defense, to exercise command and control over deployed U.S. forces through the Joint Chiefs of Staff (JCS). Essentially, the C^2 function integrates the surveillance and reaction activities of deployed U.S. military groups, thereby ensuring a unified defense force--a highly complex task vital to the nation's security. If the C^2 capability were sufficiently low, the U.S. armed forces would not function satisfactorily and the nation's defense posture would be seriously jeopardized.

In view of the significance of the C^2 function, a pertinent question is, "How much C^2 capability is enough"? It is possible to attempt to answer in the absolute, that is, say, enough C^2 capability exists when the United States armed forces can be certain of countering all projected threats and crises. Trying to answer the question of enough C^2 in the absolute is absurd, however, for if the weapons systems and personnel to be commanded and controlled are of sufficiently low quality, an excellent C^2 system will be of little value. The question of enough C^2 is but a part of the larger problem of a force capable of meeting the goal of defending the nation at all times.

In order to assess the value of a particular C^2 capability, the cost of achieving that capability must be weighed against the potential benefits of allocating funds elsewhere. Examination of the breakdown of the Department of Defense Budget would prompt a reasonable inquiry: Is this

allocation scheme the best overall scheme for meeting the long-term goal of defending the nation? More specifically, is the seven-percent allocation for C^2 sufficient to meet the need in that area? The answer necessarily involves assessing the requirements for and the benefits to be derived from expenditures in each of the specified DoD program areas. The procedures and recommendations discussed with respect to C^2 generalize trade-offs among objectives on goals at any level of generality chosen for analysis.

The objective, then, is to determine, given the fixed budget size, whether the chosen dollar allocations are optimal. The word "optimal" implies the best with respect to some cost/benefit criterion; and when cost is fixed, optimal means the option with highest value. Given a fixed set of conditions and other necessary information, the value to be attached to a particular option can be established. Part of the methodology discussed in this report addresses that question, establishing the value of particular levels of C^2 capability given a specified set of conditions.

From a decision analysis point of view, this problem involves assigning a value to the action of deciding to deploy a particular C^2 system in an uncertain future. A large decision tree would be constructed to accommodate all potentially reasonable C^2 deployments, the uncertain events, and the possible outcomes. After the assessment of probabilities and values, the tree would then be folded back (evaluated) to yield an "optimal" C^2 decision. The problem in such a case is that the decision tree is too large ("a very bushy mess," to borrow a Howard Raiffa metaphor), and meaningful probabilities and values cannot be assessed.

The structuring of decision trees and related value assessments are discussed in several sources, among them Raiffa (1968) and Keeney and Raiffa (1976). The use of scenarios as an aid in the "bushy mess" problem has been discussed in O'Connor and Edwards (1976). This report attempts to focus the foregoing material on the problem at hand.

The discussion of the problem is divided into four parts. Section 2.0 deals with the theory of assessing value for multiple attributed alternatives. For example, the expenditures in each area of the defense budget can be viewed as attributes of the budget. The level of capability that would result from a particular expenditure is an uncertain alternative which itself has many attributes. Certain desirable capabilities of the C^2 are attributes of the overall C^2 capability that can be attained for an expenditure of $\$X_1$. Finding the most preferred system that can be had for $\$X_1$ involves the assessment of trade-offs among the multiple attributes that characterize the system.

Section 3.0 discusses the use of scenarios as a solution to the so called "bushy mess" problem. The assignment of value to a multiple attributed option is dependent on adequate specification of the situation in which the option will be deployed. The use of scenarios facilitates the representation of that future. This approach involves characterizing each system as a multi-attributed alternative where the performance of the system in the scenario is one of the system attributes. The value of the system in each scenario is weighted by the scenario importance, and these weighted values are summed across scenarios to yield an overall system value.

Section 4.0 illustrates the application of value assessment procedures to a hypothetical problem of evaluating alternative architectural candidates for a World Wide Military Command and Control System (WWMCCS). The analysis was performed to determine the relative value of potential

WWMCCS crisis requirements. This discussion demonstrates a workable methodology that is applicable for the quantification of the value of requirements and the optimization of system design.

Section 5.0 further illustrates the application of utility assessment procedures to the C^2 problem by using a specific problem: the trade-offs between cost and multiple performance measures. This discussion emphasizes the necessity to find a performance measure that can be interpreted in terms of dollars. There is obviously no magic solution to the problem of comparing cost and benefit where benefit cannot be translated directly into dollars. The best approach is to find at least one scenario in which cost and performance could be traded off. Given that ability, then the trade-offs between performances across all scenarios would allow translation into dollars for all scenarios.

This report covers many aspects of utility analysis. The question of "how much C^2 is enough?" is addressed at a fairly abstract methodological level, and emphasis is on the methodology that might be used to answer it. The question, though appearing to be an absolute one, is necessarily relative, involving multi-criteria trade-offs. Most of the report deals with the methodology for making such trade-offs. That methodology is well established, and, as exemplified in Section 4.0, it has been applied repeatedly to practical problems.

CONTENTS

CONTENTS (cont.)

FIGURES

TABLES

ACKNOWLEDGMENT

This research was sponsored by the Cybernetics Technology Office of the Defense Advanced Research Projects Agency and monitored by the Office of Naval Research under contract N00014-76-C-0074 to Decisions and Designs, Incorporated. The example in Section 4.0 is based upon work done for the IBM Corporation, Purchase Order #571219, in support of the WWMCCS Contract, USAF Contract F19628-74-C-0158.

The author thanks Thomas W. Keelin, III for information and criticism provided during the development of this report.

PROCEDURES FOR ASSESSING THE VALUE OF COMMAND AND CONTROL CAPABILITIES

1.0 INTRODUCTION

Of the 112.7 billion dollars allocated for the 1977 Department of Defense Budget, the area of intelligence and communications received 7.7 billion dollars, nearly seven percent of the entire defense budget.[1] An integral part of intelligence and communications is the command and control (C^2) function (also called C^3--command, control, and communications). The national C^2 structure provides for the ability of the National Command Authority (NCA), the President and Secretary of Defense, to exercise command and control over deployed U.S. forces through the Joint Chiefs of Staff (JCS). Various levels of C^2 exist, and, in fact, a precise definition of C^2 is difficult to provide. A simple view of U.S. defenses is that they involve three necessary functions. One is surveillance for the purpose of ascertaining the capabilities and status of enemy forces. A second function is reaction. U.S. forces must be able to react appropriately to various levels of threats. A third function, C^2, integrates the surveillance and reaction functions and provides for a unified defense force. Although there exist many more aspects of C^2 than this simple discussion indicates, it is safe to say that if the U.S. C^2 capability were sufficiently low, the U.S. armed forces would not function satisfactorily in response to a threat, and the nation would be unable to defend itself adequately. In light of this, a pertinent question is, "How much C^2 capability is enough?" The answer, among other things, depends on the meaning of the term "enough."

---

[1] D. H. Rumsfeld, <u>FY 1977 Report of the Secretary of Defense</u> (United States Department of Defense, 1976), p. 259.

It is possible to attempt to answer this question in the absolute, that is, say, enough C^2 capability exists when the United States armed forces can be certain of countering all projected threats and crises. But what does "certain" mean? Does "certain" mean that all threats will be countered with probability 1.0, .99, .90, or the like? And who is to assess these probabilities? If a clairvoyant who could foresee the consequences of current decisions existed, that clairvoyant could be used to aid in designing a C^2 system. Obviously, however, expert judgment is all that is available to substitute for the clairvoyance that would provide perfect and certain answers.

Trying to answer the question of enough C^2 in the absolute is, however, absurd, for if the weapons systems and personnel to be commanded and controlled are of sufficiently low quality, an excellent C^2 system will be of little value. This correctly implies that the value to be attached to a particular level of C^2 capability is dependent upon capabilities in weapons, personnel, and the like.

The question of enough C^2 is but a part of the larger problem of a force capable of meeting the goal of defending the nation at all times. This goal is in turn part of an even higher goal of ensuring the security, freedom, and social benefits necessary for long-term sustenance of the union. The question is, therefore, one involving trade-offs among multiple objectives, and it is in this light that the question will be addressed.

In order to assess the value of a particular C^2 capability, the cost of achieving that capability must be weighed against the potential benefits of allocating funds elsewhere. The discussion will be confined to benefits derived from the defense of the nation. The procedures and recommendations to be discussed with respect to C^2 generalize trade-offs among objectives or goals at any level of generality chosen for analysis.

One breakdown of the 1977 Department of Defense Budget, a financial summary by billions of dollars, lists the following categories and associated 1977 allocations.[2]

MILITARY PROGRAM	ALLOCATION (billions of dollars)
Strategic Forces	9.4
General Purpose Forces	40.2
Intelligence and Communications	7.7
Airlift and Sealift	1.6
Guard and Reserve Forces	5.9
Research and Development	10.5
Central Supply and Maintenance	10.9
Training, Medical and Other General Personnel Activities	23.0
Administration and Associated Activities	2.1
Support to Other Nations	1.4
	112.7

A reasonable question, "Is this allocation scheme the best overall scheme for meeting the long-term goal of defending the nation?" may be asked. More specifically, is the 7.7 billion dollar allocation for C^2 sufficient to meet the need in that area? The answer necessarily involves assessing the requirements for and benefits to be derived from expenditures in each of the above areas.

An important related question involves whether or not the defense budget is large enough. It is often argued that U.S. defense needs are not being met, that the U.S. is only marginally able to deter Soviet aggression, and the like; this argument implies either more defense spending or more

---

[2] Loc. cit.

efficient use of allocated funds, or both. This question will not be addressed here. The decision on the magnitude of the defense budget as compared to other budgets should be made by considering the importance of the goal of overall U.S. defense as compared to other high-level goals. The types of inter-goal trade-offs at this higher level will be illustrated by the simplified approach using the three defense categories chosen for discussion.

The question, then, is whether, given the fixed budget size, the chosen dollar allocations are optimal? The word "optimal" implies the best with respect to some cost/benefit criterion, and when cost is fixed, optimal means the option with highest value. The problem of determining the highest value system, given a fixed level of cost, obviously depends on a specified set of conditions.

Such conditions are:

the time period under consideration,

the nature of the world situation during that period,

the nature of the enemy threat during that period,

the status of the U.S. weapons systems during that time, and

the status of the personnel forces during that time.

Given this and any other necessary information, the value to be attached to a particular option can be established. Part of the methodology to be discussed addresses that question, establishing the value of particular levels of C^2 capability given a specified set of conditions.

A decision analyst would view this problem as one of assigning a value to the action of deciding to deploy a particular C^2 system in an uncertain future. If a decision-tree approach were used, relevant uncertain events (including the decision maker's subsequent actions contingent on events) would be established, and a large decision tree which lays out all potentially reasonable C^2 deployments, the uncertain events, and the possible outcomes would be constructed. Probabilities and values would be assessed and inserted into the decision tree, which would then be folded back (evaluated) to yield an "optimal" C^2 system. The only trouble is that the decision tree is usually far too large. There are so many branches containing uncertain events and consequences that meaningful probabilities and values cannot be assessed.

The assignment of a value to a particular system corresponding to a particular level of cost thus depends on the evaluation of a large decision tree, "a very bushy mess" (to borrow a Howard Raiffa metaphor). The assignment of a value to a particular system conditional on one branch of the decision tree is but a small part of the larger problem of structuring the tree. The structuring of decision trees and related value assessments are discussed in several sources, among them Raiffa (1968) and Keeney and Raiffa (1976). The use of scenarios as an aid in the "bushy mess" situation has been discussed in O'Connor and Edwards (1976). This report will attempt to focus that material on the problem at hand.

The discussion will be divided into four parts. The first part will deal with the theory of assessing value for multiple attributed alternatives. The proposed defense budget is but one of an infinite number that could be adopted. The expenditures in each area can be viewed as attributes of the budget. The level of capability that will result from the expenditure in a particular area is an uncertain alternative which itself has many attributes. Thus, the expenditure of $\$X_1$ on a specific plan for C^2 will result in some level of capability for the NCA to interact with other heads of state. Similarly, the expenditure will lead to some unknown level of capability of the NCA to interface with the World Wide Military Command and Control System (WWMCCS). These capabilities and others are attributes of the C^2 capability that can be attained for an expenditure of $\$X_1$. One problem is to find the most preferred system that can be had for $\$X_1$, and the solution necessarily involves the assessment of trade-offs among the multiple attributes that characterize the system. The theory for doing so will be briefly outlined in Section 2.0.

As indicated, the assignment of value to a multiple attributed option is dependent on an adequate specification of the situation in which that option will be deployed, and one approach to representing that future is the use of scenarios. Section 3.0 briefly discusses the use of scenarios as a solution to the so-called "bushy mess" problem in decision analysis.

Section 4.0 provides an example of the application of value assessment procedures to evaluating alternative WWMCCS systems. Finally, Section 5.0 further illustrates the application of utility assessment procedures to the C^2 problem by using a specific problem characterized as follows. The military can procure and deploy one of N C^2 systems. The performance of each of the N systems will be observed (by simulation, war gaming, or some other strategy) in each of M scenarios. For each system in each scenario, a meaningful performance measure can be obtained. Also, for each system, a credible cost estimate, say life-cycle cost, is available. Given this information, which system should the military service procure? The discussion will attempt to illustrate alternative procedures for the application of the principles discussed in Sections 2.0, 3.0, and 4.0.

2.0 THE ASSESSMENT OF VALUE FOR MULTIPLE ATTRIBUTED ALTERNATIVES: A BRIEF OVERVIEW

Determining the "best" of several complex alternatives involves the assessment of the value[1] associated with multiple attributed alternatives (often called multi-attribute utility assessment, MAUA). The methodology to be discussed results from the theory underlying the MAUA approach, and a discussion of that approach follows.

An example of the theoretical problem being addressed is the establishment of X_1, X_2, and X_3 where

X_1 = \$$C^2$,
X_2 = \$Weapons, and
X_3 = \$Personnel

subject to the constraint that $X_1 + X_2 + X_3 \leq K$. Further, it is assumed that value increases directly with each increase of X_1, X_2, and X_3. Also, for any particular vector $\underline{X}$, a program or option can be identified that maximizes U.S. capability and thus maximizes value conditional on that budget allocation. (As indicated, the procedures for doing so will be discussed in Section 4.0.) Thus, the specification of a particular vector, $\underline{X} = (X_1, X_2, X_3)$, specifies a particular combination of capabilities with respect to C^2, weapons, and personnel. The approach to be discussed assumes that decisions are made under certainty; in other words, the values of X_1, X_2, and X_3. This is, of course a simplification, for any decision involving judgments and preferences with

---

[1]A distinction is often made between "value" and "utility," the latter term being used in decision-making involving risk. Since risk is not discussed here, the word "value" will be used in this discussion.

respect to future outcomes necessarily involves uncertainty. The theory and procedures for assessing values under conditions of uncertainty must address the question of risk preferences. This fact complicates the nature of independence conditions necessary for different functional forms of the value function as well as procedures for assessing the function. However, since the procedures to be discussed can be expanded to incorporate risk preferences when the occasion requires, this discussion will be limited to the first step, value assessments.

The approach requires the assessment of a value function U, defined on the vector space $(X_1 \times X_2 \times X_3)$, which maps each combination of C^2, weapons, and personnel into some value. The problem is to assess U and, in doing so, to identify the values of X_1, X_2, and X_3 so that U is maximized given a particular budget constraint, $X_1 + X_2 + X_3 \leq K$.

As an aside, there is, of course, the practical problem of the identity of the decision maker whose preferences U represents. Is it the President of the U.S.? Is it society? In order to assess U, it will be necessary to trade off different levels of X_1, X_2, and X_3. Often, a high-level decision maker capable of making policy trade-offs does not have a feel for the marginal benefit to be derived from changes in the levels of particular X_i, and the person able to assess the value to be associated with levels of X_i cannot make the policy trade-offs. This problem is a practical one in decision analysis, the identification of decision makers who have the information and influence to make and implement decisions. As such, part of the topic is addressed in the literature on social utility functions and will not be pursued here. It will be assumed that there exists a decision maker who can accurately express preferences among alternative vectors in the space X_i and that these preferences reflect some definable level of policy or doctrine.

2.1 The Ordinal Approach

The ordinal approach to problem solution is based on the assumption that U is an ordinal preference function such that

> U maps each vector $\underline{X} = (X_1, X_2, X_3)$ into the real numbers and
>
> U increases directly with each X_i.

The problem of assessing U and identifying the optimal (X_1, X_2, X_3) can be viewed as a non-linear programming problem where the objective function U is non-linear and the constraint $\sum_i X_1 \leq K$ is linear.

As an illustration of the approach, consider the solution to the question of the optimal levels of only the variables X_1 and X_2 on the present assumption that X_3 can be held constant in the analysis. The constraint is that $X_1 + X_2 \leq P \leq K$.

Since U is assumed to reflect an ordinal preference function, $U(\underline{X})$ is unique up to any increasing transformation $F(U(\underline{X}))$ of U. The task is to assess marginal trade-offs between different levels of X_1 and X_2 in order to ascertain the ordering imposed on the space X by the function U.

In Figure 2-1, a set of iso-preference contours for X_1 and X_2 is displayed. The decision maker has expressed indifference among all points that comprise a particular curve, with values increasing with movement of curves away from the origin.

Since it is assumed that U increases directly with increasing X_1 and X_2, and that $X_1 + X_2 \leq P$, the maximum U will occur when $X_1 + X_2 = P$. Therefore, it is desired to locate the point $\underline{X}^* = (X_{1*}, X_{2*})$ such that $X_{1*} + X_{2*} = P$ and $U(\underline{X}^*) \geq U(\underline{X})$ for all $\underline{X}$ satisfying the constraint that $X_1 + X_2 \leq P$.

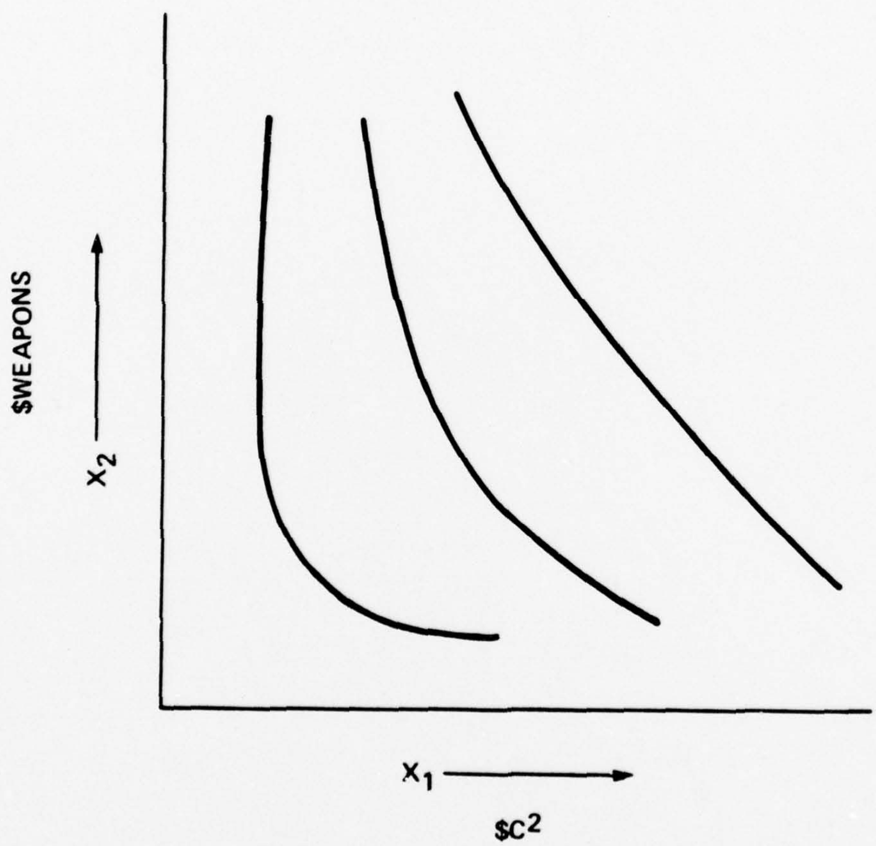

Figure 2-1

A SET OF ISO-PREFERENCE CONTOURS FOR X_1 AND X_2

In Figure 2-2, the constraint $X_1 + X_2 \leq P$ is displayed as the shaded region bounded by the linear function $X_1 + X_2 = P$. The point $\underline{X}^*$, which has the above defined qualities, is displayed.

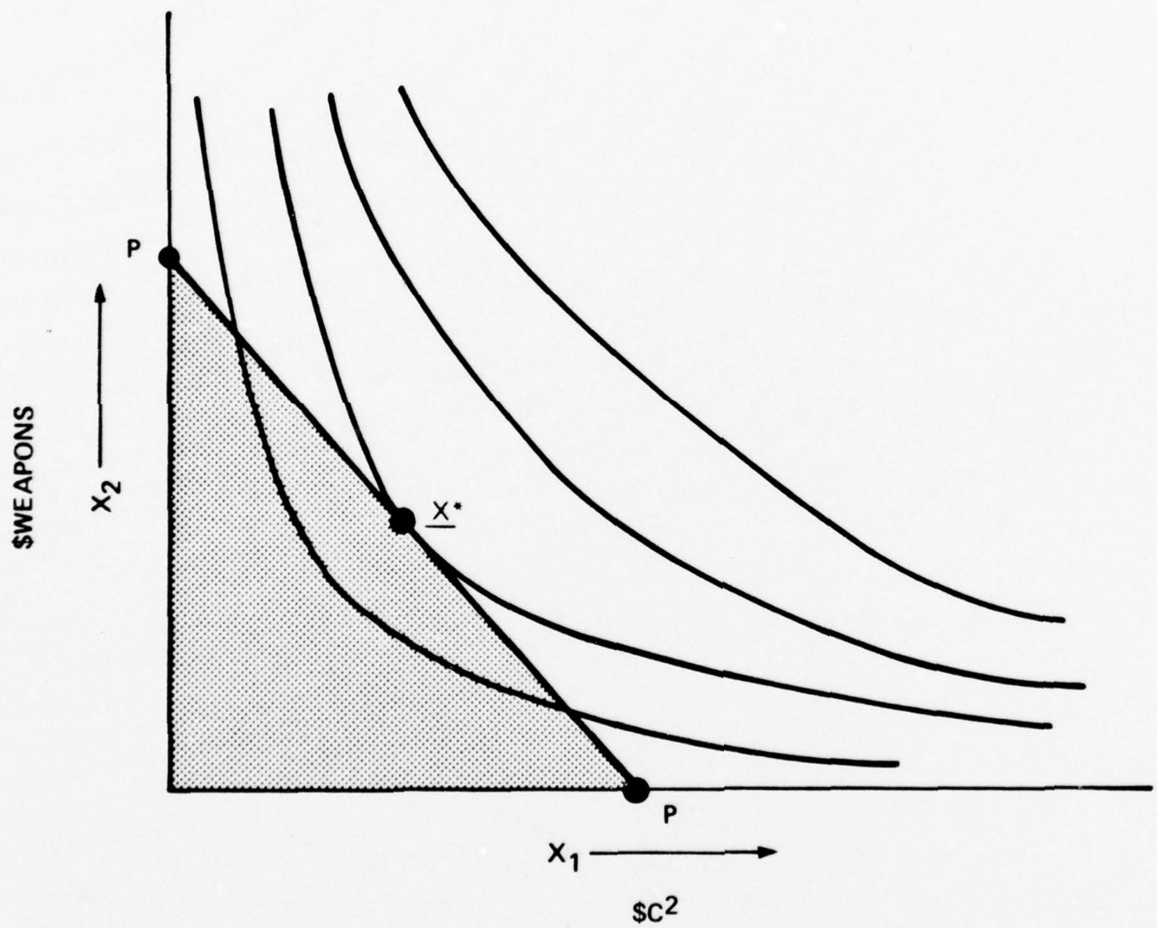

Figure 2-2
ILLUSTRATION OF PROBLEM SOLUTION

The point $\underline{X}^*$ has the simple property that any increase in either X_1 or X_2, which is necessarily matched by a corresponding decrease in the other dimension, will result in a lower overall value than is associated with the point $\underline{X}^*$.

Since $U(\underline{X}^*)$ is a maximum,

$$\frac{\partial U}{\partial X_1} + \frac{\partial U}{\partial X_2}\frac{dx_2}{dx_1} = 0 \text{ for } \underline{X}^*; \qquad 1.$$

and since $X_1 + X_2 = P$,

$$1 + \frac{dX_2}{dX_1} = 0 \text{ and}$$

$$\frac{dX_2}{dX_1} = -1.$$

Substituting in equation 1. above:

$$\frac{\partial U}{\partial X_1} - \frac{\partial U}{\partial X_2} = 0, \text{ or } \frac{\frac{\partial U}{\partial X_1}}{\frac{\partial U}{\partial X_2}} = 1 \text{ at } \underline{X}^*. \qquad 2.$$

Equation 2 implies that at the point $\underline{X}^*$, the decision maker will give up one dollar in C^2 only if compensated by one dollar in weapons and vice-versa.

Consider the set of iso-preference contours displayed in Figure 2-3. Here, the "flatness" of the indifference curves implies that the decision maker will give up a lot of X_1 to obtain a small increase in X_2. As illustrated in this case, the point $\underline{X}^*$ occurs for X_1 higher than X_2, but it is still the case that equation 2 holds. The next question involves the process of finding the point $\underline{X}^*$.

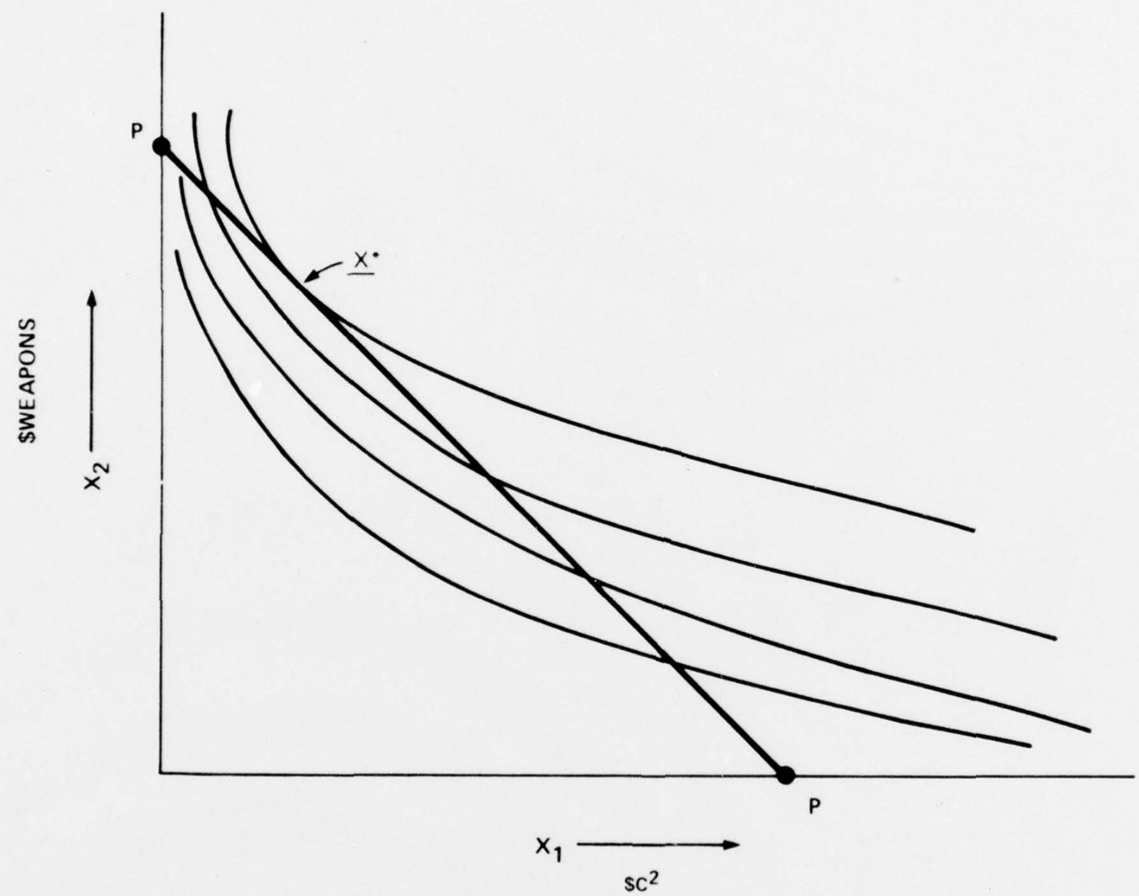

Figure 2-3

ISO-PREFERENCE CONTOURS AND $\underline{X}^*$
WHEN X_2 IS MORE IMPORTANT THAN X_1

A major difficulty with establishing the necessary U function involves the number of options ($\underline{X}$) to be evaluated. This number is potentially infinitely large, and this is especially true if more than just three dimensions, such as those used in the simplified example, are involved. Multiple trade-offs are difficult to assess if more than two dimensions are involved, and, thus, if the dimensions are defined so that complex value-wise dependencies exist between them, the assessment of U can be prohibitively difficult.

However, it is often the case that the dimensions can be defined so that a condition known as deterministic additive independence (DAI) or equivalently, mutual preference independence, holds (see Keelin, 1976 for discussion of DAI and Keeney and Raiffa, 1976 for a discussion of mutual preference independence). Specifically, this condition holds for three dimensions (X_i, X_j, and X_k) if trade-offs between levels of X_i and X_j for a fixed level of X_k do not depend on the level at which X_k is fixed. If dimensions can be defined so that this condition holds for all triples of dimensions, then the nature of U can be established by successive assessments of trade-offs between pairs of dimensions. This process involves careful definition of dimensions and then checking for DAI by assessing indifference functions between levels of X_i and X_j, such as those displayed for X_1 and X_2 in Figures 2-1 and 2-2, with the level of X_k fixed. DAI implies that the iso-preference contours in the (X_i, X_j) plane will remain invariant as a function of different levels of the fixed X_k.

Assume that dimensions have been defined so that DAI holds.

$$\text{Define} \qquad \lambda_{ij} = \frac{\frac{\partial U}{\partial X_i}}{\frac{\partial U}{\partial X_j}} \qquad 3.$$

where λ_{ij} represents the marginal rate of substitution between levels of X_i and X_j. Recall that λ_{12} evaluated at $\underline{X}^*$, for which U is conditionally maximized, will be 1.0.

Further define $$Z_{ij}(\underline{X}) = \frac{\frac{\partial \lambda_{ij}}{\partial X_i}}{\lambda_{ij}}, \qquad 4.$$

where $Z_{ij}(\underline{X})$, known as the marginal value reduction coefficient, reflects the manner in which the marginal rate of substitution between X_i and X_j changes as a function of X_i. (See Keelin, 1976, for further discussion of the marginal value reduction coefficient.) Note that both X_{ij} and $Z_{ij}(\underline{X})$ can be assessed by using appropriate assessment procedures. The questions asked involve changes in preferences with differing levels of X_i and X_j. Consider the situation in Figure 4.

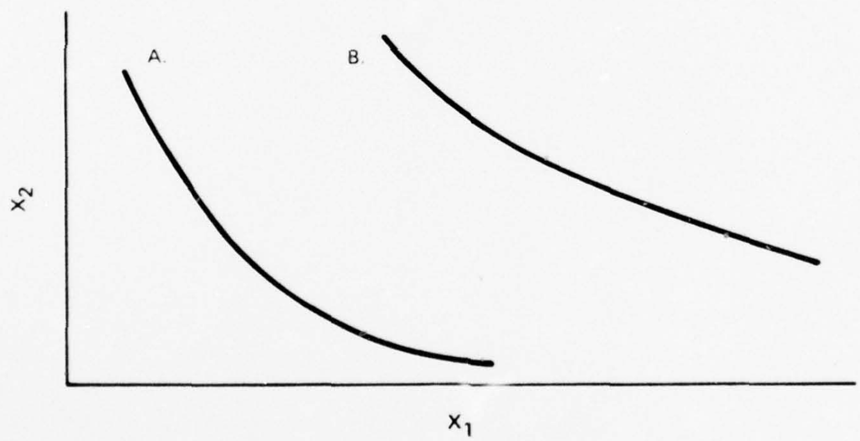

Figure 2-4

CHANGING ISO-PREFERENCE CONTOURS AS A FUNCTION OF X_1

For curve B, the decision maker will give up more X_1 for specific amounts of X_2 than he will for curve A. It is quite reasonable to assume that as one accumulates more X_1, the incremental value of more X_1 as opposed to more X_2 will decrease; curves A and B display such a preference pattern.

Keelin (1976) proves that if an additive form of U exists, that is, if

$$U(\underline{X}) = \sum_i U_i(X_i), \qquad 5.$$

then Z_{ij} depends only on X_i and will be the same for all j. Thus, for this case, $Z_{ij}(\underline{X})$ can be simply denoted as Z_i and need only be assessed for each i. Z_i can be approximated as follows:

$$Z_i \doteq \frac{{}^{\lambda}(X_i + \Delta X_i) - {}^{\lambda}X_i}{{}^{\lambda}X_i \Delta X_i}, \qquad 6.$$

and Keelin has further shown that $U(\underline{X})$ can be written in an additive form if and only if

$$U(\underline{X}) = \sum_i \int -a_i e^{-\int Z_i(X_i)} dx_i . \qquad 7.$$

This implies that in the case when an additive form of U exists, determining the set $\{Z_i\}$ for all i completely specifies U.

Some examples of different forms of an additive U are the following:

$$Z_i = 0 \text{ for } X_i \text{ implies } U(\underline{X}) = a_i x_i + \sum_{j \neq i} U_j(X_j), \qquad 8.$$

$$Z_i = 0 \text{ for } \underline{\text{all}}\ X_i \text{ implies } U(\underline{X}) = \sum_i a_i X_i, \qquad 9.$$

$$Z_i = \lambda_i, \text{ a constant, for } X_i \text{ implies } U(\underline{X}) = -a_i e^{-\lambda_i X_i} + \sum_{j \neq i} U_j(X_j), \qquad 10.$$

$$Z_i = \frac{1 + \partial}{X_i} \text{ for } X_i \text{ implies} \tag{11.}$$

$$U(\underline{X}) = -a_i X_i^{-\partial i} + \sum_{j \neq i} U_j(X_j).$$

Thus, by assessing appropriate marginal trade-offs, the nature of U can be determined. Note that with appropriate independence conditions holding, the decision maker need only answer questions of the kind, "Given X_i and X_j at levels X_i^O and X_j^O, what change in X_j would just compensate for a decrease of ΔX_i in X_i?" By using these questions, the ordinal approach can be used to ascertain the nature of the U function and to rank order the actual options or even potential options under consideration.

Also, once the rank order has been established, the nature of trade-offs between dimensions can be given meaning by trading off all options into one dimension. For example, to give meaning to the trade-offs between X_1 = \$$C^2$, X_2 = \$Weapons, and X_3 = \$Personnel, any option $\underline{X} = (X_1, X_2, X_3)$ can be compared to options of the form (X_1^O, X_2, X_3^O) where X_1^O = \$$C^2$ fixed at the status quo and X_3^O = \$Personnel fixed at the status quo. A value of X_2, X_2' is found such that $\underline{X}$ is indifferent to (X_1^O, X_2', X_3^O). In this way, the different options can be scaled in terms of equivalent benefits to be derived with respect to the weapons dimension by assuming some fixed levels of X_1 and X_3. The decision maker in effect knows that a particular vector $\underline{X}$ is indifferent to some allocation of \$Weapons given \$$C^2$ and \$Personnel fixed at some nominal levels.

It should be cautioned that the trading off of all attributes into one must be done with a judicious choice of fixed nominal levels of all other attributes. The fixed levels must be such that the judgments required of the decision maker make sense, and that there actually does exist an X_2 that satisfies the equation

$$U(X_1, X_2, X_3) = U(X_1^o, X_2', X_3^o). \qquad 12.$$

Often, one of the dimensions over which $U(\underline{X})$ can be assessed is dollars. This is especially true when dollars are an attribute with respect to which the decision maker is accustomed to making trade-offs. In private industry, for example, short-term profit can be traded off against research and design programs. Thinking in terms of dollar trade-offs is likely to be difficult for a military commander in a particular operation, for the attribute dollars is at that moment only of marginal, if any, importance. It is possible that at some higher level of the decision-making hierarchy, dollars are relevant. However, in government decisions involving cash flows, trade-offs will be of the kind discussed here, that is, between $\$C^2$ and \$Weapons or between \$Military and \$Social Welfare. In other decisions, direct dollar trade-offs, such as dollars versus energy consumed, dollars versus lives lost, and the like, may be possible.

Note that a particular level of $\$C^2$ or \$Weapons provides a specific "best" program, but even the best program may not be worth the dollars expended. Thus the trade-off here can be between the benefits associated with particular levels of each attribute and cost in terms of dollars. What is this program really worth to a decision maker?

Suppose, for simplicity, that instead of X_3 = \$Personnel, X_3 = simply \$. X_2^o corresponds to the status quo expenditure on weapons, and X_1^o corresponds to the status quo expenditure on C^2. Then, as discussed, trade-offs like those in Figure 2-5 can be made.

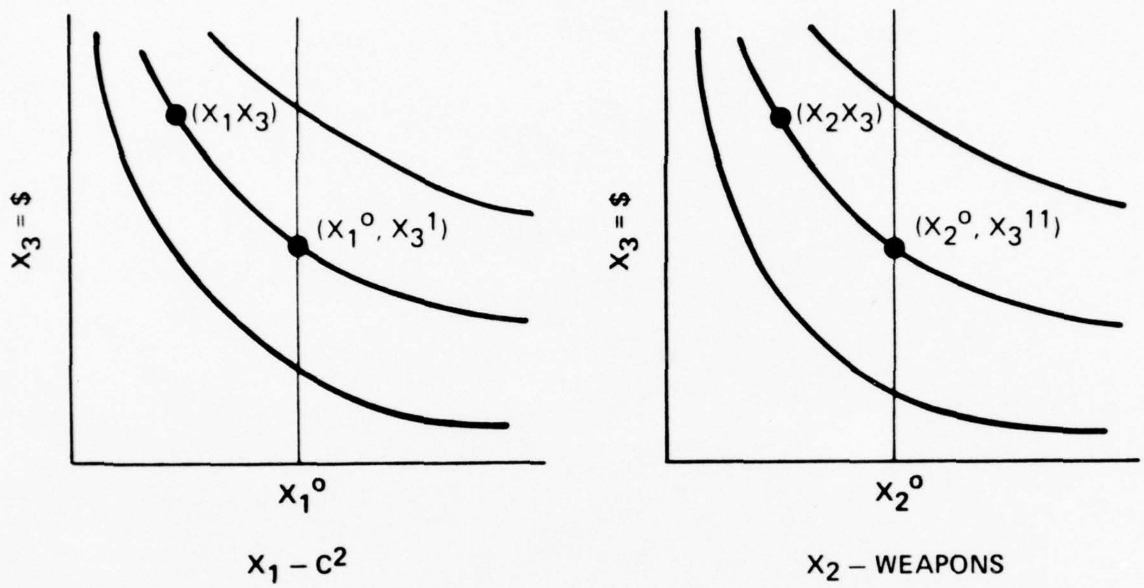

Figure 2-5
TRADE-OFFS BETWEEN $ AND C^2, AND $ AND WEAPONS

2.2 The Interval Scale Approach

The second approach to establishing the optimal levels of X_1, X_2, and X_3 assumes that U is an interval scale value function unique up to a linear transformation. This assumption implies that the decision maker, in assessing trade-offs, is providing metric information about differences in utilities.

Consider the following example involving the four indifference curves displayed in Figure 2-6.

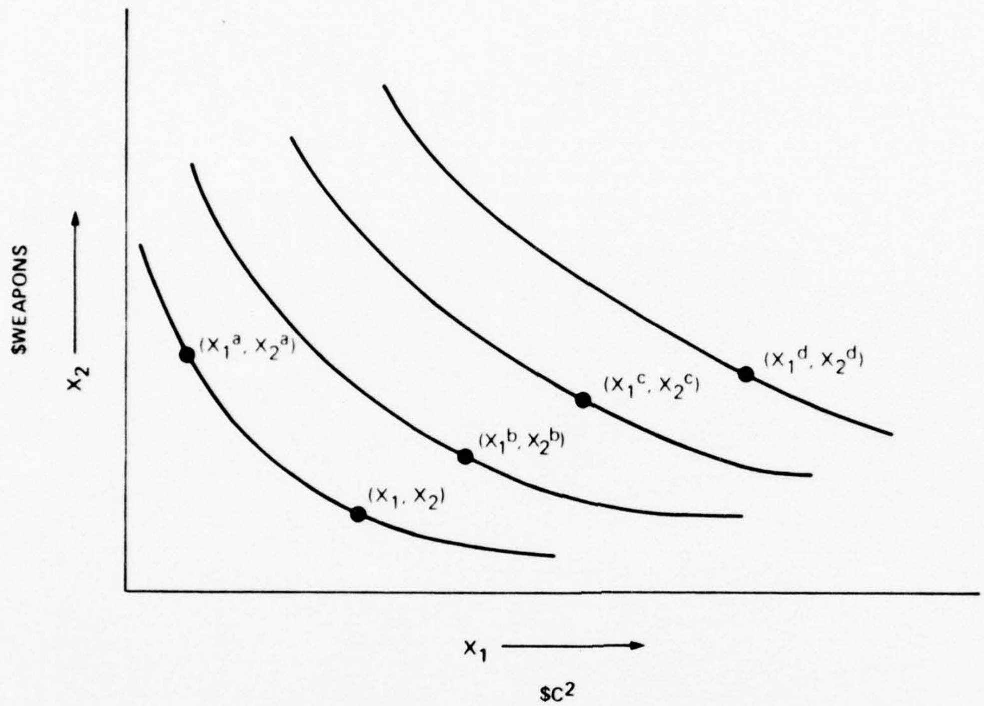

Figure 2-6

FOUR ISO-PREFERENCE CONTOURS IN $X_1 \times X_2$ SPACE

The ordinal approach described in Section 2.1 implies that the points (X_1, X_2) and (X_1^a, X_2^a) in Figure 2-6 are of equal utility. Similarly, $U(X_1^d, X_2^d) > U(X_1^c, X_2^c)$. No more information is provided in these judgments. The interval scale approach can provide information of the kind

$$\frac{U(X_1^d, X_2^d) - U(X_1^c, X_2^c)}{U(X_1^c, X_2^c) - U(X_1^b, X_2^b)} = \frac{U(X_1^c, X_2^c) - U(X_1^b, X_2^b)}{U(X_1^b, X_2^b) - U(X_1^a, X_2^a)}. \quad 13.$$

In fact, the utility differences are assumed to be scaled on a ratio scale unique up to a ratio transformation. Such metric judgments are necessarily more difficult than ordinal preferences.

However, there is considerable evidence that decision makers can validly provide such assessments.[2] The procedure for using this approach is similar to that for using the ordinal approach. Assumptions about DAI are checked and pairwise trade-offs between dimensions are assessed. However, metric information concerning the relative magnitudes of value difference is derived from judgments by using appropriate procedures. Often it is the case that U is an additive value function of the form in equation 14.

$$U(\underline{X}) = a_1 U_1(X_1) + a_1 U_2(X_2) + a_3 U_3(X_3) + a_4. \qquad 14.$$

U is an interval scale value function as are the individual $U_i(X_i)$ functions. In order for this form of U to hold, the independence assumptions of Section 2.1 must hold, and it also must be the case that the DAI condition holds not only in the ordinal form, but in the interval form; that is, the metric information provided by trade-offs between dimensions is independent of levels at which other dimensions are fixed.

The interval scale approach, when appropriate, can be used to relate changes in benefits with respect to specific dimensions to cost and thus allow cost-benefit analyses to proceed not only at a global option level (considering simultaneously all three dimensions X_1, X_2, and X_3), but also at specific dimensional levels. For example, a statement similar to the following can be made. "Increased C^2 capability costing 100 million dollars more than today's capability is worth twice as much as an increase in weapons capability costing 75 million dollars." Such trade-offs, possible also in a modified form by using the ordinal approach, are quite desirable for answering the question of trade-offs among budget categories.

---

[2] W. Edwards and A. Tversky, eds., "Introduction," Decision Making (Middlesex: Penguin Books, 1967), pp. 7-10.

An example of just how the interval scale procedure can be used is provided in Section 4.0. Specifically, the procedure is applied to the problem of examining World Wide Military Command and Control System (WWMCCS) capabilities and funding levels.

3.0 STRUCTURING THE PROBLEM: THE USE OF SCENARIOS

In Section 2.0, the theory of the MAUA approach was introduced. Of major importance in that approach is the necessity for subjective judgments about trade-offs among attributes. A C^2 system can be represented as a multi-attributed alternative having capabilities on a large number of dimensions or attributes. The relative importances of capabilities with respect to different attributes can be represented by inter-attribute trade-offs. However, as discussed in the introduction to this report, such trade-offs are conditioned upon the values of a large number of conditioning variables, acts and events that determine the specific set of circumstances in which the system will be deployed. As indicated, accurately representing the uncertain future in which the systems are to be deployed corresponds to the so-called "bushy mess" problem in decision analysis.

The utility to be attached to a system characterized by a set of parameters that are related to the eventual performance of the system can only be determined when the outcome of deployment is known. Obviously, that outcome will occur too late to be of any help in system choice, and, therefore, an estimate of that utility, an expected utility, must be assessed. The typical procedure for doing so would involve creation of a decision tree containing all relevant acts and events interrelated in an appropriate fashion.

The creation of such a decision tree begins small, by considering only the most critical acts and events. Other acts and events are added as it becomes evident that the decision under consideration could change as a function of their importance. In the system design or choice problem, the number of acts and events quickly becomes prohibitive, and the decision tree becomes a bushy mess which must be pruned. Pruning essentially involves appropriately approximating the decision tree.[1]

Other modeling approaches avoid the bushy mess problem by characterizing the problem in such a way that non-critical aspects are eliminated as modeling proceeds. Such elimination, however, must be based on accurate representation of the uncertainty inherent in the problem and on the identification of variables that discriminate between decisions. Such an analysis necessarily deals in a different fashion with the same problems to be discussed.

The decision tree approach is one way to address the problem of characterizing the uncertain future in which a system will be deployed. Alternative approaches are available as exemplified by the voluminous literature on forecasting the future for different purposes. O'Connor and Edwards have outlined the general problem discussed here and have suggested potential solutions.[2] They approach the problem by considering the use of scenarios in system evaluation. The problem addressed is identical to that discussed thus far. In order to assess the utility of a system to be deployed in an uncertain future, that future must somehow be adequately represented. One way to do so is by the use of scenarios.

A scenario can be equated with a branch of a decision tree; that is, a scenario can be viewed as a sequence of events that sets the stage for the deployment of a C^2 system.

---

[1] H. Raiffa, Decision Analysis: Introductory Lectures on Choices Under Uncertainty (Reading, MA: Addison-Wesley, 1968).

[2] M. F. O'Connor and W. Edwards, On Using Scenarios in the Evaluation of Complex Alternatives, Technical Report TR 76-17 (McLean, VA: Decisions and Designs, Inc., December 1976).

Equivalently, a scenario can be viewed as the specification of the values of a number of relevant (conditioning) variables upon which the outcome of and utility associated with system deployment are dependent. The specificity of a scenario can be characterized by the number of conditioning variables specified or, alternatively, by the length of the branch of the decision tree represented by a scenario.

The branches of a decision tree can, therefore, be viewed as a group of scenarios. Similarly, the vector space that is created by taking the cross products of all variables upon which the utility of system deployment could be dependent can be characterized as a scenario space. In either case, as already indicated, the number of potentially relevant scenarios is prohibitively large. Not all of them can be analyzed. Yet, in the deployment of a particular C^2 system, (or other weapons system) the failure to capture the essence of the future in which the system will be deployed can and probably will lead to a system that is far from optimal, perhaps far from satisfactory.

It is essential to establish criteria for choosing scenarios. Two criteria that are reasonable but may not be compatible have been labeled as "representativeness" and "discriminability."[3]

The representativeness criterion refers to the fact that in an evaluation system deployment, it is necessary to represent accurately the future in which the system will be deployed. Although not every specific event can be captured by a representation of the future, no critical event or class of events can be ignored. In representing a popu-

---

[3] Ibid.

lation of voters in an opinion poll, no critical sub-stratum of the population can be ignored or misrepresented without danger of a significant error of estimation. Similarly, in representing the future for system deployment, no critical set of conditioning variables or critical region of the decision tree can be ignored or misrepresented. Answering the question of when the U.S. has enough C^2 capability necessarily involves some projection of the future, and that projection must include representative scenarios.

Recall that one problem addressed in this report is establishing the optimal C^2 system that can be obtained for $\$X_1$. The solution to this problem necessarily involves choosing among alternative proposed systems. Yet, most system designers try to design systems to be adequate with respect to representative threats or representative futures. The systems may differ somewhat in their ability to handle certain aspects of the situation, but all in all, the difference among systems may not be large. In order to choose among systems, it is often necessary to create scenarios that discriminate in a value sense among the options under evaluation, and these scenarios may not be at all representative of the future. These scenarios will guarantee a difference among systems in terms of value, but how important is the difference?

Representative scenarios are thus not necessarily discriminative, and a set of scenarios that satisfies both criteria can be difficult to create. One solution is to use a two-step procedure. First, systems are evaluated in scenarios that are representative of the future and are mutually exclusive and exhaustive. The expected value of a system is found by multiplying the probability of each scenario by the value of the system in the scenario and aggregating these weighted values. If large differences in expected value exist, further evaluation may not be necessary.

If no system is satisfactory, the creation of new options may be necessary. If, however, a reasonable number of systems are close and satisfactory in expected value, further evaluation may be necessary.

A method of establishing discriminitive scenarios, labeled "single threading," is the following. The attributes of scenarios that would make each system look very good are identified. These attributes would be those that enhance or take advantage of the better aspects of the system. Similarly, attributes that degrade system performance are also identified. Then, for each proposed system, a set of scenarios is created which emphasizes the positive aspects of the system and deemphasizes the negative aspects of the system.

Each system is evaluated in all scenarios, those in which that system should achieve excellent performance as well as those designed to enhance others. The system performances in scenarios must then be aggregated across scenarios, but the procedure of weighting the value of the system in each scenario, multiplying by scenario probability, and aggregating is not necessarily appropriate. One reason is that the scenarios are not necessarily mutually exclusive and exhaustive as is the case with a set of representative scenarios. Also because no partition of the future exists, establishing the actual scenario probabilities may be a fairly difficult absolute judgment task.

A possibility would be to establish the conditional probability of each discriminitive scenario, given that one of the representative scenarios has occurred, and to multiply that conditional probability by the probability of the representative scenario. This procedure is repeated for each representative scenario, and the products are summed over the set of representative scenarios to obtain the probability of the discriminative scenario. This probability may be used as a weight for the differences in option values in the scenarios.

An important point must be made with respect to option values in scenarios. One view of the value of an option in a scenario is the value of the expected consequence of deploying that option in the scenario. However, that consequence may have little to do with the system. Perhaps no system would do well in the scenario. For example, in a strategic nuclear confrontation, the consequences are likely to be disastrous no matter which system is deployed. There is, in effect, a guaranteed large negative value associated with certain low probability, high importance scenarios, and since no system can do much to reduce that negative value, all systems will have low value in such scenarios. Similarly, certain high probability scenarios like the involvement of the U.S. Navy in normal operations in the West Pacific involve fairly minimal consequences and the relative impact of all systems is about the same.

Accordingly, the weight given a scenario should be a function not only of scenario probability, but also of the importance of the scenario. The importance of a scenario is a function of possible system impact in the scenario. Scenarios where no system can improve the situation, that is, those in which the value of the consequences of deployment of any system is extremely negative, should receive low weight. And scenarios where the consequences of poor system performance are minimal should also receive little weight.

A plausible procedure for weighting discriminative scenarios is the following:

1. For each scenario, the value of the consequences of deployment of the worst feasible and also the best

feasible system are established as minimum and maximum system values for that scenario. The difference between these values is called the value difference for a scenario.

2. The largest value difference across scenarios is assigned an arbitrary value, say 100 or so, and value differences for other scenarios are scaled by comparison with this difference. Note that in order to make such comparisons, value differences must be well defined. An example of a good definition would be the dollar value of equipment and lives lost as a consequence of system deployment in the scenario. Perhaps such a precise definition is difficult, but such ratings do require that there exist a sound basis for comparison of value differences across scenarios.

3. The scaled value difference of each scenario is multiplied by the scenario probability to yield an expected value difference.

4. The expected value differences are normalized to sum to 1.0 across all scenarios. These normalized values serve as scenario importance weights.

This procedure requires that scenarios do not intersect, that is, that the conditional probability of one given the other is zero. If this is not the case, value differences may be overweighted by being counted in two scenarios. When scenarios intersect, they must be separated by introducing the negation of one as a detail of the other or by combining them into one scenario.

Once the set of scenario importance weights has been established and checks have been made for overweighting, the value of each system is assessed on a 0-to-100 scale in each scenario by comparing that system performance with the performances of the worst, best, and other systems in the scenario. The value of the system in each scenario is weighted by the scenario importance, and these weighted values are summed across scenarios to yield an overall system value.

The approach to this problem thus far discussed is to characterize each system as a multi-attributed alternative where the performance of the system in a scenario is one of the system attributes. This approach will be further discussed in Section 5.0 where the specific problem outlined in Section 1.0 is addressed in detail.

4.0 AN EXAMPLE: THE DEVELOPMENT OF AN ANALYTIC PROCEDURE FOR EXAMINING THE RELATION BETWEEN WORLDWIDE MILITARY COMMAND AND CONTROL SYSTEMS (WWMCCS) PERFORMANCE CAPABILITIES AND FUNDING LEVELS

This section of the report describes the application of the value assessment methodology to a hypothetical problem of evaluating alternative architectural candidates for a World Wide Military Command and Control System (WWMCCS).[1] The procedure used is an example of the interval scale approach. The analysis was performed to determine the relative value of potential WWMCCS crisis requirements. In addition, a description of a procedure for extending the analysis in order to identify architectural candidates that yield maximum WWMCCS capability given fixed budget constraints was developed.

4.1 Introduction to Requirement Level Definitions

This study commenced with the formulation of a set of general WWMCCS requirements statements drawn from (1) a review of pertinent Defense Department documents; (2) selected "post mortem" observations about past crises management situations; and (3) first-hand knowledge from former participants in U.S. Command and Control Systems. From these general requirements, specific requirements were derived and defined in such a manner that each one could be related to a specific crises management support need and could also be understood by an operator (WWMCCS User) and an engineer (WWMCCS Designer). An example of such a specific requirement might be the description of the need for an interface among crises battle staff and analyst personnel in the National Military Command Center (NMCC) and those in the command posts of the Unified and Specified (U and S) Commands.

---

[1] The example is based on work done for the IBM Corporation, Purchase Order No. 571219 in support of the WWMCCS Contract, USAF Contract F19628-74-C-0158.

Once a comprehensive list of such performance requirements was developed, each requirement was refined to reflect different levels of capability and sophistication. For example, should the interface referred to above include a capability to transmit photographic materials within minutes from one command node to another? The different levels of capability were chosen to provide a clear, understandable distinction in operational terms of the different contributions of each to crises management. A complete description of each requirement and the levels of sophistication within each are outlined in Appendix A. The numbering system used is that used in the original study (requirements 3.2.18 and 3.2.19 are deleted).

These different levels of performance capability are generally relatable to timeliness, geographic coverage, command echelon, and other characteristics such as voice and text transmission. This method of stating requirements facilitates the evaluation of the contribution of different levels of capability to crises management in different scenarios. This evaluation forms the basis for the model (described in Section 4.2) which is used to prioritize the relative importance of specific requirements and to measure the increase in benefits derivable from higher levels of capability among requirements.

4.2 Description of Methodology and Interpretation of Values

The requirement levels described in Section 4.1 were evaluated by using the methodology explained in Section 4.3. The first step of the method involves determining the relative value of adding the highest capability level of each requirement to the system, within a given situation. This step is then repeated for each situation. The next step is to determine the relative priority of each situation for the

WWMCCS design, a step accomplished by determining the relative probability of occurrence of each situation, the potential relative impact of that situation on U.S. interests, and the relative contribution that a maximum WWMCCS system makes to the management of each situation. Combining these factors yields the relative priority sought. Next, by combining the relative value of a requirement within each situation with the priority of that situation and summing across all situations, the value of the requirement is determined.

Having these summary measures of value of the range of capability for each requirement, the next step is to determine the value of each level of capability of the requirement. This determination is made by examining each requirement and assessing the percentage of the total requirement value that is obtained by adding each level. This percentage contribution of each level is then multiplied by the requirement value to arrive at a value for each level. (When the percentage contribution of each level is dependent upon the situation, a weighted average percentage is used as the multiplication factor, with the situation priorities as weights.)

These level values, or measures of expected benefit, are comparable in the same way that the requirement values are comparable. For instance, changing from the current system for requirement 3.2.4 (Vertical-Horizontal Analysis Interface for Command Duty Personnel) to the level II improvement (value of 3.1) is half as valuable as changing from the current system to level II for requirement 3.2.9 (Intelligence Interface) (value of 6.2). Furthermore, for requirement 3.2.4, changing from level II to level III (value of 1.5) is half as valuable as changing from level I to level II (value of 3.1), and changing from level III to level IV (value of 1.6) is about as valuable as changing from level II to level III (value of 1.5). Also, the value of changing from the current system to level IV of requirement 3.2.4 (value of 6.2) is just as valuable as changing from the current system to level II of requirement 3.2.9 (intelligence interface) (value of 6.2). (The value of going to level III of requirement 3.2.9, however, is about 40% greater than the value of going to level IV of requirement 3.2.4). The reader can make other comparisons by consulting the results in Appendix A.

4.3 Value Assessment Methodology

In order to arrive at the requirement valuation displayed in Appendix A, a methodology which allowed for the comparison of the various requirements on a meaningful scale was necessary. Since the requirements considered were not reducible to natural units (such as dollars), much less to the same natural units, the methodology had to treat relative values in such a way as to arrive at a single valuation number.

The steps followed in this methodology are:

1. Assign relative importance weights to requirements within each situation,
2. Determine the relative priority of each situation,
3. Combine the factors from Steps 1 and 2 above to arrive at importance weights across situations, and
4. Assess the importance of each level of capability within each requirement.

Table 4-1 is an example of the type of input assessed in Step 1. Displayed are normalized relative importance weights for requirements in two situations. It shows, for instance, that within "BLOCK" (blockade situation), it is

Requirement \ Situation	A	B	Quake	D	E	Block	G	H	I
3.2.1 NCA HEADS OF STATE INTERFACE			4			4			
3.2.2 NCA WWMCCS INTERFACE			4			8			
3.2.3 WWMCCS WASHINGTON LEVEL INTERAGENCY INTERFACE			15			10			
3.2.4 VERTICAL-HORIZONTAL ANALYSIS INTERFACE			4			11			
3.2.5 WWMCCS COMMUNICATIONS			6			12			
3.2.6 WWMCCS ON SITE ALLIED INTERFACE			13			1			
3.2.7 TRANSPORTABLE C^3 FACILITY			15			1			
3.2.8 MONITORING FOREIGN NATIONAL BEHAVIOR			6			8			
3.2.9 INTELLIGENCE INTERFACE			7			8			
3.2.10 AD HOC PLANNING 3.2.12 INTEGRATED DATA DISPLAY 3.2.13 DYNAMIC SITUATION ASSESSMENT			6			8			
3.2.11 USER ORIENTED ADP-BASED SUPPORT			4			8			
3.2.14 CRISES MONITORING SUPPORT			4			10			
3.2.15 STANDARDIZED OPERATING PROCEDURES			4			4			
3.2.16 CRISES INFORMATION DIRECTORY			9			1			
3.2.19 INTELLIGENCE/OPERATIONS/ DIPLOMATIC COORDINATION			2			3			
	100	100	100	100	100	100	100	100	100

Note: All numbers are rounded to the nearest integer.

Table 4-1

NORMALIZED RELATIVE IMPORTANCE WEIGHTS FOR REQUIREMENTS IN SITUATIONS most important to improve the current system to the top level capability (levels are described in Appendix A) for requirement 3.2.5, WWMCCS Communication for Senior Decision Makers. Furthermore, it is three times as important to increase the capability of this requirement as it is to increase the capability of requirement 3.2.1, NCA-Heads of State Interface. The reason for this relationship is that since the current capability of requirement 3.2.1 already provides for communication with the U.S.S.R., increasing this capability is of little value in the blockade situation. Similarly, since it is doubtful that a transportable C^3 facility would be used in the blockade situation, the relative value of having such a capability (requirement 3.2.7) is judged to be very low (about 1/12 as valuable as the increased communications capability of 3.2.5).

For comparison purposes, next consider "QUAKE" (earthquake situation). In this situation, it is considered to be very important to have the transportable C^3 facility (requirement 3.27) to provide communications with the disaster area, and this requirement is assigned the highest relative importance value. Also note that in this situation, requirement 3.2.5 (which is the most important requirement for the blockade) is less than half as important as 3.2.7 for this situation. The reason for this reversal in importance is that requirement 3.2.5 is mainly a system to link overseas personnel with the U.S. and with each other. Since the earthquake situation is basically an internal problem, the overseas capability is not particularly important.

Given requirements prioritized within each situation, it is next necessary to establish the relative priorities of the different situations. The three factors most important to situation priority are:

1. The relative probability of situation occurrence;

2. The relative impact on U.S. interests of each situation; and

3. The relative contribution that a "maximum WWMCCS" would make toward the management of each situation.

Relative probabilities are established by comparing the likelihoods of each situation on a ratio scale and normalizing the values to sum to 1.0. The relative impacts on U.S. interests and also the contribution of a "maximum WWMCCS" are established by assigning that situation having the greatest impact (or contribution) a value of 100 and comparing all others to that situation as well as to each other. The final results are ratio scale impacts of impact and contribution values which are normalized to sum to 100.

A multiplicative combination rule was chosen for combining the three situation priority factors into an overall priority. Such a combination rule incorporates the obvious dependencies among the factors. For example, if any one of the three factors--situation, probability, relative impact on U.S. interests--or relative contribution of a "maximum WWMCCS" has a zero value for a situation, the priority of the situation should be zero.

Table 4-2 is an example of an elicited prioritization of situations. In this figure, each component, relative probability, relative impact on U.S. interests, and relative contribution of a maximum WWMCCS, is assessed separately and normalized. The bottom row of numbers is the normalized products of the components. (The last row of numbers appears slightly inconsistent with the first three rows because, for purposes of presentation, each row was individually rounded off to the nearest whole number. The rounded product is based on the use of more accurate component numbers.)

Components \ Situation	A	B	Quake	D	E	Block	G	H	I	
RELATIVE PROBABILITY	3	6	<.5	4	26	1	29	25	6	= 100
×										
RELATIVE IMPACT ON US INTERESTS	24	19	3	11	5	27	1	1	8	= 100
×										
RELATIVE CONTRIBUTION OF MAXIMUM WWMCCS	23	18	5	9	7	20	2	2	14	= 100
=										
PRODUCT	24	30	0	6	15	12	1	1	9	= 100

Note: All numbers are rounded to the nearest integer.

Table 4-2
PRIORITY OF SITUATIONS

There is now enough information to determine the value of each requirement by taking a weighted average. That is, the relative weight of each requirement within each situation is weighted by the priority of the situation and averaged across all situations. This process yields the overall value of each requirement. The results are displayed in Table 4-3. Here the last column shows the value of each requirement. This number has an interpretation similar to that for the number of each column but independent of situation. For example, it is most valuable to include the top level capability of requirement 3.2.5. Adding this capability gains 9.4% of the total value of a maximum WWMCCS. It is more than twice as valuable to add this capability as it is to add the top level of requirement 3.2.7.

This analysis was done with several experts, and convergence across experts was examined. That information is not reported here. Table 4-4 displays mean values for all requirements.

The final step in the analysis involved determining the value of each capability level within each requirement. Figure 4-1 shows an example of this process for requirement 3.2.3. Table 4-4 shows that the value of increasing the capability of requirement 3.2.3 from the current system to its top level is 8.9. Since requirement 3.2.3 was described by four capability levels (see Appendix A), Level IV is valued at 100% of 8.9 or 8.9. (Recall that the definition of the value scale is the <u>improvement</u> over the current capability. Thus, the value for Level I, the current system, is 0.) In this case, a consensus of the assessors valued Level III of the requirement at 90% of the total value (8.0) and Level II at 50% of the total value (4.4). (Applying the same methodology to the other requirements yielded the values shown in Appendix A.)

Requirement \ Situation	A	B	Quake	D	E	Block	G	H	I	Wtd Ave
1. NCA HEADS OF STATE INTERFACE	6	10	4	7	5	4	11	9	12	7.7
2. NCA WWMCCS INTERFACE	7	6	4	5	7	8	6	9	4	6.5
3. WWMCCS WASHINGTON LEVEL INTERAGENCY INTERFACE	8	9	15	7	10	10	6	9	8	8.7
4. VERTICAL-HORIZONTAL ANALYSIS INTERFACE	6	4	4	11	10	11	6	6	7	6.8
5. WWMCCS COMMUNICATIONS	9	6	6	16	11	12	8	11	8	9.4
6. WWMCCS ON SITE ALLIED INTERFACE	2	9	13	4	8	1	14	3	3	5.3
7. TRANSPORTABLE C^3 FACILITY	8	4	15	4	3	1	3	3	1	4.1
8. MONITORING FOREIGN NATIONAL BEHAVIOR	7	8	6	11	8	8	6	6	7	7.7
9. INTELLIGENCE INTERFACE	8	8	7	9	3	8	6	6	8	7.2
10. AD HOC PLANNING 12. INTEGRATED DATA DISPLAY 13. DYNAMIC SITUATION ASSESSMENT	8	8	6	5	7	8	11	11	7	7.6
11. USER ORIENTED ADP-BASED SUPPORT	8	6	4	4	4	8	6	6	4	6.3
14. CRISES MONITORING SUPPORT	10	6	4	11	10	10	6	6	11	9.0
15. STANDARDIZED OPERATING PROCEDURES	3	4	4	4	4	4	3	3	6	3.9
16. CRISES INFORMATION DIRECTORY	6	4	9	4	3	1	8	11	4	4.0
19. INTELLIGENCE/OPERATIONS/ DIPLOMATIC COORDINATION	2	6	2	2	8	3	3	3	8	5.0
PRIORITY	24	30	0	6	15	12	1	1	9	100

Note: All numbers are rounded to the nearest integer.

Table 4-3

REQUIREMENT VALUE ACROSS SITUATIONS

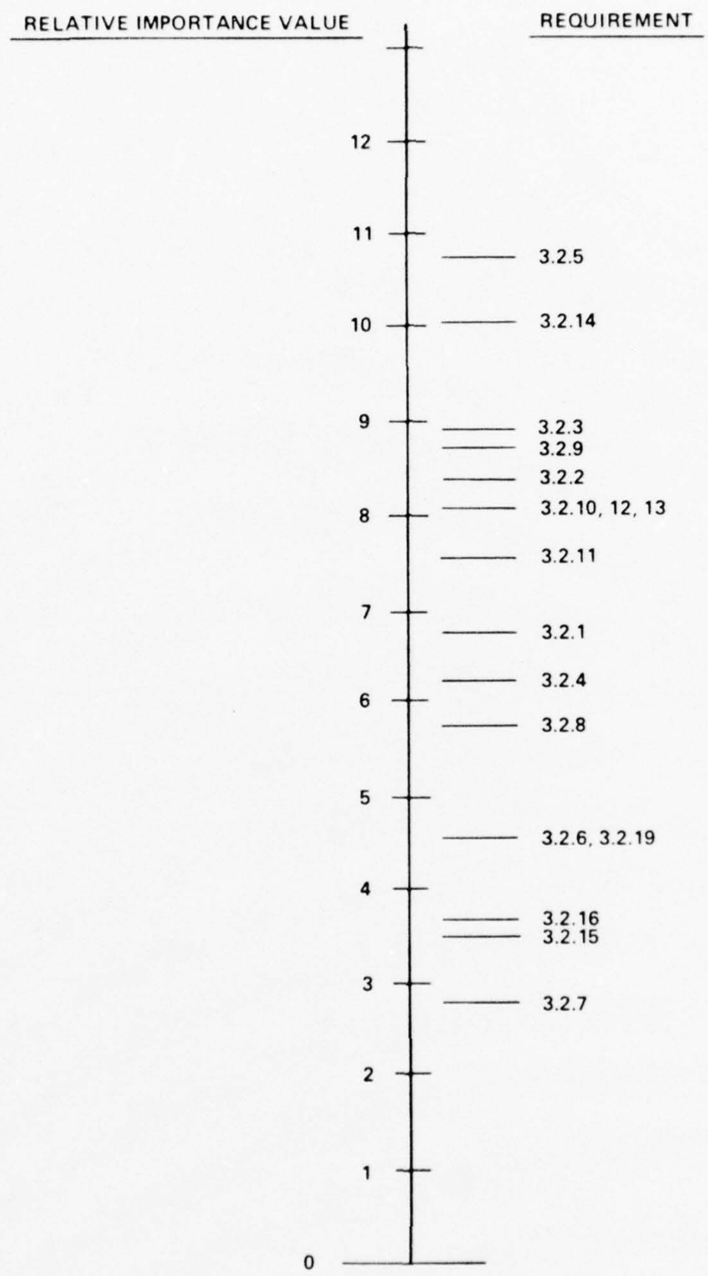

Table 4-4

RELATIVE IMPORTANCE OF REQUIREMENTS

LEVEL	% OF TOTAL UTILITY	LEVEL VALUE
IV	100	8.9
III	90	8.0
II	50	4.4
I	0	0

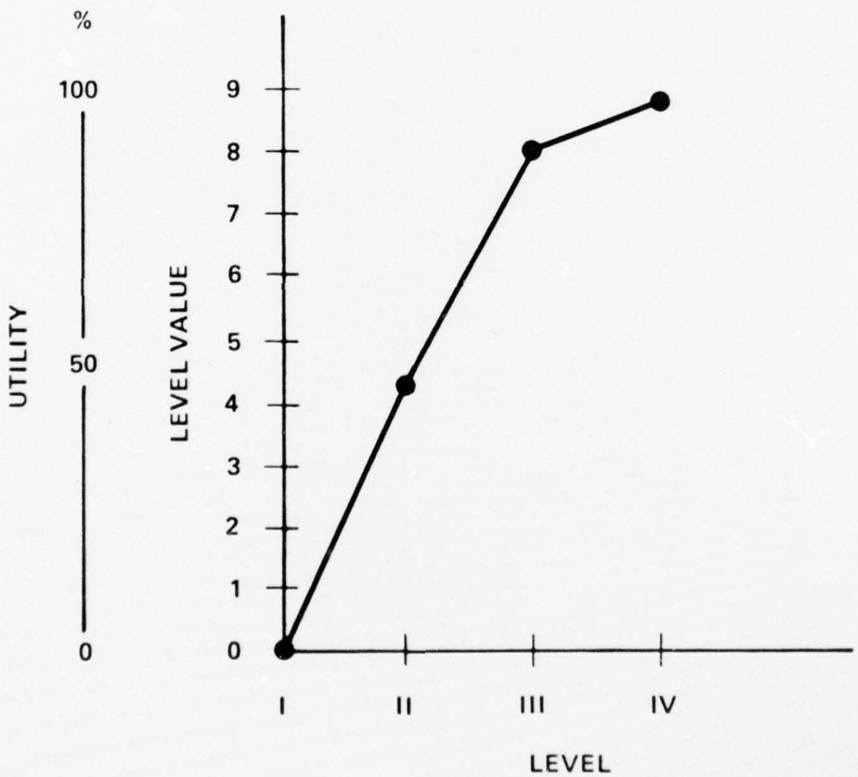

Figure 4-1

REQUIREMENT CAPABILITY LEVEL VALUE FOR REQUIREMENT 3.2.3:
WWMCCS WASHINGTON LEVEL INTERAGENCY INTERFACE

An interesting point that arose in this assessment is that, for most requirements, the percentage of total value gained at each capability level is independent of situation. This feature, while not necessary for the methodology, greatly reduces both the elicitation and computational burden involved. (For requirement 3.2.14, Crises Monitoring Support, the percentage was assessed to be different depending upon the time urgency of the situation. In this case, situations were grouped into "time-urgent situations" and "others" and a weighted average percentage was used. The weights for this weighted average were the priority of the "time-urgent situations" and the priority of the "other situations.")

4.4 Some Implications of the Analysis

Of the 15 requirements described and analyzed in this study, and based upon the crises scenarios which were given, the value of an improved system for interfacing senior U.S. decision makers (3.2.5) carries the highest relative priority weighting. Also high among the fifteen is the requirement for an improved crises monitoring capability responsive to crises support for such high-level personnel as the Chairman of the Joint Chiefs of Staff, the Secretary of Defense, and the NCA (3.2.14).

The analysis reflects the fact that the most demanding crises scenarios involved time-urgent situations requiring constant close coordination among officials in the National Military Command Center (NMCC), the military services, the overseas commanders, and established allies. Results generally reflect the need to transmit visual materials such as photography for targeting purposes and positive threat identification; for secure, rapid voice conferring among the highest level personnel; and for keeping all military elements continuously informed of the developing situation.

The analysis also points up the value of a user-oriented query and display capability for senior decision makers as a part of WWMCCS. There is an obvious need to improve the current capability for updating personnel who monitor crises developments. The current system is constrained largely to secure telephone and personal exchanges, the first of which is difficult and time-consuming for highest officials and the second of which has the additional disadvantage of being exceedingly slow.

Certain other requirements were analyzed as being of relatively low priority. One, a transportable C^3 (3.2.7) facility, reflects the fact that the current capability inherent in command and control type aircraft, surface ships and submarines is generally satisfactory, at least for the scenarios used. Another requirement of relatively low value includes a highly automated system for searching files, alerting personnel, preparing messages, initializing analysis models, and so on (3.2.15). The low value, in this instance, is partly a reflection of the crises scenarios which, for the most part, do not develop rapidly from a complete surprise situation. Two situations are exceptions; but they are also unique. The preprogramming required for a highly automated system to be responsive would not be practical.

Plotting the value of moving from the current system to the second level of each requirement produces Table 4-5. This diagram shows that it is roughly twice as valuable to improve to the second level in requirements 3.2.9, 3.2.11, 3.2.14, 3.2.2, 3.2.5, 3.2.10, 12, 13, and 3.2.3 as it is to move to the second level in the other requirements.

There are two main reasons for this difference among requirements. The most obvious reason is that, as shown in Table 4-4, some requirements are more important than others.

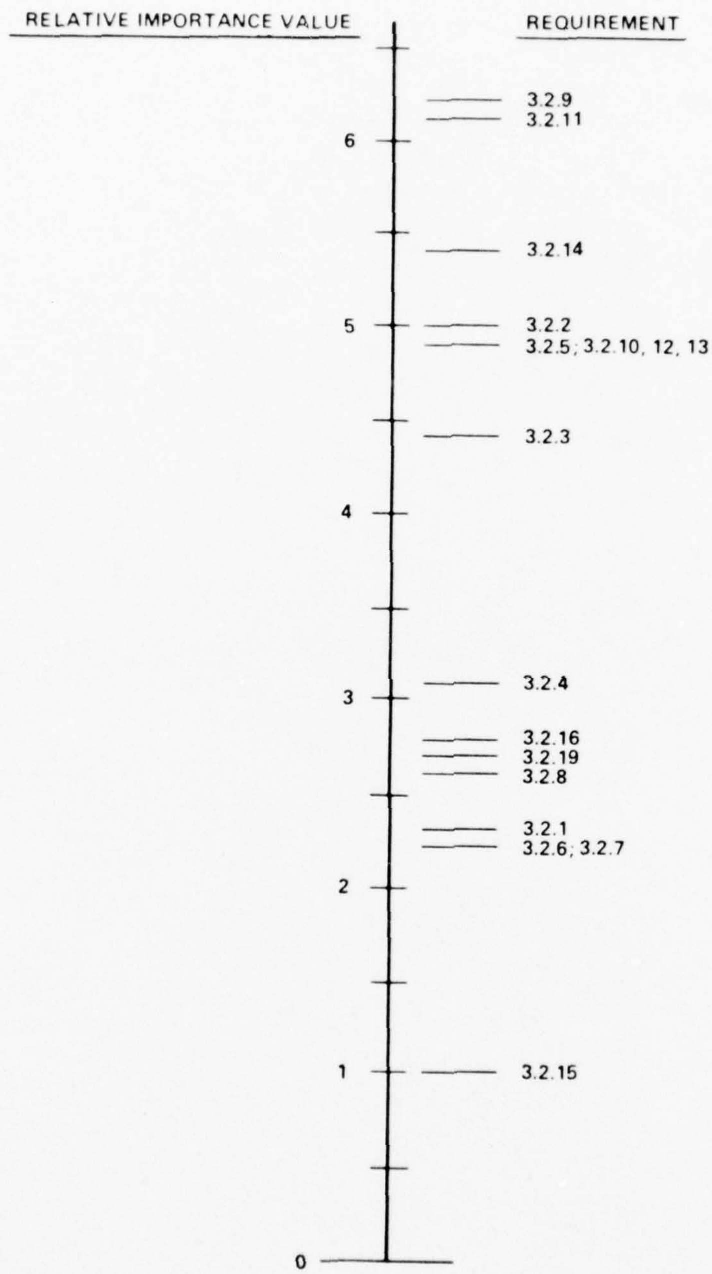

Table 4-5

RELATIVE IMPORTANCE OF LEVEL II PERFORMANCE CAPABILITIES

This, for example, is the reason that level II of requirement 3.2.2, NCA-WWMCCS Interface (value of 5), is much more important than level II of requirement 3.2.19, Intelligence/Operations/Diplomatic Coordination (value of 2.8).

There is, however, another reason for the results shown in Table 4-5 which causes this figure to differ from Table 4-4. This reason is that, for some requirements, a very large percentage of the total value of the requirement is obtained in moving from the current system to the second level of the requirement. Such is the case with requirement 3.2.11, User Oriented ADP-based Support. For this requirement, 80% of the total value is obtained by adding the second level, yielding a second level value of 6.1. Thus, the second level of 3.2.11 is more valuable than the second level of 3.2.5, WWMCCS Communications for Senior Decision Makers (where only 45% of the total value is obtained by going to level II and yields a level II value of 4.9) even though the total value for 3.2.5 is much higher (10.8 for 3.2.5 compared with 7.6 for 3.2.11).

4.5 Design Optimization and Evaluation Methodology

The total set of WWMCCS requirements consists of:

- o Crisis Requirements,
- o Theater Nuclear Requirements,
- o CONUS Nuclear Requirements, and
- o Day-to-Day Requirements

This discussion has dealt only with requirements in the crisis area, but it is a straightforward extension of the methodology to consider other areas as well. In this section, the example analysis will be further restricted to consideration of four of the 19 crisis requirements. The analysis will be extended to demonstrate how the cost factor can be incorporated and to examine the relation between system performance capabilities and funding levels.

The following four requirements:

- o NCA - Heads of State Interface,
- o NCA - WWMCCS Interface,
- o Washington Level Interagency Interface, and
- o WWMCCS Communications for Senior Decision Makers

will be considered, for the purpose of demonstration, to be the total set of requirements. Table 4-6 shows these requirements broken out into levels as earlier described. The "VALUE" column was determined by the methodology explained. The cost figures are purely hypothetical values assigned strictly for demonstrating the methodology. These numbers are interpretable as summary measures of installation cost plus five-year operating costs. Thus, the figures shown for the current system capability (level I in each case) include operating costs and are not zero. The summation figures at the bottom of the diagram show that it would cost $163 million to add the top level of each requirement and that adding this capability would produce 35% of the benefit obtainable by adding the top level of all 19 requirements.

In order to perform an optimization, it is helpful to consider not only the cost and benefit of each capability, but also the <u>incremental</u> cost and benefit of adding a capability level. These incremental costs and benefits are displayed in the columns headed "COST" and "VALUE." These columns show, for instance, that it costs $22 million to add level III of requirement 1 to a system that already contains level II of this requirement and that, by such an addition, the system value is increased by 1.1. The final column shows the ratio of increased value to increased cost for each capability level increment. For instance, considering the addition of level III of requirement 1, the benefit to cost ratio is 1.1/22, or .05. The numbers in this column show that the most benefit per unit of cost is obtained by

Requirement	Requirement Level	Cost	Value	△ Cost	△ Value	△ Value / △ Cost
NCA	V	$ 55M	6.7	$ 10M	.7	.07
HEADS OF STATE	IV	45M	6.0	15M	2.6	.17
1 INTERFACE	III	30M	3.4	22M	1.1	.05
	II	8M	2.3	7M	2.3	.33
	I	1M	0			
NCA	III	2M	8.4	.7M	3.4	4.86
2 WWMCCS	II	1.3M	5.0	1M	5.0	5.00
INTERFACE	I	.3M	0			
WASHINGTON	IV	16M	8.9	4M	.9	.23
LEVEL	III	12M	8.0	5M	3.6	.72
3 INTERAGENCY	II	7M	4.4	5.2M	4.4	.85
INTERFACE	I	1.8M	0			
WWMCCS	V	90M	10.8	15M	1.1	.07
COMMUNICATIONS	IV	75M	9.7	20M	1.6	.08
4	III	55M	8.1	30M	3.2	.11
	II	25M	4.9	22M	4.9	.22
	I	3M	.0			

Table 4-6

REQUIREMENT LEVEL: COSTS AND VALUES

additions of requirement 2 capabilities. Thus, in designing a system, the first amount of resources available should be devoted to increasing the capability of requirement 2.

Table 4-7 shows how this optimization is done. First, consider designing the system that provides the most benefit within a $20 million budget. This figure shows that the first $6.1 million is devoted to operating at the current level of capability for all requirements. The next $1.7 million is then devoted to raise the capability of requirement 2 to its highest level. Finally, the next $10.2 million is used to raise the capability of requirement 3 to level III. A total of $18 million is now committed, and no further improvements are possible (all other improvements cost at least $7 million). The value of this system configuration is 16.4 (of a maximum of 35), and no alternative allocation of the $20 million produces a higher value. Similarly, a $110 million budget provides a value of 29.3 by including the level II capability of equirement 1, level III of requirement 2, level IV of requirement 3, and level IV of requirement 4. Again, while there are alternative ways of allocating the $110 million, none of these alternatives produce a higher value.

This example shows how it is possible to use this methodology to optimize the WWMCCS design within a fixed budget. In the case of a full-scale problem, the next step would be to perform a sensitivity analysis on both the cost and value numbers to identify areas that deserve further attention. For instance, consider the cost figures for requirement 2. Even if these cost estimates are less than one-half of the actual costs, the output of the analysis remains unchanged. That is, level III of this requirement would be a part of any budget over $20 million. Thus, it would be a waste of resources to devote any effort to determining better cost figures for this requirement (the same

Requirement	Requirement Level	Cost	Value	△ Cost	△ Value	△ Value / △ Cost	Budget $20M	Budget $110M
NCA	V	$ 55M	6.7					
				$ 10M	.7	.07		
HEADS OF STATE	IV	45M	6.0					
				15M	2.6	.17		
1 INTERFACE	III	30M	3.4					
				22M	1.1	.05		
	II	8M	2.3					X
				7M	2.3	.33		
	I	1M	0				X	
NCA	III	2M	8.4				X	X
				.7M	3.4	4.86		
2 WWMCCS	II	1.3M	5.0					
				1M	5.0	5.00		
INTERFACE	I	.3M	0					
WASHINGTON	IV	16M	8.9					X
				4M	.9	.23		
LEVEL	III	12M	8.0				X	
				5M	3.6	.72		
3 INTERAGENCY	II	7M	4.4					
				5.2M	4.4	.85		
INTERFACE	I	1.8M	0					
WWMCCS	V	90M	10.8					
				15M	1.1	.07		
COMMUNICATIONS	IV	75M	9.7					X
				20M	1.6	.08		
4	III	55M	8.1					
				30M	3.2	.11		
	II	25M	4.9					
				22M	4.9	.22		
	I	3M	.0				X	

Maximum Total Utility = 34.8
Maximum Total Cost = $163M

	$20M	$110M
Total Utility	16.4	29.3
Total Cost	$18M	$101M

Table 4-7

OPTIMIZATION PROCEDURE

thing holds with regard to further value analysis for this requirement as well). On the other hand, a slight increase in the value of requirement 1 or decrease in value of requirement 4 would cause the optimum system for the $110 million budget to include a higher capability level of requirement 1 and a lower capability of requirement 4. This indicates that additional effort is justified to refine the estimates for these requirements.

Whether or not a sensitivity analysis is performed and the values modified, the result of the analysis provides a useful guide to the overall WWMCCS design. This is demonstrated by Figure 4-2. This figure shows that about one-half of the total value of a maximum WWMCCS can be obtained

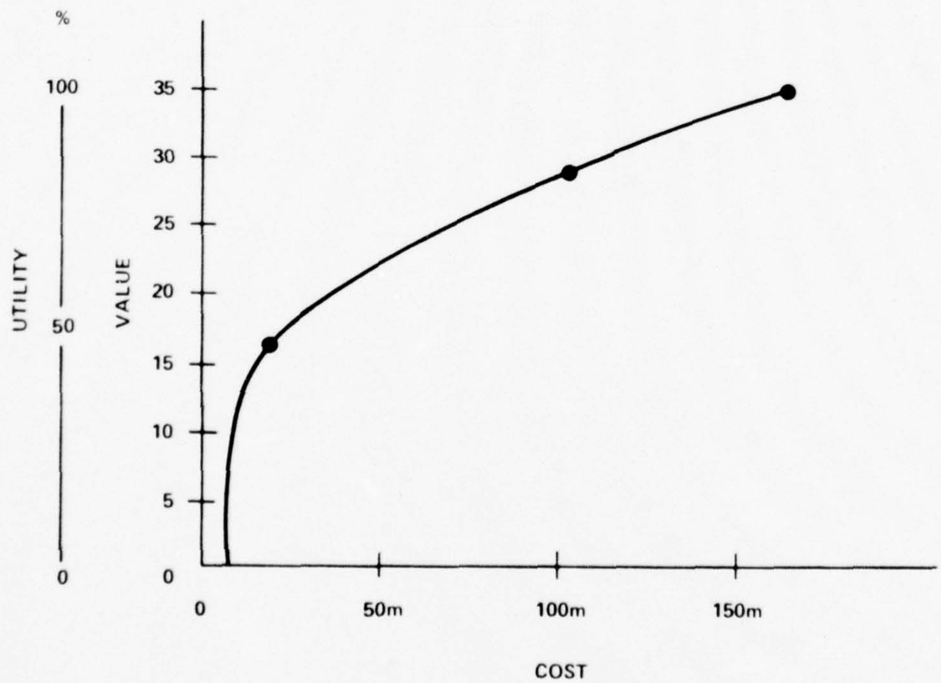

Figure 4-2
VALUE VERSUS COST

for about 11% of the cost of the maximum system. Another 35% of the total value can be obtained for another 50% of the total cost (of course, a refined model will produce numbers that are much more defensible). Such a result is useful in the determination of the value of an increased budget and the determination of a minimum budget.

4.6 Remarks on the Example

The major effort so far has been in the quantification of crisis requirements; for example, the question is not whether messages are transmitted from node A to C, but how important it is to send messages from A to C. This discussion demonstrates a workable methodology that is applicable for the quantification of the value of requirements and the optimization of system design. This effort, while useful in providing a rough guide to the importance of requirements, needs to be extended in order to arrive at a definitive statement of the value of various WWMCCS architectural candidates. Such a further extension must include a consideration of all requirements as well as all cost factors.

The reader will note that the procedure used here was an interval scale approach. In fact, at certain times, ratio scale judgments were made. Rather than use indifference judgments, the procedure used direct ratings by setting a specific requirement at some value and comparing others to it. The reader will also note that the priority given situations closely resembles the importance weights for scenarios discussed in Section 3.

Finally, the optimization done in this example assumed a fixed budget that would be expended on the alternatives under consideration. In such a case, the use of a benefit-to-cost ratio is appropriate. An important consideration in the general use of such an approach is that the benefit scale should be related to dollars. A benefit-to-cost ratio of 100/6.5 million means little until the dollar value of 100 units of benefit is established. For example, if that dollar value were 3 million, the choice of the alternative associated with that ratio would be a poor one. If, as is the case in the WWMCCS example, the decision maker is considering options where the functions are extremely critical, and all options will lie in Region I of Figure 4-3, then establishing the actual dollar value associated with benefit numbers, though advisable, may not be imperative. Obviously, assumptions about where options lie in Figure 4-3 should be made very carefully.

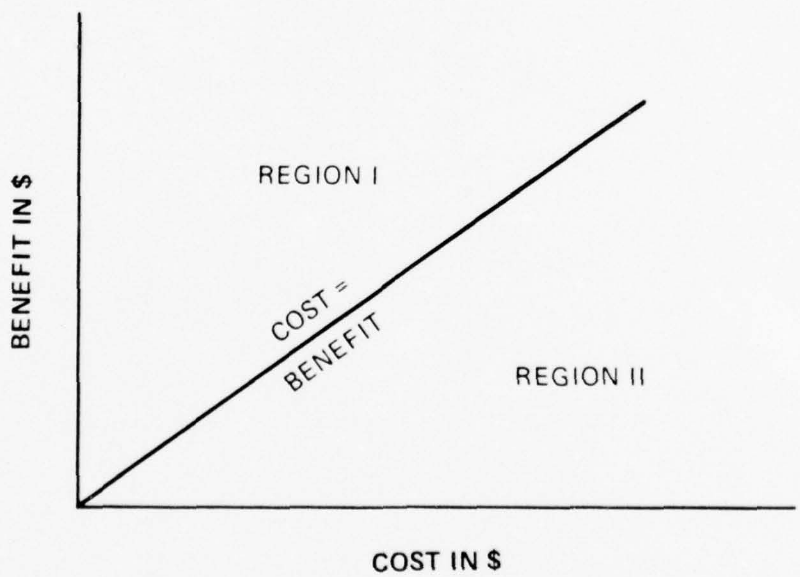

Figure 4-3
BENEFIT VERSUS COST IN DOLLARS

5.0 THE CHOICE OF ONE OF SEVERAL SYSTEMS CHARACTERIZED BY MULTIPLE PERFORMANCE MEASURES

As discussed in Section 4.6, the use of cost-to-benefit ratios is optimal as a criterion for choice given a fixed budget constraint where the dollars are to be allocated among many alternatives. A different problem is the choice of one of several systems, each characterized by multiple performance measures. Specifically, the problem outlined in Section 1.0 is the following. The military has available N different C^2 systems denoted as alternatives A_1, $A_2 \ldots$, A_N. Further, a set of M scenarios denoted as $\{S_1, S_2, \ldots, S_M\}$, acceptable given the criteria discussed in Section 3.0, has been established. For each scenario, an acceptable performance measure has also been established, and the performance of each system in each scenario can be observed. The performance of system A_i in scenario S_j is denoted as P_{ij}. Also available for each system is a valid projection of life cycle cost (or some other acceptable cost estimate). The cost of system A_i is denoted as C_i. Given all this information, which system should the military choose?

This description implies that many of the practical problems, discussed in earlier sections of this report, have been solved. The question here is a straightforward one of applying decision-analytic techniques to the choice of one of several options each characterized by multiple attributes and cost.

The reader will note a similarity between this problem and that addressed in the example in Section 4.0. In that example, however, a fixed set of systems was not available. Rather, a particular combination of capabilities characterized a hypothetical system, and the problem was one of determining the optimal hypothetical system that could be obtained for exactly the cost constraint. Nonetheless, the methodology used for scaling benefits, direct estimation of interval scale value functions, is one approach to establishing the value of multiple attributed alternatives. Discussion of that approach will not be repeated here. Rather, two similar approaches to the problem will be discussed, the first characterized by stronger assumptions concerning the ability to trade-off performance in each scenario with dollars than is the second.

5.1 Intra-Scenario Dollar Trade-offs

Each system A_i can be considered to be a multiple attributed alternative, where the M + 1 attributes for each system are the performance measures in each of the scenarios and also system cost. Thus, A_i can be characterized as:

$$A_i = \{P_{i1}, P_{i2}, \ldots, P_{ij}, \ldots, P_{iM}, C_i\}.$$

It should be noted that P_{ij} is most likely also a multiple attributed measure, an aggregate of several different performance measures. That problem is not addressed here, and it is assumed that the P_{ij} is a meaningful measure with respect to which judgments can be made. It should be noted that if P_{ij} is an aggregate other than a meaningful expected value, it may be difficult to assess trade-offs among the P_{ij}'s. This practical problem merits attention and can greatly increase the difficulty of the procedures to be discussed, for both require that the P_{ij}'s be interpretable measures. The problem will be further discussed as necessary, but the reader should assume for purposes of discussion that the P_{ij} are interpretable, meaningful measures.

The reader will also note that "observed" scenario performances are actually projections of expected system performance given that the scenario actually occurs in the future. The values of these performances can thus be weighted by scenario probabilities to yield an expected value.

The first case to be discussed assumes that the P_{ij} can be directly translated into dollars in each scenario. A possibility for P_{ij} would be a measure consisting of lives and equipment lost because of system performance, given that the scenario has, in fact, occurred. In order to use such a measure, an assumption must be made about a base cost. One base to use would be the cost of the performance of the current system in the scenario. Assume, for purposes of discussion, that all systems achieve levels of performance in each scenario superior to those of the current system denoted as P_{cj} for S_j. The benefit of A_i in S_j is, then, the dollar savings associated with the difference between P_{ij} and P_{cj}. Call this dollar savings B_{ij}. (By definition, $B_{cj}=0$.) B_{ij} is calculated for each A_i in each S_j. Then, given that scenario probabilities have been correctly assessed, the expected benefit of deploying each A_i can be calculated. Denote the probability of S_j as p_j. Then the expected benefit of deploying A_i, in dollars, is denoted as $EB(A_i) = \sum_j p_j B_{ij}$.

Necessary for further calculation is the life cycle cost of deploying the current system, C_c. The incremental cost of deploying A_i is $(C_i - C_c) = \Delta C_i$. The quantity $[EB(A_i) - \Delta C_i]$ is the overall expected value of system A_i denoted as $EV(A_i$, measured in dollars ($EV(A_c)=0$ as defined). The system with the highest expected value is chosen.

This approach has the very desirable characteristic that all benefits are equated to a meaningful numeraire, in this case, dollars, which enhances communication and helps to ensure the validity of the measurement. As might be expected, the main difficulty is establishing a performance measure that can be transferred directly into dollars. The measure chosen for this example can be transformed into dollars (assuming that agreement on the dollar value of a life has been reached), but there exists a problem with it, for as defined it does not necessarily reflect the importance of the scenario. In certain scenarios, for example, normal patrol operations, loss of <u>any</u> lives or equipment is unacceptable. However, in others like a general NATO war, the loss of large numbers of lives and equipment will be acceptable if an acceptable outcome is achieved. In other words, the dollar value of lives and equipment lost may not reflect all the factors that determine the relative importance of a scenario. Somehow, the social value for a life may be different for the two cases, probably larger in the peacetime case. The loss of a life is, most likely, best characterized as a multiple attributed outcome.

This discussion does not condemn the use of this procedure. Rather, it points out that certain measures, easily translatable to dollars, may not at all be reflective of the decision maker's true preference function. The seemingly simple answer is to find an alternative measure that is. For example, a reasonable substitute would be the dollar value associated with the difference in the outcomes for the entire U.S. of deploying either the alternative under consideration or the current system. However, such a loss is reflected in loss of world influence, loss of lives and equipment, expected future loss of freedom, loss of economic power, loss of markets, and the like. To translate such measures into a dollar figure is obviously not an easy task, but some method of doing so must be found if the procedure discussed is to be used. If a valid, meaningful, performance measure can be found, one which can be translated into dollars, the procedure can be used. Section 5.2 discusses an alternative procedure that attempts to make this translation.

5.2 Intra- and Inter-Scenario Subjective Trade-offs

The problem will be characterized by using the same notation used in Section 5.1. However, it will be assumed that the P_{ij} cannot be directly transformed into dollars. Examples could be certain simulation outputs such as the expected number of enemy targets destroyed, expert subjective ratings of the quality of system performance in each scenario, or a statistical aggregate of several performance indicators observed for each system in a scenario. Whatever measure is chosen, direct translation into a dollar value that would be an accurate reflection of the system performance in the scenario is not available.

Note that the system performance measures in each scenario can be considered to be independent attributes. That is, deterministic additive independence (DAI), as discussed in Section 2.0, is likely to hold. This, of course, is not to say that the system performance measures are necessarily statistically independent. Rather, the decision maker can make judgments about the value of P_{ij} without considering the performance of A_i in the other scenarios. This implies that if it is desired to assess a multiple attribute utility function, one of the additive forms discussed in Section 2.0 is likely to hold. System values in scenarios can be established by using the methodology discussed, and an expected system value can then be calculated.

Recall the earlier assumption that the performance of the current system A_c was inferior to that of all other systems in each scenario. If the value of achieving the performance P_{ij} in S_j is denoted as $U(P_{ij})$, then it is assumed that $U(P_{cj}) \leq U(P_{ij})$ for all i, j. The worst system that could be deployed is A_c. This assumption can, of course, be dropped with some added complication of discussion.

For each S_j, there is a P_{ij} that is superior to all others in S_j. Denote that as P_{sj}. Then the value difference for S_j is $\left[U(P_{sj})-U(P_{cj})\right]=I_j$.

Note that P_{sj} is the actual performance of one of the $\{A_i\}$ under consideration. Accordingly, I_j is a relative value difference for S_j dependent on the particular set of options under consideration and conditional on scenario occurrence. Thus, even if a scenario S_j is extremely critical, if the P_{ij} for S_j are all nearly equal, I_j will be very low, probably less than that of other less critical scenarios. This result occurs because it is assumed that only the set $\{A_i\}$ under consideration is available; that is, the alternatives are fixed. In a design problem, where the option of introducing a new system is of major importance, a different upper bound on P_{ij} would be appropriate, perhaps that of a hypothetical perfect system. The approach using the upper bounds of the alternatives under consideration is a "relative" one as opposed to an "absolute" approach using so-called "perfect" performances. The relative approach has the advantages that the upper bound performance for each S_j has been observed, and judgments with respect to it are less difficult. The "absolute" approach allows the introduction of alternatives other than the elements of the set under consideration. As indicated, the relative approach is discussed here.

The procedure to be described involves first assessing intra-scenario value trade-offs. Then inter-scenario value trade-offs can be used to yield an overall value measure. Consider scenario S_j. $U(P_{sj})$ will be set at 100. Similarly, $U(P_{cj})$ will be set at 0.0. The value of A_i for S_j, $U(P_{sj})$ is obtained by having the decision maker assess the relative position of P_{ij} with respect to P_{cj} and P_{sj}. Given the arbitrary assessment such that $\left[U(P_{sj})-U(P_{cj})\right]=100$, the value $U(P_{ij})$ will be some number between 0 and 100. Lottery methods can be used to obtain $U(P_{ij})$. This approach is an iterative one that asks the decision maker to choose between two options:

Option 0_1 - P_{ij} for certain S_j, and

Option 0_2 - A gamble in which the decision maker will receive P_{sj} with some probability q_{ij}, otherwise P_{cj}.

The decision maker is asked to choose either 0_1 or 0_2, and an indifference point is sought. When 0_1 is in fact observed to be indifferent to 0_2, then given that certain independence conditions earlier discussed do, in fact, hold,

$$U(P_{ij}) = q_{ij}U(P_{sj}) + (1-q_{ij})\ U(P_{cj}) = 100q_{ij}.$$

All P_{ij} are scaled in this manner for each S_j establishing M intra-scenario (or intra-attribute) value functions, all on a scale of 0 to 100.

Note that the q_{ij} can be used to scale benefits. The dollar benefit value of P_{cj} can be set at 0.0, and the dollar benefit value of P_{sj} can be assessed by using straight subjective estimations. Suppose that value can be assessed as B_{sj}. Then the dollar benefit value of P_{ij} would be $q_{ij}B_{sj}$. Given the scenario probabilities, the expected dollar benefit of A_1 would be $\sum_j p_j q_{ij} B_{sj}$. This would, of course, require only a single dollar benefit estimate per scenario. The cost of A_c would then be assumed to be zero, and a procedure similar to that in Section 5.1 would be used. The only difference is that the benefit values are straightforward subjective estimates. Of course, as indicated, such estimates require that the decision maker interpret the performance measure in terms of dollars.

Alternatively, it could be the case that the decision maker cannot assign an intra-scenario dollar equivalent to the benefit measure as described. Then it is still possible that the intra-scenario benefits can be aggregated across scenarios to yield an overall measure that can somehow be traded off against dollars. It is difficult to think of a case where intra-scenario dollar trade-offs cannot be assessed but where trade-offs can be assessed between an aggregate performance measure and cost. Nonetheless, this general problem can be addressed. With all systems scaled relatively within scenarios, it is necessary to aggregate values across scenarios.

To compare benefits across attributes, a hypothetical A_s is defined where A_s achieves P_{sj} for each S_j given that S_j has occurred. That is, $A_s=(P_{s1}, P_{s2}, \ldots, P_{sM})$. Recall that $I_j=\left[U(P_{sj})-U(P_{cj})\right]$. It is necessary to establish the relative values of the I_j. Again, the lottery approach will be discussed. Since a fixed set of alternatives is under consideration, only the relative values of the I_j are necessary and an arbitrary 0 to 1.0 scale is employed.

With respect to establishing I_k, the decision maker is offered the following two options:

OPTION 0_1. The decision maker can have a system which performs at the level of A_c for all scenarios except S_k. In S_k the system achieves P_{sk}. That is,

$$0_1 = A_{sk} \text{ for certain where}$$

$$A_{sk} = (P_{c1}, P_{c2}, \ldots, P_{sk}, \ldots, P_{cM})$$

OPTION 0_2. The decision maker is given a gamble in which he gets A_s with probability w_k, otherwise A_c. Again, several iterations are performed to achieve indifference between 0_1 and 0_2. When that is achieved, with appropriate independence checks holding, it assures an additive form of the overall value function and also assigns P_{ck} a value of 0 and P_{sk} a value of 1.0 for each S_k; and the following is true:

$$U(0_1) = U(0_2),$$

$$U(A_{sk}) = U(P_{c1}, P_{c2}, \ldots, P_{sk}, \ldots, P_{cM}) = w_k U(A_s) + (1-w_k) U(A_c),$$

$$U(A_{sk}) - U(A_c) = w_k[U(A_s) - U(A_c)],$$

$$U(A_{sk}) - U(A_c) = w_k(1.0),$$

$$\text{But } U(A_{sk}) - U(A_c) = I_k;$$

$$\text{Thus, } I_k = w_k.$$

The procedure guarantees that $\sum_j w_j = 1.0$. The relative benefit for A_i in S_j is then

$$w_j(100q_{ij}),$$

and the expected benefit of A_i is

$$EU(A_i) = \sum_j P_j w_j(100q_{ij}).$$

With this aggregate expected benefit for each system, it is necessary to consider trade-offs between benefit and cost. Typically, when the benefit measure is interpretable in terms of dollars, the procedure results in iso-preference contours such as those displayed in Figure 5-1.

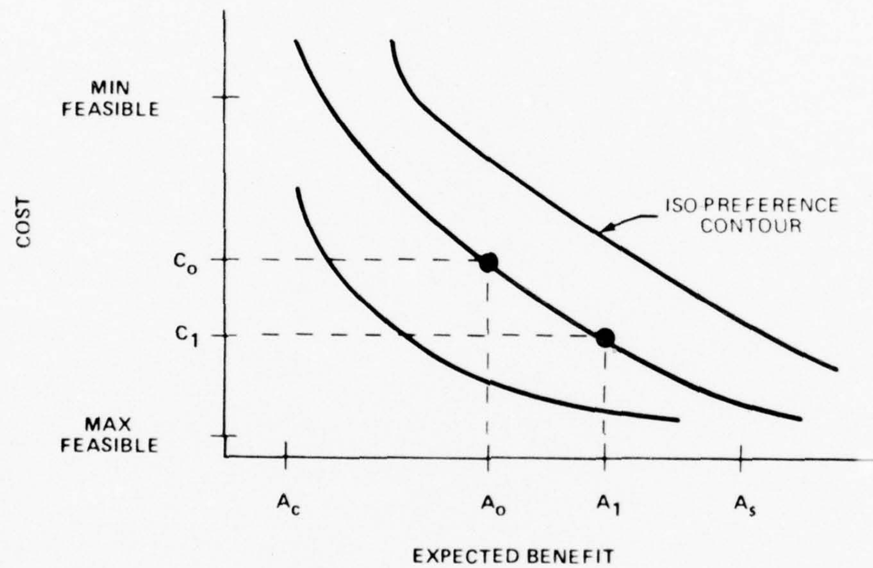

Figure 5-1
COST-BENEFIT TRADE-OFFS

The decision maker is asked questions of the sort: suppose that for a cost of C_o, you could have a system that provides an expected benefit (or performance) of A_o; and suppose performance could be increased to A_1 and cost to C_1; which option would you prefer, $0_1=(A_o,C_o)$ or $0_2=(A_1,C_1)$?

Indifference between options is sought, and indifferent options form iso-preference contours as displayed in Figure 5-1. Then, any system will be represented as a point in the cost/benefit space, and the system on the iso-preference contour farthest to the right is chosen (assuming it is affordable).

The difficulty here involves the nature of the performance measure. It is an aggregate expected performance, where no trade-offs into dollars have been made. The point A_c represents the expected benefit associated with deploying A_c. Similarly, the point A_s represents the expected benefit attainable if the best performance could be had in each scenario. Of course, this point cannot occur given the options unless one system is best in all scenarios, in which case, there is no decision problem. These two points may be interpretable, but intermediate points may be hard to interpret. An A_1 of 50 would correspond to a system that on the average provides about 50 percent of the benefit of A_s. Each system maps into a point along the continuum, but the meaning of the points may be very difficult to establish.

Several points along the continuum could be given meaning by the following procedure. Suppose that A_c performs miserably in all scenarios. This result is not unlikely, for it is reasonable to consider scenarios in which the current system is found lacking. For each scenario, performances of the following kinds can be defined: barely adequate, slightly better than adequate, good, and the like. Hypothetical systems that attain the same level in each scenario can be defined. These systems will then achieve scores that represent a stable performance readily characterized as barely adequate, slightly better than adequate, good, and the like. The decision maker can most likely make meaningful trade-offs with respect to these points. Systems under consideration will then fall along the continuum with respect to these systems. Note, however, that the uncertainty associated with the systems under consideration will be greater, for they do not reliably achieve the same performance level in each scenario.

This discussion emphasizes the necessity to find a performance measure that can be interpreted in terms of dollars. There is obviously no magic solution to the problem of comparing cost and benefit where benefit cannot be translated directly into dollars. The last approach discussed can be used, but it would be better to find at least one scenario in which cost and performance could be traded off. Given that ability, then the trade-offs between performances across all scenarios would allow translation into dollars for all scenarios.

6.0 CONCLUSION

This report has covered many aspects of utility analysis. The question of "how much C^2 is enough?" has been addressed at a fairly abstract methodological level. Emphasis has been on the methodology that might be used to answer the question. As indicated in Section 1.0, the question, though appearing to be an absolute one, is necessarily relative, involving multi-criteria trade-offs. Most of the report has dealt with the methodology for making such trade-offs. That methodology is well established, and, as exemplified in Section 4.0, it has been applied repeatedly to practical problems.

Section 5.0 has specifically addressed trade-offs between cost and multiple performance measures. The discussion has emphasized the necessity for somehow establishing a benefit measure that can be interpreted with respect to dollars. As discussed, this can be accomplished by direct translation of performance to dollars or by subjective trade-offs between levels of an aggregate performance measure and dollars. As indicated in the discussion, the more directly interpretable the performance measure in terms of dollars, the less difficult the trade-offs between cost and performance.

APPENDIX: RESULTS OF THE WWMCCS ANALYSIS

APPENDIX: RESULTS OF THE WWMCCS ANALYSIS

The following pages contain the results of the initial attempt to define requirement levels and to evaluate the levels in a consistent and comparable manner. These level definitions and valuations are to be interpreted as a guide to the importance of meeting requirements to varying degrees. (It was concluded in the study that extension of the results to the justification of architectural engineering candidates for WWMCCS systems could require redefinition or refinement of performance levels in some cases.) The meaning of establishing these importance values is presented in Section 4.3.

WWMCCS CRISIS REQUIREMENT LEVELS

Relative Importance Value		
	3.2.1	NCA - Heads of State Interface
6.7	V	Secure point to point voice; secure high-speed text; near simultaneous voice and text translation; with 14 countries (understandable throughput in about 5 minutes).
6.0	IV	Secure voice; secure high-speed text; manual on call translation; 14 countries (system activation in 5 minutes/understandable throughput in 30 to 45 minutes).
3.4	III	IV above, with 8 countries (system activation in 5 minutes/ 20 to 45 minutes understandable throughput).
2.3	II	Secure voice only with 8 countries Manual on call translation. (15 to 30 minutes for system activation).
0	I	Current capability - voice and TWX to two capitals. Otherwise through State/embassy channels.

3.2.2 NCA - WWMCCS Interface

8.4	III	Secure voice with video; visual/photo transmission; graphics display both fixed and mobile.
5.0	II	Secure voice and graphics (data) only; fixed and mobile.
0	I	Current system mobile (secure in most modes) voice; text to White House situation room; intelligence net to situation room; LDX to situation room from the NMC.

3.2.3 WWMCCS Washington Level Interagency Interface

8.9	IV	Secure, dedicated multi-node voice with video; message generation capability; visual/photo transmission rate of 15 to 20 photos per hour among the MNCC and control rooms of approximately 15 departments/ agencies.
8.0	III	Above, except no video and 5 agencies instead of 15.
4.4	II	Secure, dedicated multi-node voice plus text and photo transmission among 5 nodes.
0	I	Current system - point to point secure voice and intelligence warning net; LDX among White House situation room, NMCC, CIA, and State.

3.2.4 Vertical-Horizontal Analysis Interface for Command Post Duty Personnel (Operations, Intelligence, Logistics Analyst)

6.2	IV	Secure, multi-node voice; multi-node on-line text transmission; and multi-node visual/photo at 15 to 20 per hour rate; vertically and (CINC to CINC) horizontally to include transportable C^3.
4.6	III	Above, but without horizontal CINC to CINC capability and CINC to transportable C^3.
3.1	II	Secure multi-node voice and on-line text in vertical mode only.

0	I	Current system - point to point secure (not dedicated) voice and text.
	3.2.5	WWMCCS Communication for Senior Decision Makers
10.8	V	Secure multi-node voice; visual/photo transmission at 15 to 20 per hour on-line message generation among NMCC, established U and S command and control facilities, JTF, NATO and four or five selected Allies.
9.7	IV	Secure multi-node voice; visual/photo transmission and on-line text transmission among NMCC, U and S commands, JTF and NATO.
8.1	III	Secure multi-node voice; visual/photo transmission; on-line text among NMCC and U and S commands; same except no visual/photo for JTF and NATO.
4.9	II	Secure multi-node voice with instant activation and on-line text among NMCC, U and S commands, JTF and NATO.
0	I	Current system - multi-node voice and text transmission among NMCC, U and S commands, JTF and NATO.
	3.2.6	WWMCCS Fixed Site Allied Interface (a small, highly transportable capability for augmenting normal embassy facilities)
4.5	III	Secure point to point voice; high-speed text transmission; photo/visual transmission capability at rate of 15 to 20 per hour. Manual language translation; capability to operate at almost any embassy location. Capability to connect with nearest CINC, as well as NMCC. Deploy time one to two ways.
2.2	II	Same general requirements as III, with more limited linguistic capability and operating area. Capability to connect with NMCC only.
0	I	Current system - standard embassy facilities. Almost no secure voice; limited text facilities.

3.2.7 Transportable C^3 Facility (An overall capability generally comparable to a CINC-level C^3 facility)

2.8 III Secure multi-node voice; on-line message generation; visual/photo; ADP storage-retrieval system; connection with NMCC and CINCS. En route up-date capability for operation in air, sea, and land mode (for use in situations when permanent facilities as in 3.2.5 do not exist). Deploy time one to two days.

2.2 II Same as III above, except transportable by sea and air; operates in land-based mode only.

0 I Current system - none, except such developmental systems and such mobile facilities as are inherent in command-control type aircraft and ships.

3.2.8 Monitoring Foreign National Behavior

5.8 IV Stored, crises oriented data on the behavior patterns/characteristics of approximately 30 foreign nations, with rapid up-date capability for access and display (within 5 minutes) at NMCC, the CINCS, the JTF, and selected Washington agencies and departments (i.e., CIA, State).

5.2 III Same as IV above, except with access and display at NMCC, White House situation room, CIA and State.

2.6 II Same as III above, except with access and display only at NMCC.

0 I Current system - manual data handling; incomplete data.

3.2.9 Intelligence Interface

8.8 III A direct, NMCC interface with all major intelligence agencies, with some capability to access and display both stored and incoming intelligence from a variety of sources and to task those sources directly for specific information in near real-time.

6.2 II An interface with NMIC and reliance on the NMIC worldwide intelligence system for automated intelligence displays in the NMCC and for tasking DoD and certain other intelligence resources through the NMIC in support of WWMCCS.

0 I Current, entirely manual system; mostly hard copy; some direct access to files of other agencies through NMICC.

3.2.10 Ad Hoc Planning

3.2.11 User Oriented ADP-Based Support

7.6 III An audio-visual display/query capability specifically oriented to the specific needs of NCA, CJCS, the U and S commanders, and other high-level decision makers desiring direct access to synthesized, yet traceable, day to day and crises management problem-solving situations.

6.1 II Same as III above, but access limited to Washington area decision makers, i.e., CJCS, Secretary of Defense, NCA.

0 I Current system, which is almost completely manual, responds in hours, not in minutes.

3.2.12 Integrated Data Display

3.2.13 Dynamic Situation Assessment

8.1 III NMCC crisis team access to WWMCCS intelligence, operations and logistics data files with near real-time capability to integrate data and display it in the form of situation summaries, executive up-dates and optional courses of action to NCA, CJCS, the State and CIA control centers and selected CINCS (when required). This includes a capability for the crisis team to display source data from other agency and U and S command files.

4.9	II	Some as III above, except that integrated displays are not available to U and S commands, the JTF, State and CIA; and information from files outside of WWMCCS cannot be accessed and displayed by crisis teams in NMCC (an internal NMCC system).
0	I	Current system with limited display capability. Almost all of the integration process is manual. Reaction times are in hours, not minutes.

3.2.14 Crises Monitoring Support

10.1	III	An audio-visual display/query crises monitoring system continuously available to the NCA, Secretary of Defense, CJCS, and other high-level officials that provide the status of crises actions and results continuously as the situation changes and whenever the system is queried. System is decision maker oriented and provides analysis support during "day to day" situations.
5.4	II	Same as III above, except system is up-dated periodically (normally 4 to 6 hour up-dates) as opposed to continuously in III above.
0	I	Secure voice, message, courier, etc. from NMCC to decision makers.

3.2.15 ADP-based Standardized Operating Procedures

3.4	IV	An advanced ADP-based system for alerting personnel of a crisis (or impending crises), initiating the data file search, generating reports on the status of the data base on the area of interest, identifying tasking requirements, initializing data for analysis models and other automated problem-solving support; available to NMCC, NCA, U and S command, and JTF.
2.6	III	Same as IV above, but available to NMCC only.
1.0	II	ADP-based print-outs and graphic displays of SOPS and the location of key personnel; available to NMCC only.

0 I Current system, which has almost entirely manual checklists and educators, some limited off-line modeling.

3.2.16 Automated Crises Information Directory

3.5 III Automated system for displaying location and status of information files and knowledgeable substantive experts within/outside the DoD to NMCC and the U and S commands with the directory information available also to selected Washington agencies.

2.8 II Same as III above, with access and display for NMCC only.

0 I Manual containing limited number of files/personnel.

3.2.19 Intelligence/Operations/Diplomatic Coordination

4.5 IV Voice conferencing within each area or community; point to point message; photo transmission among elements (operations; intelligence, diplomatic) within area.

3.8 III Same as IV above, except no photo transmission.

2.7 II Secure conference voice only at the above locations (IV).

0 I Current system, which does not have dedicated facilities at most locations.

REFERENCES

An Analytic Procedure for Examining the Relation Between WWMCCS Performance Capabilities and Funding Levels. Report prepared for the IBM Corporation in support of U.S.A.F. Contract F19628-74-C-0158. McLean, VA.: Decisions and Designs, Inc., March, 1975.

Edwards, W., and Tversky, A., eds., Decision Making. Middlesex, England: Penguin Books, 1967.

Keelin, T.W., III. A Protocol and Procedure for Assessing Multi-Attribute Preference Functions. Ph.D. Dissertation, Stanford University, September, 1976.

Keeney, L., and Raiffa, H. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. New York: John Wiley, 1976.

O'Connor, M.F., and Edwards, W. On Using Scenarios in the Evaluation of Complex Alternatives. Technical Report TR 76-17. McLean, VA.: Decisions and Designs, Inc., December, 1976.

Raiffa, H. Decision Analysis: Introductory Lectures on Choices under Uncertainties. Reading, MA.: Wesley-Wesley, 1968.

Rumsfeld, D.H. FY 1977 Report of Secretary of Defense. United States Department of Defense, 1976.

CONTRACT DISTRIBUTION LIST
(Unclassified Technical Reports)

Director Advanced Research Projects Agency Attention: Program Management Office 1400 Wilson Boulevard Arlington, Virginia 22209	2 copies
Office of Naval Research Attention: Code 455 800 North Quincy Street Arlington, Virginia 22217	3 copies
Defense Documentation Center Attention: DDC-TC Cameron Station Alexandria, Virginia 22314	12 copies
DCASMA Baltimore Office Attention: Mr. K. Gerasim 300 East Joppa Road Towson, Maryland 21204	1 copy
Director Naval Research Laboratory Attention: Code 2627 Washington, D.C. 20375	6 copies
Office of Naval Research Attention: Code 102IP 800 North Quincy Street Arlington, Virginia 22217	6 copies

SUPPLEMENTAL DISTRIBUTION LIST
(Unclassified Technical Reports)

Department of Defense

Director of Net Assessment
Office of the Secretary of Defense
Attention: MAJ Robert G. Gough, USAF
The Pentagon, Room 3A930
Washington, DC 20301

Assistant Director (Net Technical Assessment)
Office of the Deputy Director of Defense
Research and Engineering (Test and Evaluation)
The Pentagon, Room 3C125
Washington, DC 20301

Assistant Director (Environmental and Life Sciences)
Office of the Deputy Director of Defense
Research and Engineering (Research and Advanced Technology)
Attention: COL Henry L. Taylor
The Pentagon, Room 3D129
Washington, DC 20301

Director, Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209

Director, Cybernetics Technology Office
Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209

Director, ARPA Regional Office (Europe)
Headquarters, U.S. European Command
APO New York 09128

Director, ARPA Regional Office (Pacific)
Staff CINCPAC, Box 13
APO San Francisco 96610

Dr. Don Hirta
Defense Systems Management School
Building 202
Ft. Belvoir, VA 22060

Chairman, Department of Curriculum Development
National War College
Ft. McNair, 4th and P Streets, SW
Washington, DC 20319

Defense Intelligence School
Attention: Professor Douglas E. Hunter
Washington, DC 20374

Command and Control Technical Center
Defense Communications Agency
Attention: Mr. John D. Hwang
Washington, DC 20301

Department of the Navy

Office of the Chief of Naval Operations (OP-987)
Attention: Dr. Robert G. Smith
Washington, DC 20350

Office of the Chief of Naval Operations (OP-951)
Washington, DC 20450

Office of Naval Research
Assistant Chief for Technology (Code 200)
800 N. Quincy Street
Arlington, VA 22217

Office of Naval Research (Code 230)
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
Naval Analysis Programs (Code 431)
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
Operations Research Programs (Code 434)
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research (Code 436)
Attention: Dr. Bruce MacDonald
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
Information Systems Program (Code 437)
800 North Quincy Street
Arlington, VA 22217

Director, ONR Branch Office
Attention: Dr. Charles Davis
536 South Clark Street
Chicago, IL 60605

Director, ONR Branch Office
Attention: Dr. J. Lester
495 Summer Street
Boston, MA 02210

Director, ONR Branch Office
Attention: Dr. E. Gloye
1030 East Green Street
Pasadena, CA 91106

Director, ONR Branch Office
Attention: Mr. R. Lawson
1030 East Green Street
Pasadena, CA 91106

Office of Naval Research
Scientific Liaison Group
Attention: Dr. M. Bertin
American Embassy - Room A-407
APO San Francisco 96503

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps (Code RD-1)
Washington, DC 20380

Headquarters, Naval Material Command
(Code 0331)
Attention: Dr. Heber G. Moore
Washington, DC 20360

Head, Human Factors Division
Naval Electronics Laboratory Center
Attention: Mr. Richard Coburn
San Diego, CA 92152

Dean of Research Administration
Naval Postgraduate School
Attention: Patrick C. Parker
Monterey, CA 93940

Naval Personnel Research and Development
Center
Acquisition and Initial Service (Code 310)
Attention: Dr. Leonard P. Kroeker
San Diego, CA 92152

Naval Personnel Research and Development
Center (Code 305)
Attention: LCDR O'Bar
San Diego, CA 92152

Navy Personnel Research and Development
Center
Manned Systems Design (Code 311)
Attention: Dr. Fred Muckler
San Diego, CA 92152

Naval Training Equipment Center
Human Factors Department (Code N215)
Orlando, FL 32813

Naval Training Equipment Center
Training Analysis and Evaluation Group
(Code N-00T)
Attention: Dr. Alfred F. Smode
Orlando, FL 32813

Director, Center for Advanced Research
Naval War College
Attention: Professor C. Lewis
Newport, RI 02840

Naval Research Laboratory
Communications Sciences Division (Code 540
Attention: Dr. John Shore
Washington, DC 20375

Dean of the Academic Departments
U.S. Naval Academy
Annapolis, MD 21402

Chief, Intelligence Division
Marine Corps Development Center
Quantico, VA 22134

Department of the Army

Deputy Under Secretary of the Army
(Operations Research)
The Pentagon, Room 2E621
Washington, DC 20310

Director, Army Library
Army Studies (ASDIRS)
The Pentagon, Room 1A534
Washington, DC 20310

U.S. Army Research Institute
Organizations and Systems Research Laboratory
Attention: Dr. Edgar M. Johnson (PERI-OK)
1300 Wilson Boulevard
Arlington, VA 22209

Director, Organizations and Systems
Research Laboratory
U.S. Army Institute for the Behavioral
and Social Sciences
1300 Wilson Boulevard
Arlington, VA 22209

Technical Director, U.S. Army Concepts
Analysis Agency
8120 Woodmont Avenue
Bethesda, MD 20014

Director, Strategic Studies Institute
U.S. Army Combat Developments Command
Carlisle Barracks, PA 17013

Commandant, Army Logistics Management Center
Attention: DRXMC-LS-SCAD (ORSA)
Ft. Lee, VA 23801

Department of Engineering
United States Military Academy
Attention: COL A. F. Grum
West Point, NY 10996

Chief, Studies and Analysis Office
Headquarters, Army Training and Doctrine
Command
Ft. Monroe, VA 23351

Commander, U.S. Army Research Office (Durham)
Box CM, Duke Station
Durham, NC 27706

Department of the Air Force

Assistant for Requirements Development
and Acquisition Programs
Office of the Deputy Chief of Staff for
Research and Development
The Pentagon, Room 4C331
Washington, DC 20330

Air Force Office of Scientific Research
Life Sciences Directorate
Building 410, Bolling AFB
Washington, DC 20332

Commandant, Air University
Maxwell AFB, AL 36112

Chief, Systems Effectiveness Branch
Human Engineering Division
Attention: Dr. Donald A. Topmiller
Wright-Patterson AFB, OH 45433

Director, Advanced Systems Division
(AFHRL/AS)
Attention: Dr. Gordon Eckstrand
Wright-Patterson AFB, OH 45433

Commander, Rome Air Development Center
Attention: Mr. John Atkinson
Griffis AFB
Rome, NY 13440

IRD, Rome Air Development Center
Attention: Mr. Frederic A. Dion
Griffis AFB
Rome, NY 13440

HQS Tactical Air Command
Attention: LTCOL David Dianich
Langley AFB, VA 23665

Other Government Agencies

Chief, Strategic Evaluation Center
Central Intelligence Agency
Headquarters, Room 2G24
Washington, DC 20505

Director, Center for the Study of
Intelligence
Central Intelligence Agency
Attention: Mr. Dean Moor
Washington, DC 20505

Office of Life Sciences
Headquarters, National Aeronautics and
Space Administration
Attention: Dr. Stanley Deutsch
600 Independence Avenue
Washington, DC 20546

Other Institutions

Institute for Defense Analyses
Attention: Dr. Jesse Orlansky
400 Army Navy Drive
Arlington, VA 22202

Director, Social Science Research Institute
University of Southern California
Attention: Dr. Ward Edwards
Los Angeles, CA 90007

Professor Raymond Tanter
Political Science Department
The University of Michigan
Ann Arbor, Michigan 48109

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: TR-77-4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): PROCEDURES FOR ASSESSING THE VALUE OF COMMAND AND CONTROL CAPABILITIES		5. TYPE OF REPORT & PERIOD COVERED: TECHNICAL
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Michael F. O'Connor		8. CONTRACT OR GRANT NUMBER(s): N00014-76-C-0074
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Decisions and Designs, Incorporated, Suite 600, 8400 Westpark Drive, McLean, Virginia 22101		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Defense Advanced Research Projects Agency, 1400 Wilson Boulevard, Arlington, Virginia 22209		12. REPORT DATE: July 1977
		13. NUMBER OF PAGES: 92
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Office of Naval Research, 800 North Quincy Street, Arlington, Virginia 22217		15. SECURITY CLASS. (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

command and control (C^2) function	discriminative scenario
utility analysis	representative scenario
ordinal approach	performance capability
interval scale approach	value assessment methodology
multiple-attributed alternatives	design optimization

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The command and control (C^2) function, an integral part of intelligence and communications, provides the structure which enables the National Command Authority (NCA) the President and Secretary of Defense, to exercise command and control over deployed U.S. forces through the Joint Chiefs of Staff (JCS). In view of the significance of the C^2 function, a pertinent question is, "How much C^2 capability is enough"? In order to assess the value of a particular C^2 capability, the cost of achieving that capability must be

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. evaluation methodology
cost-benefit ratio

20. weighed against the potential benefits of allocating funds elsewhere. Examination of the breakdown of the Department of Defense Budget would prompt a reasonable inquiry: Is this allocation scheme the best overall scheme for meeting the long-term goal of defending the nation? More specifically, is the seven-percent allocation for C^2 sufficient to meet the need in that area? The answer necessarily involves assessing the requirements for and the benfits to be dervied from expenditures in each of the specified DoD program areas. The procedures and recommendations discussed with respect to C^2 generalize trade-offs among objectives on goals at any level of generality chosen for analysis.

The objective, then, is to determine, given the fixed budget size, whether the chosen dollar allocations are optimal. From a decision analysis point of view, this problem involves assigning a value to the action of deciding to deploy a particular C^2 system in an uncertain future. A large decision tree would be constructed to accommodate all potentially reasonable C^2 deployments, the uncertain events, and the possible outcomes. The problem in such a case is that the decision tree is too large ("a very bushy mess," to borrow a Howard Raiffa metaphor), and meaningful probabilities and values cannot be assessed.

The discussion of the problem is divided into four parts. Section 2.0 deals with the theory of assessing value for multiple attributed alternatives. Section 3.0 discusses the use of scenarios as a solution to the so called "bushy mess" problem. Section 4.0 illustrates the application of value assessment procedures to a hypothetical problem of evaluating alternative architectural candidates for a World Wide Military Command and Control System (WWMCCS). Section 5.0 further illustrates the application of utility assessment procedures to the C^2 problem by using a specific problem: the trade-offs between cost and multiple performance measures.

This report covers many aspects of utility analysis. The question of "how much C^2 is enough?" is addressed at a fairly abstract methodological level, and emphasis is on the methodology that might be used to answer it.