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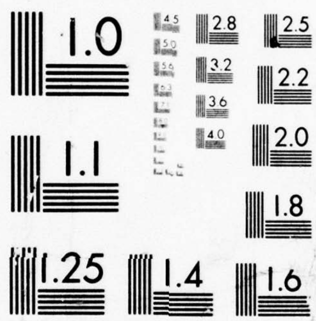

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Final Report *September 1977*

DECISION STRUCTURING AID: CHARACTERIZATION AND PRELIMINARY IMPLEMENTATION

Prepared for:

OPERATIONAL DECISION AIDS PROJECT
(CODES 431, 434, 437, 455)
OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
ARLINGTON, VIRGINIA 22217

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The process of building a decision model that captures the important relationships of a decision situation is generally recognized as the most time consuming and difficult aspect of decision analysis. This report documents research designed to develop aids for facilitating the model-building process. The ultimate goal of this research is a design for a man-machine system that will help a task force commander and his staff structure the relevant factors of a decision into a formal decision model.

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20 ABSTRACT (Continued)

The research has resulted in the specification of a structuring process composed of four basic structuring functions: decision bounding, preliminary structuring, model expansion, and model contraction. The structuring process has three important advantages over the methods currently used by analysts for model building. First, it contains algorithms for directing the analysis toward the important factors of the decision problem. Second, tests are provided to ensure that effort is not wasted on modeling aspects of the decision problem that have no chance of impacting the decision. Third, the process continually provides a current best estimate of the optimal decision strategy, an estimate that is improved as more and more factors are included in the decision model. A preliminary computer program for assisting a task force commander and his staff in applying the structuring process has been developed. Testing and further development of algorithms and computer support for the structuring process is recommended.

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EXECUTIVE SUMMARY

Task force commanders must function in an environment where stress and limited decision time can be expected to degrade human decision-making ability significantly. Research has shown that under stress, decision makers often fail to consider all available alternatives, overlook consequences of alternatives, and behave irrationally.[1] Therefore, decision aids that assist task force commanders in identifying, organizing, and deducing the implications of relevant decision factors hold potential for improving task force decisions.

SRI International's research into decision structuring has resulted in the specification and preliminary computer implementation of a process to assist a task force commander and his staff in structuring the relevant factors of a decision into a formal decison model. A decision model is a precise quantitative representation of a decision situation. An advantage of structuring a decision as a decision model is that the model can be analyzed using standard computer-supported solution techniques. By applying computer-aided analysis methods to a decision model of his situation, the task force commander can obtain a much more thorough evaluation of alternatives than can be produced using less formal, intuitive methods for decision making.

Description of the Structuring Process

The proposed structuring process is based on concepts and methods of decision analysis. Construction of a decision model is accomplished through

the iterative application of four basic structuring functions: decision bounding, development of preliminary model structure, model expansion, and model contraction. Important component inputs to the process are a value model (for representing the relative importance of basic military objectives) and outcome calculators (battle simulators for predicting the outcomes of various military engagements). Because value models and outcome calculators are not decision specific, they can be developed prior to the decision and supplied to the structuring process as inputs.

The structuring process is designed to be implemented as a man-machine system. A computer is used to improve and expand the skills of a member of the commander's staff (staff analyst) who works with the commander to help him structure his decisions. The computer has three basic functions: to provide a medium for facilitating the construction of the decision model, to perform analyses of the model as it is developed, and to serve as a sophisticated prompting system.

From the point of view of the commander, the structuring process consists of a well directed dialog with the staff analyst. The commander supplies information in response to questions posed by the analyst. The questions and the general direction of the conversation between the analyst and the commander are guided by prompts from the computer. The staff analyst converts the information provided by the commander into inputs that the computer uses to expand the model representation.

Model Expansion Algorithm

A major research effort of this project was devoted to the model expansion function of the structuring process. Model expansion consists of identifying alternatives and events relevant to the decision that have been overlooked and incorporating these into the decision structure. This is regarded as the most difficult structuring function for a decision maker to perform.

As a key component of the structuring process an algorithm and associated computer program for model expansion have been developed. The expansion algorithm is based on a calculation of the value of further modeling. An existing model of the decision situation is analyzed to identify where in that model resolution of residual model uncertainty is most likely to clarify the decision at hand. The identified model area then forms the basis for generating a prompt. The prompt is a specific question designed to uncover important contingencies that have been omitted from the analysis: for example, a sample application of the algorithm resulted in a series of prompting questions that included the following:

> Suppose the air strike alternative is chosen. Is there any event that could cause you to lose more aircraft?

If the commander is unable to identify such an event, additional questions based on other areas with high values of modeling are generated. For example, a "no" answer to the above question might result in the following prompt:

> Suppose the air strike alternative is chosen. Is there any event that could cause the risk of Blue-Red war to be significantly increased?

Events and new alternatives that are identified through the prompting questions are tested using the existing model to determine whether their addition to the model structure may impact the decision. Events that pass the test are then incorporated into the model.

Conclusions and Recommendations

Additional work is required to develop the structuring process and model-expansion algorithm so that an accurate assessment can be made of their potential value as decision aids for the task force environment. However, we are optimistic that the preliminary algorithm can be developed into a useful aid because:

- Initial informal structuring experiments using the current algorithm have consistently produced satisfactory decision models.
- The structuring process appears applicable to a very wide selection of decision problems.
- The expansion algorithm quickly and continually provides an estimate of the decision maker's best course of action. This estimate is improved as the structuring process progresses.
- The expansion algorithm tests new factors for relevance to the decision at hand, enabling the avoidance of time-consuming modeling effort when it has no impact on the decision.
- The algorithm provides a method for identifying events that are of critical concern to the task force commander. Such events could be used as triggers (for example, setting alerts) in the DAISY system, which is being developed by the University of Pennsylvania.

In view of the advantageous characteristics of the preliminary structuring process and the success of initial testing, the principal recommendation of this report is that development and testing be continued. Algorithms and computer code should be developed for the remaining structuring functions not addressed by the model-expansion algorithm (decision bounding, prestructuring, and model contraction). Of these, the prestructuring function, which consists of specifying the problem structure as initially perceived by the commander, appears most important.

I INTRODUCTION

This report describes research performed by SRI International's Decision Analysis Group to develop a computer-assisted decision structuring process for use by a naval task force commander and his staff. The research was funded by the Operational Decision Aid (ODA) Program of the Office of Naval Research and represents the second phase of SRI's research in this area.

1.1 ODA Program Background

The ODA Program is a multiyear, multicontractor effort whose objective is the development and implementation of decision aids for supporting tactical decision making at the task-force-commander level. To accomplish this goal, the program employs an interdisciplinary approach. Research participants draw upon techniques and methodologies from the fields of decision analysis, operations research, computer science, systems analysis, and organizational research in an effort to bring about the effective application of advanced man-machine system technologies to task force command and control.

To date, participants in the ODA Program have focused their efforts primarily in three areas: information processing, outcome calculators, and decision structuring. The work in information processing has concentrated on developing an information base for the Program (2,3) and a decision-aiding information management system (4,5). Outcome calculators (6,7) are mathematical models for simulating, and thereby estimating, the outcomes of various military engagements. The objective of the work on decision structuring has been to provide aids to guide the commander's decision making according to the logic of normative decision theory.

1.2 Motivation for Developing Aids for Decision Structuring

Normative decision theory prescribes a solution technique that consists first of structuring and then solving a decision model that reflects the decision maker's knowledge and preferences concerning his decision situation. For the purposes of this report, structuring is, therefore, defined as the process of identifying and organizing the relevant factors of a decision into a framework that facilitates the identification of an optimal course of action.

Task force commanders have considerable experience and knowledge that helps them formulate a course of action for dealing with difficult situations. For this reason it seems probable that errors in military planning are generally not due to a failure by the commander to identify an appropriate course of action for his perceived situation, but because of his incorrect perception of his situation. Structuring the decision to reflect adequately the reality of his situation is, therefore, an essential part of the commander's decision-making process.

Many, perhaps most, of the decisions the commander faces are easily structured. This is because most of the decisions for which the commander is responsible are routine or repetitive in nature. However, a threat to the task force or a critical mission assignment may result in complex, one-of-a-kind decisions that are very difficult to structure. Crucial decisions often have one or more of the following characteristics that make structuring difficult:

- Complexity in the relationships between decisions and possible outcomes
- Uncertainty
- Vagueness about the relative values of the possible outcomes.

Failure to account adequately for one or more of these characteristics can easily result in a bad decision. For example, it is easy to bring to mind military disasters that occurred because a decision was made that failed to account properly for systematic relationships between decisions and outcomes, that ignored or overlooked uncertainties that later proved critical, or that were inconsistent with broader military values and objectives.

Unfortunately, the task force commander's decision-making environment can cause structuring to be even more difficult than one would expect merely from the characteristics of the decision situation. The most crucial decisions a commander is likely to face will be made in an environment where the level of stress can be expected to degrade significantly human decision-making ability. Stress may be created or increased because of the importance of the decisions the commander is required to make, the limited time available for the decision making, or by fatigue. A body of research has shown that under stress, decision makers often fail to consider all available alternatives, overlook consequences of alternatives, and exhibit inadequate coping behavior (8). An aid that would help a commander logically structure a decision would counteract the tendency of stress to produce poor decisions and enable him to deal with the complexity that is typical of crucial one-of-a-kind decision situations.

1.3 Inadequacy of Relying Solely on Prestructured Decision Models

One approach to improve an individual's decision-making ability is to provide him with prestructured decision models. In prestructured models, the relevant factors for certain types of decision problems and their relationships are identified and modeled in advance. When the decision maker finds himself faced with a decision for which he has a prestructured model, he merely supplies the appropriate model with the required inputs, runs the model, and then translates the model outputs into a decision strategy.

The difficulty in relying solely on this approach is that the number of possible military situations is infinite. Therefore, there will be a large number of decisions to which the prestructured aids cannot be applied. An even greater problem with prestructured decision aids is that unless they are used with care they may stifle the creativity of the decision maker or cause him to overlook a critical aspect of his problem that is unique to his current situation.

To help the task force commander with decision problems that cannot be anticipated and structured ahead of time, he needs a systematic procedure for rapidly structuring and solving decision problems as they arise. Unfortunately, there has been little research focused on developing a systematic structuring procedure.

1.4 A Critique of Previous Research on Decision Structuring

Structuring requires that the factors relevant to a decision be identified and that these factors be organized to clarify the decision-making process. Efforts devoted to developing aids for decision structuring almost invariably have emphasized one or the other, but not both, of these two components of the decision-structuring process.

Some research has concentrated on the identification aspect of structuring. For example, the work by Kepner and Tregoe (9) and the Navy manual NWP-11(B) (10) are designed to help the decision maker identify all of the components of a decision situation that have a bearing on his decision. These approaches use checklists and forms for the decision maker to fill out. The reasoning behind these aids is that they force the decision maker to think through his problem in more detail, thereby reducing the chance that he will overlook some important aspect of the problem. Because these aids are based on a principle of an exhaustive search through each potentially important aspect of the problem, they tend to be time-consuming. The other major drawback of these aids, assuming that they are successful at promoting the identification of important decision factors, is that no systematic procedure is supplied for arriving at the implications of the factors for decision making.

Most of the computer aids developed for decision structuring are really particular structural formats that simplify the subsequent analysis. The format is generally designed so that some computational technique can be applied directly to solve the decision model. Examples are the various aids for analyzing decision trees developed by SRI (11) and Decisions and Designs Inc. (12). Unfortunately, these aids are more useful to a skilled decision analyst than to an unskilled user because it takes considerable experience both to place a decision situation into the format required by the decision aid and to ensure that the required inputs to the aid are correctly specified. Specification of the inputs is often a difficult process, because the more general model formats usually require a very large amount of input specification. To avoid this problem, some researchers have grossly simplified the model format. An example is the work by Selvidge (13). Typical simplifications require the assumption that the likelihood of an event is independent of the alternative chosen, or that sequential decisions are not allowed. Although these simplifications may substantially reduce the input requirements of the aid, they also limit the scope of decisions that can be modeled. Furthermore, the result is still more appropriate for use by an experienced decision analyst than by an untrained decision maker, because the experience of the analyst is required to verify that the approximations embodied in the simplified model format are appropriate to each decision situation.

Leal (14) is one of the few researchers to propose a systematic procedure for developing a structural model. His method is based on the concept of decision tree expansion. In this approach, a simple decision tree model of a decision situation is constructed and then expanded by successively adding additional nodes to the ends of the tree. This approach is extended and discussed in more detail in Chapter III. From an operational standpoint, a shortcoming of Leal's procedure is that it supplies little guidance for identifying the factors that should be added to the ends of trees as additional nodes.

1.5 Design Goals

To be most effective, a structuring process should deal with both aspects of structuring: identification of important decision factors and organization of the factors into a decision model. Furthermore, the process should integrate these two aspects of structuring. The decision factors generated through identification should provide the inputs required to build the model.

In the absence of a formal theory of decision structuring, decision makers and analysts have relied on experience and various heuristics to structure decisions. Development of a formal structuring process therefore requires that consideration be given to the degree to which algorithms can be developed to supplant or augment experience as an aid to decision structuring.

1.5.1 The Degree to Which Structuring Can Be Formalized

From a technical standpoint, the easiest approach to supplying task force commanders with assistance in decision structuring would be to limit the development of formalized routines to only the most technical aspects of structuring, and to rely upon the creativity of a trained and experienced decision analyst for the bulk of the structuring activity. Given the limited number of trained people currently applying decision analysis to realistic decision problems, however, this approach is not practical on a large scale. It would require a training program for members of the task force commander's staff far more ambitious than anything contemplated.

An approach at the other extreme would be to attempt to develop highly sophisticated, interactive computer programs that would, for all practical purposes, duplicate the role of the experienced decision analyst. Because the purpose of the aid would be to replace the analyst, it would be designed to be operated by a decision maker who has very little decision analysis training. It may eventally be possible to develop such an aid, but the large amount of computer hardware and software required to interact with an untrained user would make it difficult to realize this goal for many years. Furthermore, it would probably be unwise to invest the time and effort required to design an aid of this type until more experience is gained with relatively simple decision aids.

The best approach, given the current state of the art, falls somewhere between the extremes of a highly trained, experienced decision analyst and a totally interactive computer program capable of dealing with an untrained user. A realistic design goal is a computer assisted decision structuring aid designed to augment the capabilities of the task force commander and his staff and to minimize the amount of training they need in analytical techniques for structuring decision problems. The idea behind this approach is to use the computer in areas where it can do the best job: calculating the logical implications of decisions and events described by the decision maker and prompting him to think of new factors that should be included in the analysis. It may be possible for a task force commander with the necessary training to interact directly with such a structuring aid, but it is more likely that a commander will prefer to have a trained member of his staff interact with the computer and to summarize its output verbally.

1.5.2 Decision-Specific Versus Non-Decision-Specific Structuring Functions

To gain a better understanding of therole the computer can play in improving the decision structuring process of a task force commander, it is useful to identify those structuring functions that can be developed ahead of time as opposed to those that are decision-specific and must be performed after the need for a decision has arisen. Because the time for analysis may be an important constraint placed on the commander's decision making, it is important to preprogram as much of the structuring process as possible. Structuring functions that are not decision-specific may be supplied to the structuring process as prestructured models.

There are two major inputs to the structuring process that are largely independent of the specific decision being analyzed. One of these is the specification of value trade-offs--the relative worth of the various outcome attributes that the commander must trade off against one another in his decision making. The other is the specification of the relationships required to estimate the outcomes that can be expected from various types of military engagements.

Value tradeoffs can be specified before the task force commander is faced with a difficult decision. Research into the areas of value theory has indicated that a compact and precise method for representing value tradeoff judgments is through the specification of a value function (also called a "multiattribute utility function"). Several applications to military decision making have demonstrated that, with some assistance from analysts, military decision makers can construct value functions that represent their preferences over the possible outcomes of a decision, and that these value functions can then be used to support the decision-making process (15). Because in many cases, a value function should logically be independent of the specific decision facing the task force commander, it could be established ahead of time, preferably at the time the commander's mission is established, and could be supplied to the commander by his superiors.

Specification of the many basic relationships that are required to estimate military outcomes is the second major input to the structuring process that usefully can be preprogrammed prior to its use for a specific decision. A decision among alternative courses of action open to the commander will require some estimate of the military outcomes that can be expected under each of the proposed alternatives. These estimates often can be generated by considering the effectiveness and detailed characteristics of the individual force elements that will be deployed under each alternative. Research conducted by SRI's Naval Warfare Research Center (7) and General Research Corporation (6) indicates that for certain classes of military engagements these relationships can be preprogrammed to produce automated outcome calculators. Ideally, outcome calculators should be flexible enough to be used for calculating the possible outcomes associated with a broad spectrum of task force decision problems.

A major portion of the structuring activity needed for a decision cannot be performed ahead of time because it is unique to the decision at hand. For those aspects of structuring that are decision-specific, aids can be provided to simplify, speed up, and improve the process of developing the decision model necessary to represent the unique characteristics of the decision.

Because model building is largely a creative process, it may seem that the computer can offer little help in this area. The power of the computer lies in its ability to perform complicated but well-defined calculations with great speed. Poorly defined tasks or tasks that require drawing conclusions from information that is unstructured is much more difficult for the computer to perform. Nevertheless, the computer can perform an important role in assisting the task force commander and his staff in this role. A decision model is developed gradually. As more and more factors are identified and included in the model, it becomes a better representation of reality. The computer can be used to analyze the decision model as it develops. The results of analyzing the existing decision model can then be used to help focus the creative capabilities of the commander and his staff on those elements that need to be expanded or refined.

1.5.3 Components of a Decision Structuring Man-Machine System

Figure 1 shows the basic components of a man-machine system for decision structuring. The computer is used to augment the structuring abilities of the commander and a member of the commander's staff (staff analyst). Structuring functions that are not decision-specific, such as value models and outcome calculators, are developed prior to the decision and supplied to the computer as inputs. The task force commander supplies information in response to questions posed by the staff analyst. The computer acts as a prompting system. The questions and the general direction of the conversation between the analyst and the commander are guided by output from calculations performed by the computer. The staff analyst converts the information provided by the commander into inputs that the computer uses to expand the model representation. The computer then analyzes the expanded decision model, and, depending upon the results, requests that the analyst seek additional information or prompts him to explore other areas of the decision situation with the commander.

A structuring process of this type is described in the remaining chapters of this report. Chapters III and IV describe the technical aspects of a process that constructs a series of decision tree models to capture progressively more of the commander's decision situation. Chapter II discusses the use of decision trees as a means for representing decision structure.

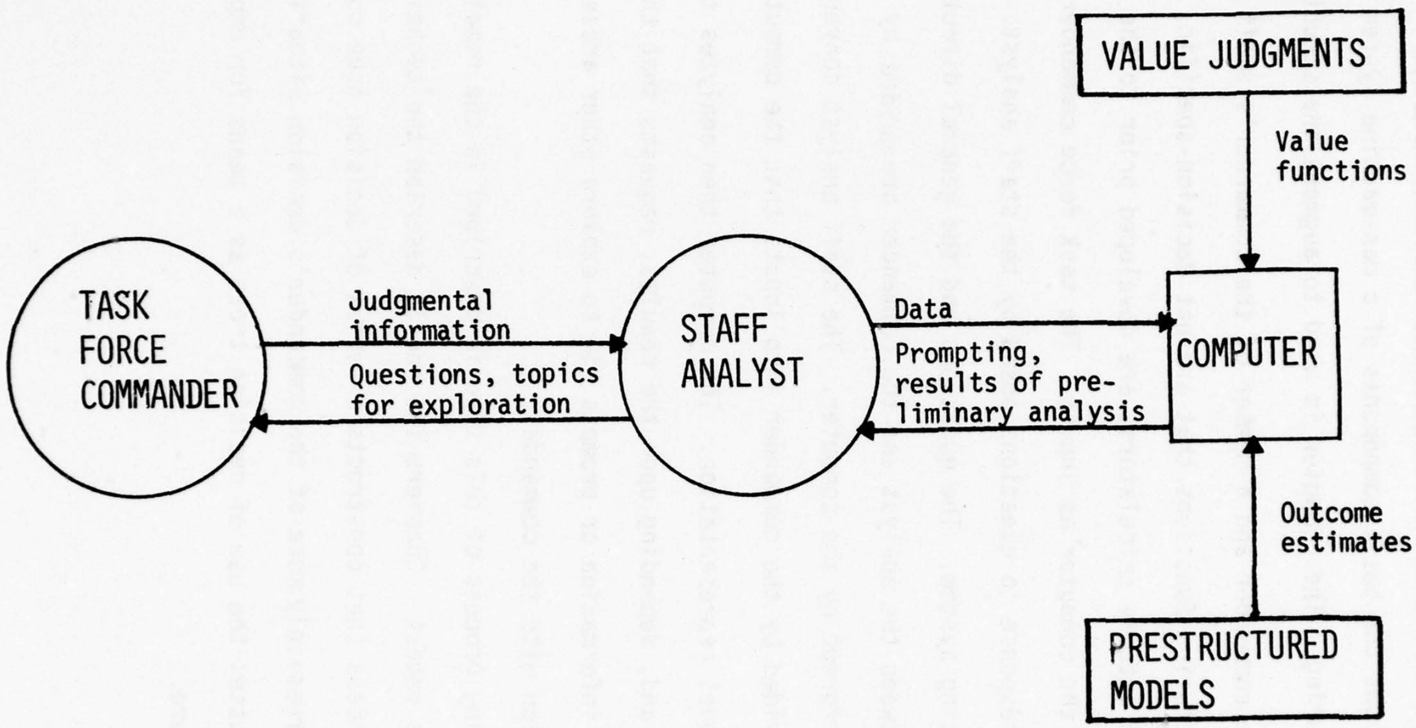

FIGURE 1: COMPONENTS OF A MAN-MACHINE SYSTEM FOR DECISION STRUCTURING

II STRUCTURING WITH DECISION TREES

The single tool employed most often by decision analysts to structure decision situations is the decision tree. A decision tree is used to organize and display future events and decisions that may be relevant for selecting an alternative.

The use of decision trees for structuring has two advantages that account for its popularity among decision analysts. First, a decision tree is a remarkably general, flexible, and efficient means for representing the sequential and dynamic nature of a complex decision situation. Second, a decision tree is a powerful solution aid. Through a series of well-defined steps, a properly designed decision tree may be solved to produce a decision strategy that is, in a very general sense, optimally consistent with the objectives and information of the decision maker.

This chapter discusses the use of a decision tree as a means for problem structuring. The generality, convenience, and intuitive appeal of decision trees indicate that a useful structuring aid would result if a formal process could be developed to permit individuals without considerable experience and training in decision analysis to construct accurate decision tree representations of their decisions. Chapter III presents an algorithm for structuring task force decisions by constructing a decision tree.

2.1 Decision Trees

Figure 2 illustrates a decision taken from the ONRODA scenario* (16). The decision is whether the Blue task force commander should plan to neutralize ONRODA air field with an air strike or through a blockade. Important considerations for this decision, represented by the tree, include whether Red will have nonmilitary aircraft, such as hospital planes, on ONRODA airfield at the time at which the commander might launch his airstrike, and whether Red will attack the task force as a result of the commander's actions.

In the decision tree format, decisions are represented by small squares, called decision nodes, with the various alternatives shown as lines emanating from each square. Uncertainties, such as enemy actions and other occurrences over which the decision maker has no control, are represented in the diagram by small circles, called chance nodes. The branches emanating from the chance nodes represent the various possible outcomes to each uncertain event.

The ordering of decision and chance nodes in the decision tree is arranged to match the order in which decisions must be made and in which outcomes of uncertain events will be revealed to the decision maker. This sequential format makes it easier to keep track of the dependencies between events and decisions. Each possible path leading from left to right through the tree represents a different possible sequence of decisions and events that might occur.

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* "The ONRODA Strike Warfare Scenario" describes the recent political and military history leading to a potential military conflict involving the hypothetical countries of Blue, Red, Grey, and Orange and the Island of ONRODA. This scenario has been designed to be used by contractors to test and illustrate decision aids proposed within the ODA Program.

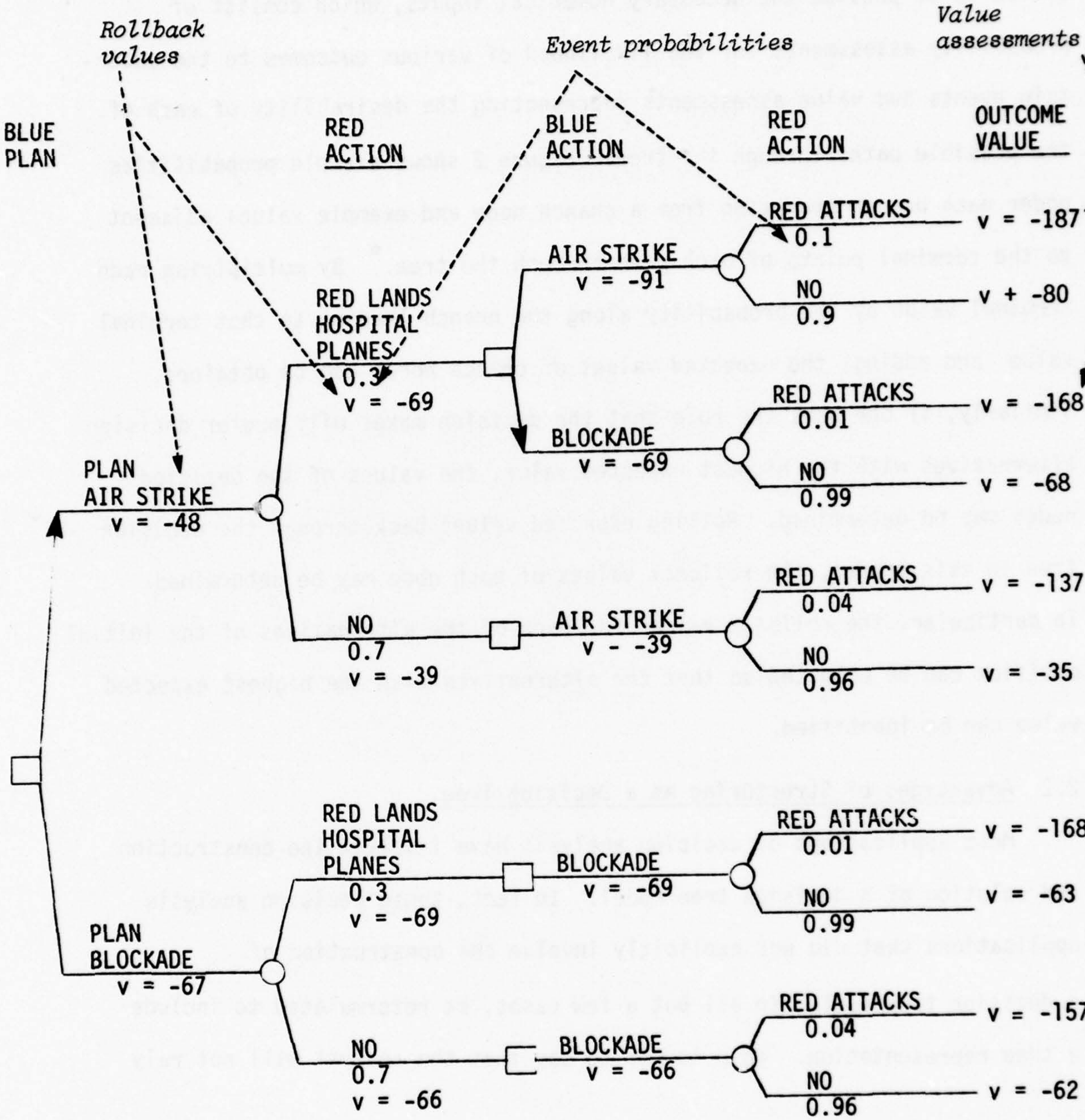

Figure 2: Decision Tree Representing Decision Taken from the ONRODA Scenario

The first step toward solving the tree to obtain an optimal course of action is to provide the necessary numerical inputs, which consist of probability assessments for the likelihood of various outcomes to the uncertain events and value assessments representing the desirability of each of the possible paths through the tree. Figure 2 shows example probabilities under each branch emanating from a chance node and example values adjacent to the terminal points of each path through the tree.* By multiplying each terminal value by the probability along the branch leading to that terminal value and adding, the expected values of chance nodes can be obtained. Similarly, if one uses the rule that the decision maker will prefer decision alternatives with the highest expected value, the values of the decision nodes may be determined. Rolling expected values back through the decision tree in this manner, the rollback values of each node may be determined. In particular, the rollback values for each of the alternatives of the initial decision can be computed so that the alternatives with the highest expected value can be identified.

2.2 Advantages of Structuring as a Decision Tree

Most applications of decision analysis have involved the construction and solution of a decision tree model. In fact, those decision analysis applications that did not explicitly involve the construction of a decision tree could, in all but a few cases, be reformulated to include a tree representation. This is not to say that the analyst will not rely

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* The values assigned to terminal nodes represent the desirability of the outcomes corresponding to each path through the tree. If a decision maker's risk preference is also assessed, these values can be converted to utilities that account for the feelings of the decision maker with regard to risk. Although we have chosen not to consider risk preference in this report, all results can be easily extended to reflect risk preference.

on other models in addition to the tree. Often a decision tree model will be used to summarize the decision structure, while other models will be used to generate specific inputs to the decision tree--for example, probability model to generate the probabilities associated with the chance nodes on the tree, an outcome calculator to generate the outcomes associated with various paths through the tree, and a value model to convert the outcomes associated with each path to a value measure. However, the decision tree is generally the tool used to represent the sequential decision structure of the situation.

The widespread use of the decision tree can be attributed to its generality, convenience, and the intuitive appeal. It is difficult to conceive of a decision that cannot be represented as a decision tree (although there are special classes of decisions that are more conveniently represented using other model formats). Generally speaking, the decision tree tends to be a more efficient model structure for complex, sequential decisions that involve uncertainty. The decision tree is convenient because it provides an efficient, graphic means for organizing the basic components for a decision: what the decision maker can do (represented by the decision nodes and their branches), what the decision maker knows and believes (represented by the tree structure and the probabilities assigned to the branches emanating from the chance nodes), and what the decision maker wants (represented by the values assigned to the various paths through the tree). The fact that the decision tree is an intuitively appealing representation is amply demonstrated by the fact that corporate and government decision makers frequently comment that the decision tree allows them to "see" and, therefore, understand their decisions much more clearly.

2.3 Review of SRI's Previous Contracts on Decision Structuring

Because of the importance of decision trees to the structuring process, initial research conducted by SRI was directed toward gaining a better understanding of the process by which experienced decision analysts develop decision tree models. For this purpose, several experimental decision analyses of task force commander decision problems based on the ONRODA scenario were conducted, transcribed, and then analyzed with the objective of identifying the techniques and procedures that were most effective in eliciting from the decision maker a decision tree representation of his situation. This work is summarized in a previous SRI report (17).

The major result of this research was the specification of a complete set of elemental structuring procedures for describing the various functions that a decision analyst performs as he structures a decision mode. The research showed that the process of building a decision model could be represented as a sequential application of these procedures. In an attempt to convert the procedures into an aid for directing -- rather than merely describing -- the modeling process, rules for ordering the application of the structuring procedures were developed. This analysis, which was essentially an attempt to formalize the structuring process currently used by decision analysts, produced a number of important conclusions:

- The current technique used by decision analysts to elicit decision trees is a poorly defined translational process that is carried out through discussions and interviews between the analyst and the decision maker. The analyst attempts to direct the conversation and phrase his inquiries in a manner that efficiently elicits the information required to construct the decision tree. The process tends to be time consuming.

- Following the completion of a decision analysis, often it is apparent that much effort was spent exploring and modeling aspects of the problem that have little or no impact on the decision. In this sense, current structuring methods tend to be inefficient.
- Current structuring methods support a method of decision analysis that provides little indication of which alternative being analyzed is best until the final stages of the analysis. This is a serious drawback if the user often finds it necessary to terminate analyses prematurely.

2.4 Evaluation of the Effectiveness of Using the Elemental Structuring Procedures for Directing the Structuring Process

The first stage of SRI's current research effort on decision structuring consisted of evaluating the degree to which the elemental structuring procedures and rules for ordering these procedures (described in Ref. 17) facilitate the process of developing a decision model. The evaluation, which included several applications to current and past decision problems, indicated that the procedures provide useful guidance for translating known decision factors into a mathematical model for representing the implications of those factors to the decision. However, the major limitation of the procedures was that they failed to provide guidance for identifying the important factors that should be included in the model.

A structuring process that will be used by individuals without extensive experience in decision analysis must enhance the creative ability of the user to identify important decision factors. Much of the effort devoted to structuring a decision problem appears to be focused on identifying a complete set of the important variables that represent the uncertainties and subsequent decisions relevant to the decision. The necessity of recognizing all of these major factors cannot be over-emphasized. No amount of modeling or analysis will produce insight into a decision situation if some of the major factors that affect the decision have been overlooked. An analysis based on an inadequate representation of a decision situation probably will produce a suboptimal solution. For this reason, the research described in this report has emphasized procedures for identitying critical decision factors. Chapter III shows that the process of identifying new factors to include in a decision analysis can be viewed as an expansion of the structure of an existing decision tree model.

III DECISION TREE EXPANSION

As discussed in Chapter II, a decision tree may be thought of as a graphic representation of a decision model. Because each node in the tree represents some factor that is relevant to the decision, the more factors that are brought into the model, the bigger the tree becomes. Thus, the process of identifying and then organizing factors into a decision model can be viewed as expansion of a decision tree.

Normally, the analyst will gather all of the information required to structure the decision tree before assessing the probabilities that should be assigned to the branches emanating from chance nodes and the values that should be placed at the ends of the tree. Thus, the tree is not analyzed until after the major portion of the structuring activity is complete. An alternative approach, which is described in this chapter, is to structure a very simple decision tree and then to analyze that tree to determine where in the tree additional nodes should be added, what the nature of those nodes should be, and when and how those nodes should be added. The result is a systematic structuring process based on the principle of tree expansion.

3.1 Principle of Tree Expansion

Consider the ONRODA scenario in which a task force commander must develop a plan for neutralizing ONRODA airfield. The commander's decision is between two alternative courses of action: plan an airstrike or plan a blockade. A decision analysis of this problem resulted in a decision tree that is partially represented in Figure 3.

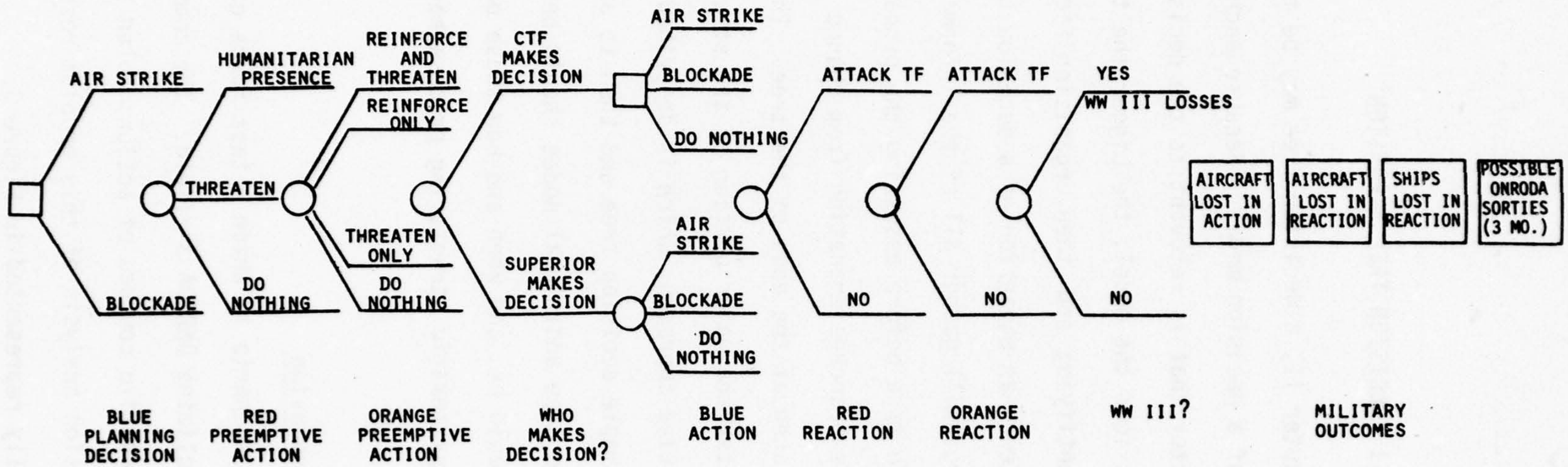

FIGURE 3: DECISION TREE DEVELOPED IN EXPERIMENTAL DECISION ANALYSIS OF ONRODA SCENARIO

The purpose of constructing the decision tree of Figure 3 was to provide a means for estimating the relative value to the commander of each alternative plan so that the plan with the highest value could be identified. As described in Chapter II, the expected value of an initial decision in a decision tree is computed by assigning values to each of the outcomes represented by the terminal points in the tree and then rolling these values back through the tree. The rollback value that is obtained for each initial alternative is then a measure of the value of that alternative to the decision maker.

Although the construction of a decision tree tends to be time consuming, the effort is justified by the belief that the expected values that are computed by rolling back the decision tree are much more accurate estimators than would be produced through asking the decision maker to assess the value of each alternative directly. The analyst usually refrains from asking for direct value judgments on alternatives but prefers to construct them by decomposing the situation into sequences of decisions and events, which are represented as a decision tree; he then asks for probability and value judgments for the individual elements of the tree. This course of action reflects the belief that mechanistically developed judgments are a more accurate representation of the decision maker's information and experience than are direct holistic judgments internally processed by him.

Suppose, however, that the decision maker is asked, prior to the construction of the complete decision tree, to provide assessments of the expected values that would be produced for each alternative if the complete decision tree were developed and solved. Because the decision maker is understandably uncertain about these values, the assessments would have to be provided in the form of probability distributions. The value of resolving the uncertainty on the rollback value of each alternative could then be computed using the standard value of information calculation of decision analysis. Because constructing the complete decision tree is a means for resolving this uncertainty, the value computed for resolving the uncertainty on the rollback value for a given alternative can be interpreted as the expected value of developing the portion of the decision tree emanating from that alternative. Thus, the value of resolving the existing uncertainty in the decision maker's estimate of the expected value of an alternative can be interpreted as a value of modeling that alternative.

This value-of-modeling concept can be used to provide a systematic procedure for expanding a decision tree structure. Suppose a simple but incomplete decision tree is developed to represent some decision situation. As an example, suppose the decision tree shown in Figure 4 is used to represent the commander's choice between an airstrike and a blockade. The decision tree is incomplete because it is recognized that there are significant decision factors that could be represented as additional nodes and branches in the tree. Identifying these additional factors and adding them to the tree requires further problem structuring, and such structuring would result in expanding the existing tree. For example, one of the factors that has been omitted from the tree in Figure 4 is whether the Red task force, upon observing an airstrike launched against ONRODA, would immediately attack the Blue task force. Adding this possibility to the decision tree results in the original tree

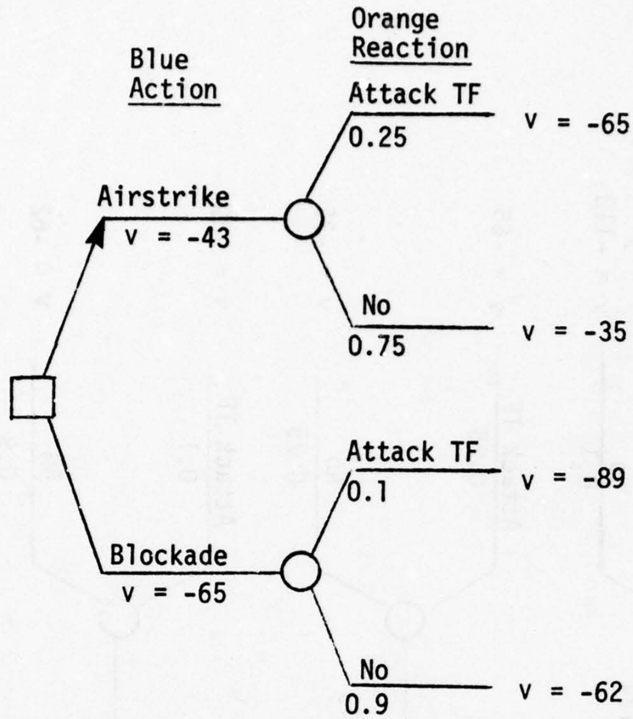

Figure 4: Simplified Decision Tree Representing Commander's Choice Between Airstrike and Blockade

being expanded from the branch labeled "airstrike." The expanded tree is shown in Figure 5.

Because an incomplete decision tree such as that shown in Figure 4 (or Figure 5) is only an approximation to the complete tree, the rollback values that appear at each node in the tree are only approximations of the rollback values for the corresponding nodes in the complete tree. If the decision maker has constructed only the simplified tree, he is uncertain about what the rollback values are for the corresponding nodes in the complete tree. The rollback values in the simplified tree that have the greatest need for expansion are those nodes for which the value of resolving

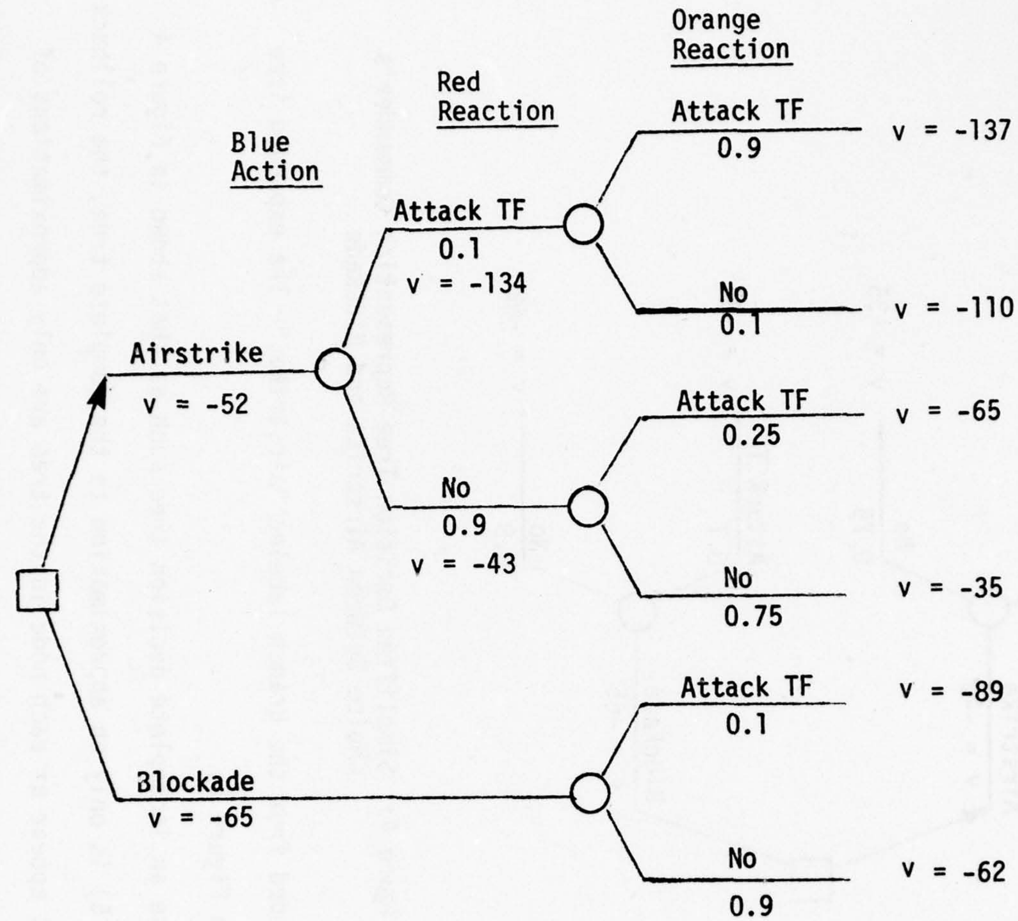

Figure 5: Expanded Decision Tree Representing Commander's Choice Between Airstrike and Blockade

the current uncertainty on true rollback value is the highest. Therefore, the value of resolving uncertainty on the rollback values of each node serves as an upper bound for the value of expanding that node by adding additional nodes to that location of the tree. Thus, the value-of-modeling concept can be used to recommend nodes in an existing decision tree expansion.

Chapter IV of this report demonstrates that a rule of expanding the node in the existing tree with the highest value of modeling may be used as a means for directing the structuring process. In other words, an algorithm for tree expansion forms the basis for a systematic process for structuring a decision. The tree expansion algorithm consists of five basic steps. Step 1 is to obtain an estimate for the uncertainty in the rollback value at each node in the current decision tree. Step 2 is to compute the value of resolving each of these uncertainties. Attention is then addressed to the node in the current tree with the highest value of uncertainty resolution. Step 3 is to determine the decision sensitivity of each outcome variable at that node. The outcome variable with the highest decision sensitivity is used as a guide for identifying additional factors to add to the given location in the tree. In Step 4, factors proposed for addition to the tree are tested to ensure that their addition will have some chance of affecting the decision. Finally, in Step 5, those factors that are verified potentially to impact the decision are modeled and added to expand the existing tree structure. These five steps may be repeated until the decision tree has been expanded to the point that the value of resolving residual uncertainty is low.

3.2 Concepts and Calculations for Implementing the Tree Expansion Algorithm

The remaining sections of this chapter describe concepts and calculations that may be used to implement the five steps of the tree expansion process. The current implementation does not represent a rigorous realization of the steps described above. A completely rigorous implementation of the five steps would not result in a practical structuring aid for a task force commander, as it would require the commander to provide a very large number of complicated assessments. The implementation of the structuring steps that is described below relies heavily on engineering approximations and heuristics deduced from experimental structuring exercises to obtain a practical tradeoff between accuracy derived from theoretical completeness and simplicity of use.

Step 1: Obtain Estimates for the Uncertainty in the Rollback Value at Each Node in the Current Decision Tree

The uncertainty the decision maker assigns to the value of the various alternatives that are open to him, after he has seen the rollback results from a simple decision tree model of his situation, is a measure of his confidence in that model. Thus, the uncertainties assigned to the rollback values at each node in a current decision tree should reflect the decision maker's confidence in that portion of the decision model that is represented by the given node in the tree. Unfortunately, direct assessment by the decision maker of these uncertainties would be difficult and time consuming, because decision makers are not accustomed to thinking in terms of rollback values.

Therefore, to implement this step of the tree expansion process a surrogate distribution is constructed. The decision maker is asked to provide estimated outcomes and the worst and best outcomes that he expects for each terminal node in the existing decision tree. A technique for obtaining these outcome assessments that makes use of outcome calculators is illustrated in Chapter IV. A value model is used to convert each worst, estimated, and best case outcome to a minimum, median, and maximum value for each terminal node in the tree. A probability distribution is then fitted to each set of minimum, median, and maximum values associated with each terminal node. These distributions serve as surrogates for the uncertainties in rollback value at terminal nodes in the tree. Approximations for the distributions on rollback values for any interior node in the tree may be obtained if one makes some assumptions concerning the probabilistic dependence among the distributions on rollback values fitted to the node's successor nodes. For simplicity, the current realization of the tree expansion algorithm assumes these distributions are independent.

Step 2: Compute the Value of Resolving Rollback Uncertainty at Each Node in the Decision Tree

A useful concept for computing the value of resolving model uncertainty is delta, the amount by which the rollback value of a node would have to change so that another alternative would be preferred at the initial decision node. Figure 6 shows a simple decision tree in which the deltas associated with each node in the tree have been calculated and displayed. Alternative A, with a computed rollback value of 10 units, is preferred to Alternative B, which has a rollback value of 6 units.

The deltas corresponding to each node in the tree of Figure 6 are obtained by determining the amount by which the value of that node would

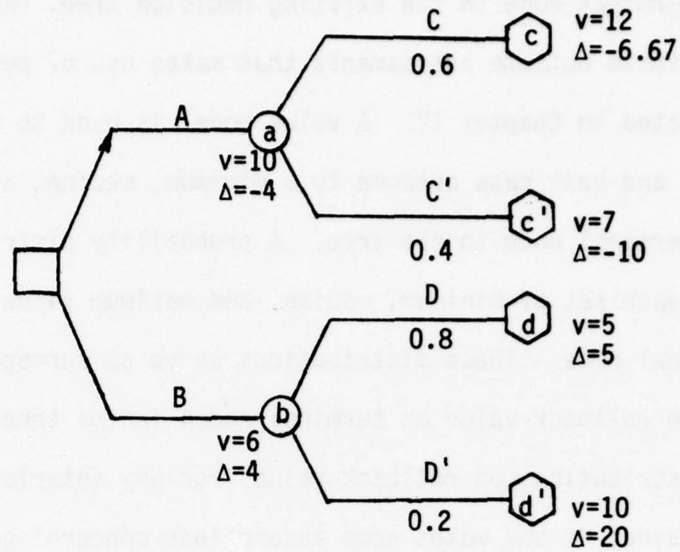

Figure 6: Decision Tree With Rollback Values and Deltas

have to increase or decrease so that the optimal decision would be B rather than A. Thus, for example, if the value at the node labeled "a" were decreased by 4 units, then the new rollback value for node "a" would be 6 units, sufficient just to cause a decision switch from A to B. Similarly, if the value at the node labeled "d" were increased 5 units, to 10, then the new rollback value at node "b" would be 10 units, which would be just enough to cause a decision switch. Notice that the sign of delta indicates the direction of change that is necessary to cause a decision switch.

Leal (18), who refers to the deltas as sensitivity differentials, has noted that a recursive relation may be used for computing the delta associated with any node i. Let $\Delta(i)$ denote the delta associated with a node i, and let $\Delta(i-1)$ denote the delta for the node in the decision tree that preceeds node i. Then

$$\Delta(i) = \begin{cases} \dfrac{\Delta(i-1)}{p_i} & \text{if node i is a chance node} \\ v(i-1) - v(i) + \Delta(i-1) & \text{if node i is a decision node} \end{cases} \qquad (1)$$

where p_i is the probability along the branch leading from node i-1 to node i, and v(i) and v(i-1) are the respective rollback values at nodes i and i-1.

If the probability distribution describing the uncertainty in the true rollback value is known for a given node in the decision tree, the value of resolving that uncertainty may be computed from a simple formula. Let the node have a computed rollback value equal to v and delta equal Δ, and let p_a be the product of all of the probabilities along the path leading to node i. If the node lies along a path that contains no nonoptimal decision branches (branches without arrows), then the value of resolving the uncertainty in the true rollback value of the node is

$$V = P \cdot p_a(v + \Delta - m), \qquad (2)$$

where

$$P = \text{Prob}\,[\text{true rollback value} \leq v + \Delta]$$

is the probability that the true rollback value will be found to be less than $v + \Delta$, and m is the conditional mean of the true rollback value given that it is less than $v + \Delta$. If the node lies along a path that contains nonoptimal decision branches, the value of resolving rollback uncertainty at that node is

$$V = -Q \cdot p_a(v + \Delta - n), \qquad (3)$$

where

$$Q = \text{Prob}\ [\text{true rollback value} > v + \Delta]$$

is the probability that the true rollback value will be found to be greater than $v + \Delta$, and n is the conditional mean of the true rollback value given that it is greater than $v + \Delta$. Equations (2) and (3) are derived in the Appendix. By using Equations (1), (2), and (3) the value of resolving rollback uncertainty may be computed for each node in a decision tree, and the node with the highest value of resolving rollback uncertainty may be identified.

Step 3: Determine the Decision Sensitivity of Each Outcome Variable

Once a node with a high value of modeling has been found, the next step is to identify factors that may be used to expand that node. To facilitate the identification of factors to bring into the decision tree, the outcome variables are ranked according to the likelihood that resolution of their uncertainty will indicate that the current best initial decision is no longer optimal.

Suppose a linear multiattribute value model

$$v(x_1,x_2,\ldots,x_N)=a_1x_1 + a_2x_2 + \ldots + a_Nx_N$$

is used to estimate the value of an outcome vector $(x_1,x_2,\ldots,x_N)$. In Step 1 the decision maker has been asked to assess worst, estimated, and best case outcomes for each outcome variable, x_i, at each terminal node in the decision tree. Therefore, through the rollback procedure, worst, estimated, and best outcomes, x_{min}, $\hat{x}_i$, x_{imax}, for each outcome variable may be obtained at each node in the tree. If all outcome variables except x_i were held constant at their estimated values, a change in x_i of Δ/a_i would be sufficient just to cause a decision switch. If Δ is positive, x_i would have to increase to cause a decision switch; if Δ is negative, x_i would have to decrease to cause a decision switch. The quantity

$$r_i = \begin{cases} \dfrac{a_i(x_{imax} - \hat{x}_i)}{\Delta} & \text{if } \Delta > 0 \\ \dfrac{a_i(x_{imin} - \hat{x}_i)}{\Delta} & \text{if } \Delta < 0 \end{cases}$$

gives the fraction of the change required for a decision switch that is possible through the resolution of the uncertainty on that outcome variable. The larger this number, the more likely resolution of the uncertainty in this outcome variable is to cause a switch in the indicated optimal decison.

Step 3 is to compute the ratios r_i for each outcome variable and then rank the outcome variables according to the magnitude of r_i . To facilitate the identification of additional factors to bring into the decision tree at the node under consideration, structuring activity is focused on resolving the outcome uncertainty that is associated with the outcome variable with the highest ranking. This permits the discussion to focus on identifying factors that resolve the uncertainty most relevant to the optimal decision. The example application (Chapter IV) illustrates the manner in which the ranking of the outcome variables can be used to generate questions for identifying factors for addition to the decision tree.

Step 4: Verify That Factors Proposed for Addition to the Decision Tree Have Some Chance of Impacting the Decision

The process of representing decision factors as nodes in a decision tree, although relatively straightforward, is time consuming. Sensitivity analyses of decision trees often show that many nodes in the tree could be eliminated without affecting the solution. Thus, it is worthwhile to verify that factors proposed for addition to the tree have some chance of impacting the optimal decision before major effort is spent to include these factors in the tree. Step 4 tests factors proposed for addition to the decision tree to verify that the addition of these factors has some chance of indicating a change in the optimal decision.

For a chance node added as a predecessor to an existing node in the tree to affect a decision, it must include an event outcome that produces a rollback value at the existing node that exceeds the current rollback value of the node by more than delta. Furthermore, the probability of the event must be sufficiently high that the event has some impact on the decision. To test these conditions, the probability of an event proposed for addition to the decision tree is roughly estimated. Because it is not necessary that this estimate be precise, it should be possible to obtain this assessment fairly rapidly from the decision maker. The test consists of estimating the impact the event would have on the possible outcomes and then calculating the probability of the event that would be required to switch the optimal decision. Let $(x_1',\ldots,x_n')_1$, $(x_1',\ldots,x_n')_2$, etc., be the extreme effect that the occurrence of the event could have on the outcome vectors associated with terminal nodes in the tree lying on paths leading from the node, and let v' be the rollback value implied by these outcomes. Then the required probability for a decision switch is

$$p_r = \frac{\Delta}{v'-v} \quad . \tag{4}$$

If the required probability is much higher than the estimated probability, modeling the event and adding it to the decision tree will clearly not affect the decision. On the other hand, if the required probability is in the neighborhood of the estimated probability, or lower, modeling the event may impact the decision, so it should be added to the decision tree.

Step 4 obtains estimates of the worst case outcomes (if node is on path from current best initial decision) or best case outcomes (if node is not on path from the current best initial decision) that could conceivably result from the occurrence of the event under consideration for addition to the tree. If the worst case outcomes are being considered, contingency plans are sought that could be employed that would mitigate the effect of the event on the decision outcome. The required probability necessary for the event to cause a decision switch is then computed from Equation (4) and compared to the estimated probability of the event. If it is less than the estimated probability, the event and any related decisions are verified as potentially impacting the initial decision and recommended for addition to the tree.

Step 5: <u>Expand the Decision Tree to Include Those Factors That Are Verified as Potentially Impacting the Decision</u>.

Once an event or an event plus additional decisions has been verified as potentially impacting the initial decision, they should be modeled and added as additional nodes to the decision tree. The formal steps that an analyst goes through to represent a factor as a node in a decision tree are discussed in the literature.* Briefly, the appropriate node type for representing the factor is first determined. If the factor is a decision, then it is symbolized by a decision node. Events are indicated by chance nodes. Next, a list of alternatives or event outcomes, as the case may be, is identified. Each element in the list is to be represented by a branch emanating from the node. Normally, the alternatives or outcomes are defined so that the number of possibilities is relatively small (between 2 and 5) to avoid causing the tree to grow too large. In some cases this may require a discretization or an aggregation of a much larger number of possibilities, but, unless it is necessary to distinguish between very similar alternatives, this generally introduces a little error into the analysis.

The definitions of the alternatives and outcomes must be expressed in an unambiguous manner and such that the possibilities are mutually exclusive and form an exhaustive set. If the factor is an event, probabilities must be assessed for each possible outcome to the event. A process for assessing event probabilities is described in (19). In addition, several computerized decision aids for assessing probabilities have been developed and implemented. (12, 20).

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*See for example pp. 162-162 and pp. 246-254 in Ref. 8.

IV A STRUCTURING PROCESS BASED ON THE DECISION TREE EXPANSION ALGORITHM

The decision tree expansion algorithm described in Chapter III forms the basis for a systematic process for structuring a decision tree model of a task force commander's decision situation. This chapter describes and illustrates this structuring process.

4.1 Overview of the Structuring Process

The decision tree expansion algorithm is an important part of the entire decision structuring process. Figure 7 illustrates as a flow chart a structuring process developed around the concept of decision tree expansion. The boxes in the chart represent identifiable functions that must be carried out to complete the structuring process. The arrows connecting the boxes indicate the order in which these functions are performed. The loops formed by arrows around some of the boxes indicate that the corresponding functions may be repeated several times before structuring is complete. The various functions that make up the structuring process are described below.

4.1.1 Decision Bounding

Once a decision is recognized,* the first step in the structuring process consists of bounding the decision. In particular, it is necessary

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* The step of recognizing the need for a decision is not as trivial as it sounds. Often, decision makers proceed along a certain course of action without realizing that they should at least consider alternative actions. This is especially true in organizations where things are done "by the book." While recognition of a decision problem logically precedes the structuring of that problem, decision recognition is beyond the scope of this research.

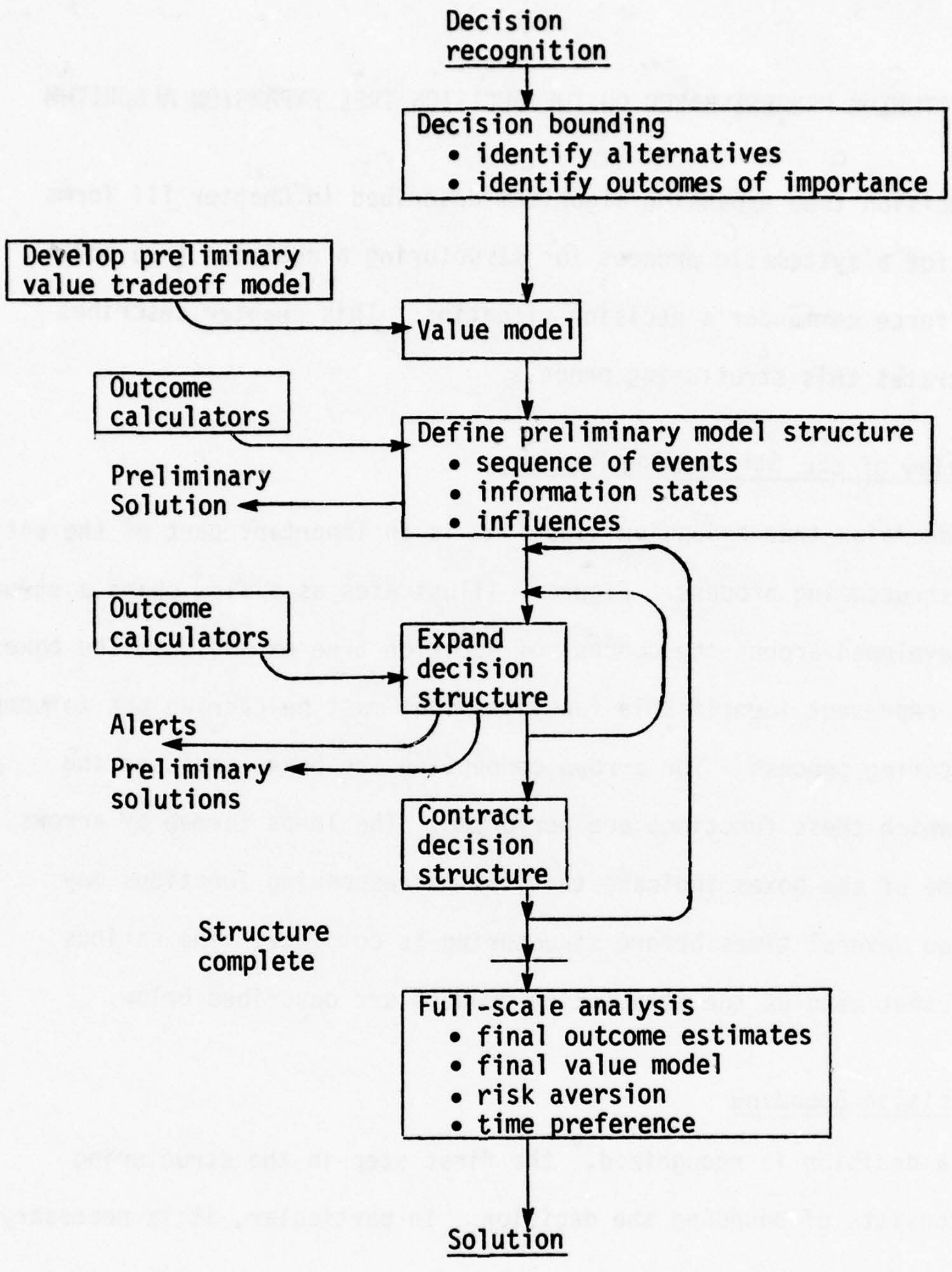

Figure 7: Flowchart of Structuring Process

to specify the alternatives available to the decision maker. This is an important step because no amount of analysis will lead to the selection of an alternative if it has not been included in the analysis. Unfortunately, little is known about the process of defining alternatives. Limited research in this area indicates that the process of defining new alternatives can be encouraged by involving several individuals with different points of view in the decision-making process, by trying various brainstorming techniques, and by using morphological methods (21, 22, 23, 24). Few of these techniques, however, have been developed to the point that they could be employed as decision aids to help a task force commander with this part of the structuring process.

Another aspect of bounding the decision is specifying decision outcomes of importance. In other words, an identification is made of the possible outcomes of concern to the decision maker that may make it desirable to choose one alternative over another. A task force commander typically would be concerned with outcomes such as the number of men, aircraft, and ships lost in a particular operation, and the extent to which his objectives are achieved. The most common reason for a decision maker to fail to accept the recommendations resulting from a decision analysis is that one or more of the outcomes of importance to him was not included in the analysis. This typically occurs when the outcome in question involves a quantity that is difficult to quantify, such as the value of human life or the political importance of achieving certain objectives. If the structuring process is to result in a comprehensive decision model, it is important that as many significant outcomes as possible be identified and included in the structure.

4.1.2 Value Model

A necessary task in Figure 7 is the development of a preliminary value trade-off model. When individuals carry out the structuring process intuitively, they rarely assign quantitative values to the important outcomes. This is an adequate procedure when the structuring is intuitive, but some type of preliminary, quantitative value model is needed if an automated decision aid is to assist in the structuring process.

The purpose of constructing a preliminary value model is to provide a basis for developing the model structure and ensuring that all of the important aspects of the problem are included in the model. A relatively simple value model will suffice for this purpose. Typically, this means that each outcome measure is assigned a weight, and the resulting quantities are added to produce a linear value function.

4.1.3 Define Preliminary Model Structure

The next phase in the structuring process is to describe a preliminary model structure based on the commander's initial understanding of the problem. It may not always be possible (and it is not essential for the operator of the structuring process) for the decision maker to specify a preliminary structure. However, task force commanders have considerable experience with decisions needed to carry out the mission of the task force. A structuring process that does not make effective use of a commander's intuition and experience would be relatively inefficient and unlikely to win his confidence.*

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* There is, however, a risk inherent in asking a decision maker to define a preliminary model structure. Development of a preliminary model may cause him to anchor his thinking on one particular model structure and make it difficult for him to accept revisions to that structure. Additional research is necessary to indicate the proper way to elicit a preliminary model structure without encouraging the decision maker to anchor his thinking.

The information that can be supplied in this phase of the structuring process includes the sequence of events that the decision maker expects to occur if he selects various alternatives and the manner in which the various events in his scenarios depend on each other (e.g., Event A is very unlikely unless Event B occurs). Another useful piece of information that a decision maker could supply at this point is the sequence of information states that he expects to occur for each of his scenarios. This means that he would explain how much he expects to know about the occurrence of uncertain events at different points in time. Once a decision maker has prepared a preliminary outline of a decision model, it should be put in a form that can be modified easily during the subsequent steps of the structuring process.

4.1.4 Expand Decision Model

The two major phases of the structuring process involve the expansion and contraction of the model structure. The expansion phase is relatively difficult to perform because it requires one to deal with potential model elements that are not well-defined. However, expansion is an essential element of the structuring process if the resulting decision model is to be comprehensive. The tree expansion algorithm described in this report focuses on expansion because this phase of the structuring process is most in need of development.

As part of the expansion algorithm, the decision maker is asked to estimate the outcomes that would occur under certain scenarios. To do so, he may find it useful to make use of a prestructured outcome calculator. Both the preliminary value model developed in the initial stages of the structuring process and any available outcome calculator are important inputs to the expansion algorithm.

The decision structure is expanded by identifying new events of importance. A commander may wish to be alerted whenever one of these events occurs. Thus, it may be desirable for an automated aid to keep track of some of the new events and alert the decision maker whenever information is received indicating that one of the events has occurred. For this reason, Figure 7 shows alerts as outputs of the structuring process.

Whenever the structure of a decision model is revised, either through expansion or contraction, the new version of the model can be used to update the model solution and recommend a course of action. Having updated solutions to the evolving decision model is especially important when the time available for analysis is uncertain. One useful feature of the expansion routine described in this report is that it constantly produces an updated estimate of the best decision alternative.

4.1.5 Contract Decision Structure

There are a variety of ways to test the importance of existing model parameters and to contract the model to eliminate those that are relatively unimportant. Typically, model contraction by elimination of less significant parameters is accomplished through sensitivity analysis or a calculation of the value of information associated with each model variable. A more significant type of model contraction occurs, not when model parameters are eliminated, but rather when they are grouped together according to similar characteristics and combined into a smaller number of aggregate parameters. This type of model contraction is harder to accomplish because it requires a more complete understanding of the nature of existing model parameters.

However, it may be possible to design automated decision aids to assist with the consolidation of existing model parameters. Parameters could be grouped by categories, such as the direction in which they influence the decision maker's choice of alternatives, their affect on various outcome measures, and their affect on the likelihood of other variables or events. Variables that fall into roughly the same categories for each of these methods of classification would be candidates for consolidation into composite variables. Although the decision structuring algorithm described in this report does not deal with the contraction of a decision model, it could be extended to include this capability.

4.2 The Decision Tree Expansion Algorithm as a Component of the Structuring Process

Figure 8 shows how the decision tree expansion algorithm of Chapter III might be implemented as a computer aid to assist a task force commander in the model-expansion phase of decision structuring. The figure distinguishes between those structuring functions that require human judgment and, therefore, must be performed by the staff (shown in boxes with right-angled corners), and those functions that the computer can perform independently (shown in boxes with rounded corners). Outcome calculators and a value model, although requiring subjective assessments, are not specific to any decision. As described earlier, these can be developed before the time they are needed and supplied to the structuring process as prestructured models. Outcome calculators and the value model are shown in six-sided boxes.

The process starts at the top of the flow chart. It is assumed that the staff, with guidance from the commander, has identified alternatives for

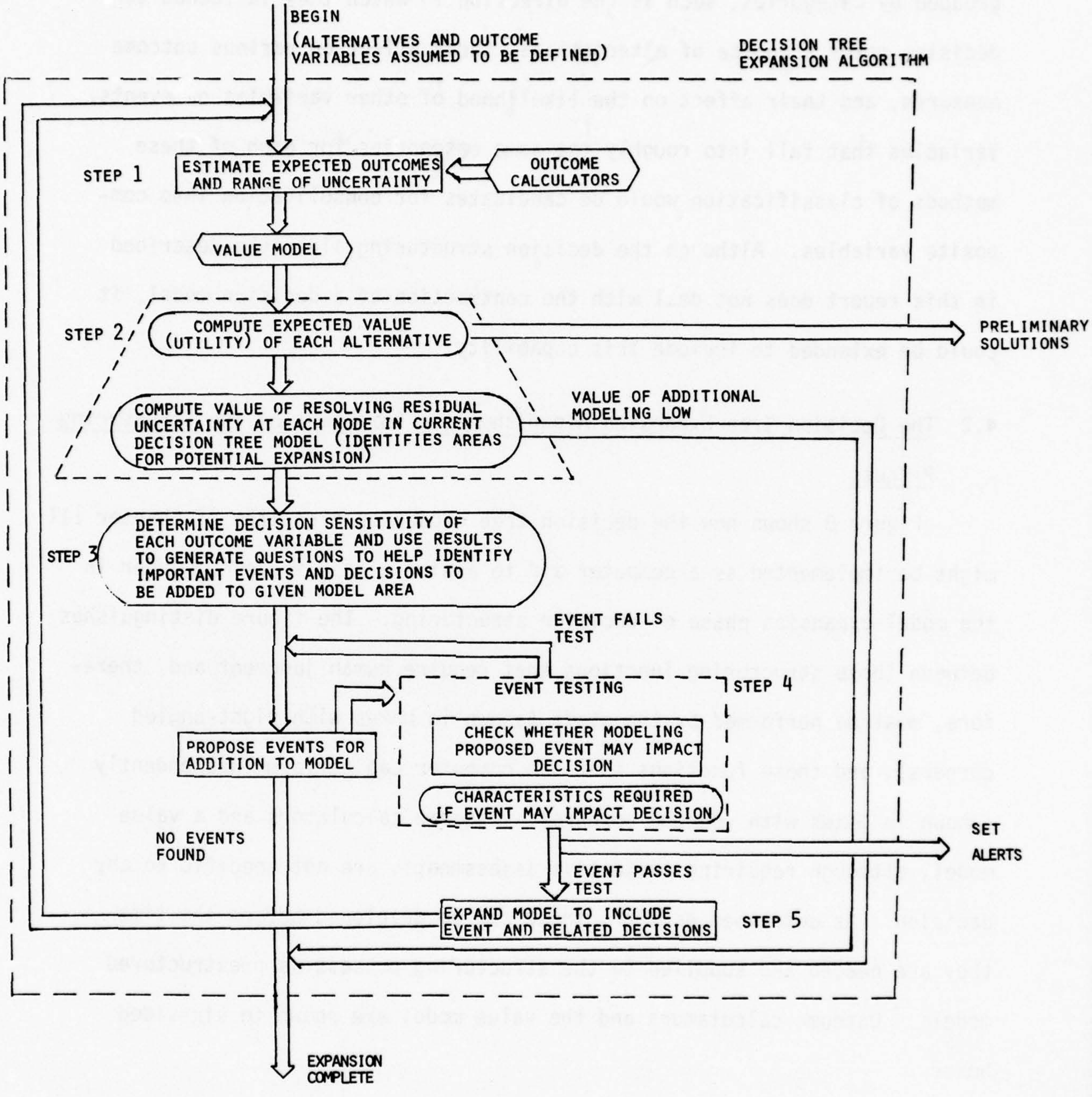


FIGURE 8: FLOW CHART OF DECISION TREE EXPANSION ALGORITHM SHOWING TASKS FOR STAFF: ▭, COMPUTER: ⬭, AND PRESTRUCTURED MODELS ⬡

analysis and specified the outcome variables of importance. The first step is to estimate outcomes and assess a range of uncertainty for the outcomes anticipated to result from the choice of each alternative under analysis. Outcome calculators may be used to help generate these quantities, but it is important that the uncertainty ranges used accurately reflect the commander's confidence in his estimates.

The function of the computer is to provide three basic calculations. It computes the expected value of each alternative. It computes the value of resolving residual uncertainty at each node in the decision tree, thereby indicating areas for clarification or expansion. Finally, the computer generates questions to help identify events and decisions not included in the current model.

Using the computer-generated questions, the staff and the task force commander propose events for addition to the decision tree model. The computer then calculates the probabilities that the proposed event would have to possess if its inclusion in the model is to affect the decision. The staff compares the estimated probability of the event with the required probability and decides whether effort should be devoted to adding the new event to the model. If the event passes the test, the tree is expanded to include the event and any related decisions. After expansion, the process is repeated. The structuring process terminates if the value of resolving the remaining modeling uncertainty is low or if additional decisions or events cannot be proposed for addition to the decision tree.

4.3 Illustrative Application of the Structuring Algorithm

In this section we describe an illustrative application of the decision tree expansion algorithm to a decision taken from the ONRODA scenario.

As described in the scenario, a Blue task force commander has been ordered to prepare a plan for neutralizing Orange forces on ONRODA Island so as to defend Grey. The decision analyzed is whether Blue should plan to neutralize ONRODA with an airstrike or through the construction of a blockade between ONRODA and the Grey mainland.

4.3.1 The Structuring Process from the Viewpoint of the Commander

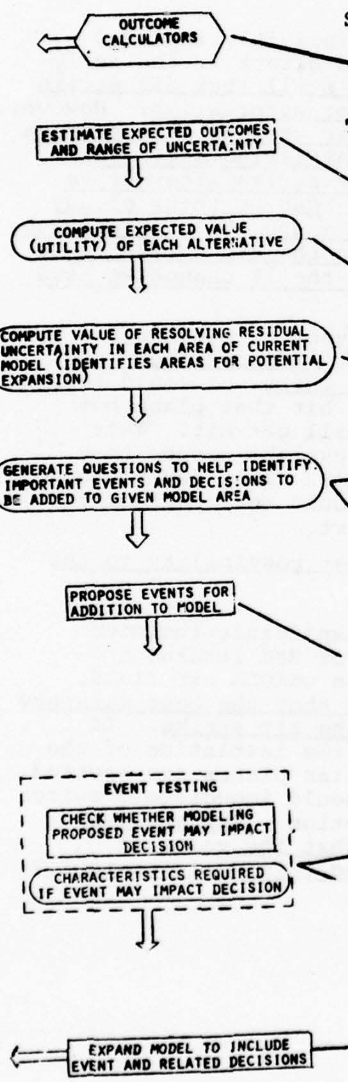
The commander and his staff each see the structuring process from different viewpoints: the staff must be concerned with detailed aspects of the process, the commander need not. We first illustrate how the structuring process applied to the ONRODA example would appear to the commander and then how the more detailed elements of the procedure would appear to the staff.

Table 1 shows the interaction that might occur between the commander and a staff member who is supported by the computerized structuring aid. The boxes on the left side of the table point out where in the dialogue reference is made to the specific functions of the tree expansion algorithm shown in the flow chart of Figure 8.

Staff begins by reviewing with the commander the staff's preliminary analysis and the outcome estimates for each alternative. Outcome calculators can be used to help produce the outcome estimates. The commander then has the option of revising or modifying these estimates. When the commander agrees with the outcome estimates, the computer displays the expected value of each alternative and indicates that there is a high value to analyzing the possibility that the outcome of an air strike may be less favorable than estimated. In particular, the computer directs staff to ask whether there are potential events that could cause aircraft losses to be

TABLE 1:

SAMPLE DIALOG BETWEEN TASK FORCE COMMANDER (TFC) AND STAFF MEMBER SUPPORTED BY COMPUTERIZED STRUCTURING AID



STAFF: Sir, you've seen the preliminary analysis of the air strike and blockade alternatives. Do you want to make any changes to the outcome estimates made by the outcome calculators

TFC: Yes, there are several estimates I can't agree with. To begin, the outcome calculators say I'm going to lose between 7 and 10 F-14's if I run a four day strike. I think that estimate may be high. Let's make it between 1 and 8 with a best estimate of 3. Also, I want to change the estimated range of ship damage ...

STAFF: With the revised outcome estimates air strike has an estimated value about 40% higher than blockade, but there is a high value to analyzing the possibility that the outcomes to an air strike may not be as favorable as we have estimated. What could cause our aircraft losses to be much higher than we have estimated?

TFC: A number of things might cause us to have higher than expected air losses, but I can't see how I could lose more than at most a dozen F-14s and several A-6s and A-7s.

STAFF: Then, how about ship losses?

TFC: Well, a Red attack on the task force could cause us to have higher ship losses than our estimated values. There is more risk of a Red attack under the air strike alternative than under the blockade alternative.

STAFF: How likely is it that Red would attack following an air strike on ONRODA?

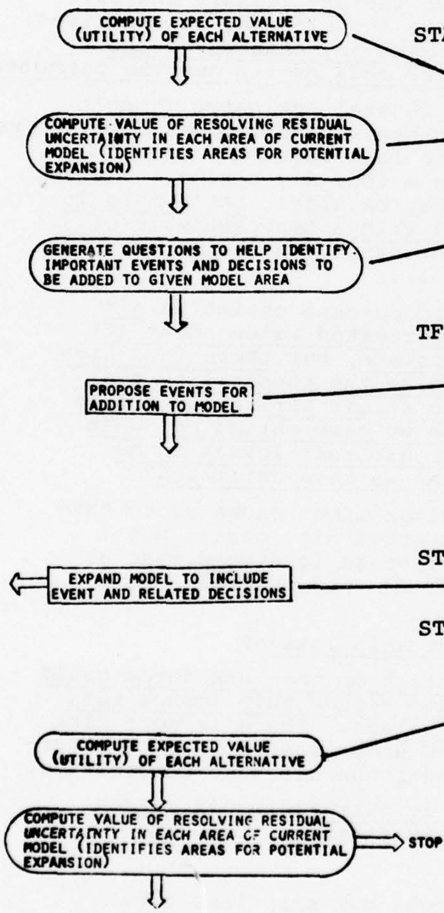
TFC: Maybe, 15%.

STAFF: How serious might our ship losses be?

TFC: I don't expect it, but we could lose a cruiser, maybe even disable one of the carriers.

STAFF: All right, according to the computer we better add this possibility to the analysis...

Table 1:
Sample Dialog (Continued)



STAFF: Now that we've explicitly included the risk of a Red attack in the analysis, the results still show air strike to be the superior alternative. However, we should consider whether our estimate of the risk of initiating a Blue-Red war under the air strike alternative is satisfactory. Can we think of any event that might cause the risk of Blue-Red war following the air strike to be much higher than the 1% chance we have assumed?

TFC: Red wants to prevent my striking ONRODA air field. Suppose they land a hospital plane there. I could tell my pilots not to hit that plane, but chances are it will get hit. That could give Red just the excuse they may be looking for. They haven't done it yet, but it could be an effective move on their part.

STAFF: We better add that possibility to the analysis ...

STAFF: Now that we've explicitly included the possibility of Red landing a hospital plane on ONRODA air field, the results show that the best strategy is to plan for the air strike. If between now and the initiation of the strike Red civilian planes are spotted on ONRODA, we should immediately switch to a blockade action. The analysis also indicates that the value of further analyzing this decision is low.

much higher than estimated. When the commander answers that he does not foresee such an event, the computer directs staff to ask about ship losses. In this case, an event is identified: the possibility of Red attacking the task force. The staff then tests this event to see if it should be included in the analysis. The test consists of asking how likely the event is and how serious the outcome of the event might be. The answers given prompt a decision to expand the analysis to include the possibility of a Red attack.

When the model has been expanded to include the possibility of a Red attack, staff informs the commander that airstrike still appears to be the superior alternative and that any further analysis should consider whether the current estimate of the risk of Blue-Red war under the airstrike alternative is satisfactory. Might the risk be greater than 1%? The commander considers whether events exist that would cause the risk of war under the airstrike alternative to be significantly higher. The possibility of Red landing a hospital plane on ONRODA is suggested. The decision is made to add this possibility to the analysis. When this is done, staff reports that the best strategy is to plan for the airstrike, but then to shift to a blockade alternative if Red civilian planes are spotted on ONRODA airfield. The structuring aid indicates at this point that the value of further analysis is low.

4.3.2 The Structuring Process from the Viewpoint of the Staff Coordinator

Throughout the dialogue summarized in Table 1, staff uses the computer to build a series of decision tree representations of the commander's decision problem. The computer then analyzes these tree representations, and the results assist staff in efficiently conducting his dialogue with the commander. The process follows the five steps outlined in Section 3.2.

4.3.2.1 Outcome Estimates

The first step of the structuring process is to obtain estimates and a range of uncertainty for the outcomes under each alternative course of action. For this problem, decision outcomes of importance were judged to be own-force losses (various aircraft and ships), the degree of neutralization of ONRODA forces that is achieved as measured by the number of potential Orange sorties that could be launched from ONRODA following the Blue action, and the risk of Blue-Red war. An estimate and a range of uncertainty must be assessed for each of these outcome variables, for the airstrike alternative, and for the blockade alternative. The assessments obtained for this example are shown in Figures 9 and 10.

To simplify the process of obtaining outcome estimates, it may be possible to use prestructured outcome calculators such as those being constructed for the ODA Program by SRI's Naval Warfare Research Center. The Navy has equations for estimating losses and effectiveness under various battle situations. These equations can be incorporated in outcome calculators. Figure 11 shows the outcome calculator that was used in this analysis to estimate the number of F-14s that would be lost under the airstrike alternative.

4.3.2.2 Value Model

A value model is needed to help in the identification of important factors that are omitted from the current model.* Figure 12 gives the value model that was used in this analysis. The parameters in the value model represent the relative values of the attributes of the decision

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* The development of value models is beyond the scope of this research project.

ESTIMATE EXPECTED OUTCOMES AND RANGE OF UNCERTAINTY

ALTERNATIVE: AIR STRIKE FOLLOWED BY ORANGE-ONRODA BLOCKADE

	OUTCOME VARIABLE	RANGE AND LIKELY VALUE
AIRCRAFT LOSSES	NUMBER OF F-14'S LOST	3 (1 – 8)
	NUMBER OF A-6'S LOST	0.3 (0 – 3)
	NUMBER OF A-7'S LOST	0.5 (0 – 5)
SHIP LOSSES	FRACTION OF CRUISER CAPABILITY DISABLED	0.1 (0 – 0.5)
	FRACTION OF CARRIER CAPABILITY DISABLED	0.1 (0 – 0.3)
DEGREE OF NEUTRALIZATION ACHIEVED	NUMBER OF POTENTIAL ORANGE SORTIES	4000 (1000 – 5000)
RISK OF BLUE-RED WAR	PROBABILITY THAT A BLUE-RED WAR RESULTS	.01 (0.001 – 0.05)

FIGURE 9: OUTCOME ESTIMATES AND RANGES FOR AIRSTRIKE ALTERNATIVES

ESTIMATE EXPECTED OUTCOMES AND RANGE OF UNCERTAINTY

ALTERNATIVE: AIR BLOCKADE OF ORANGE FLIGHTS FROM ONRODA TO GREY

	OUTCOME VARIABLE	RANGE AND LIKELY VALUE: LIKELY	LOW	HIGH
AIRCRAFT LOSSES	NUMBER OF F-14'S LOST	5	0	7
	NUMBER OF A-6'S LOST	0	0	0
	NUMBER OF A-7'S LOST	0	0	0
SHIP LOSSES	FRACTION OF CRUISER CAPABILITY DISABLED	0.2	0	1
	FRACTION OF CARRIER CAPABILITY DISABLED	0.3	0	0.5
DEGREE OF NEUTRALIZATION ACHIEVED	NUMBER OF POTENTIAL ORANGE SORTIES	4000	3000	6000
RISK OF BLUE-RED WAR	PROBABILITY THAT A BLUE-RED WAR RESULTS	1/1000	1/10,000	1/100

FIGURE 10: OUTCOME ESTIMATES AND RANGES FOR BLOCKADE ALTERNATIVE

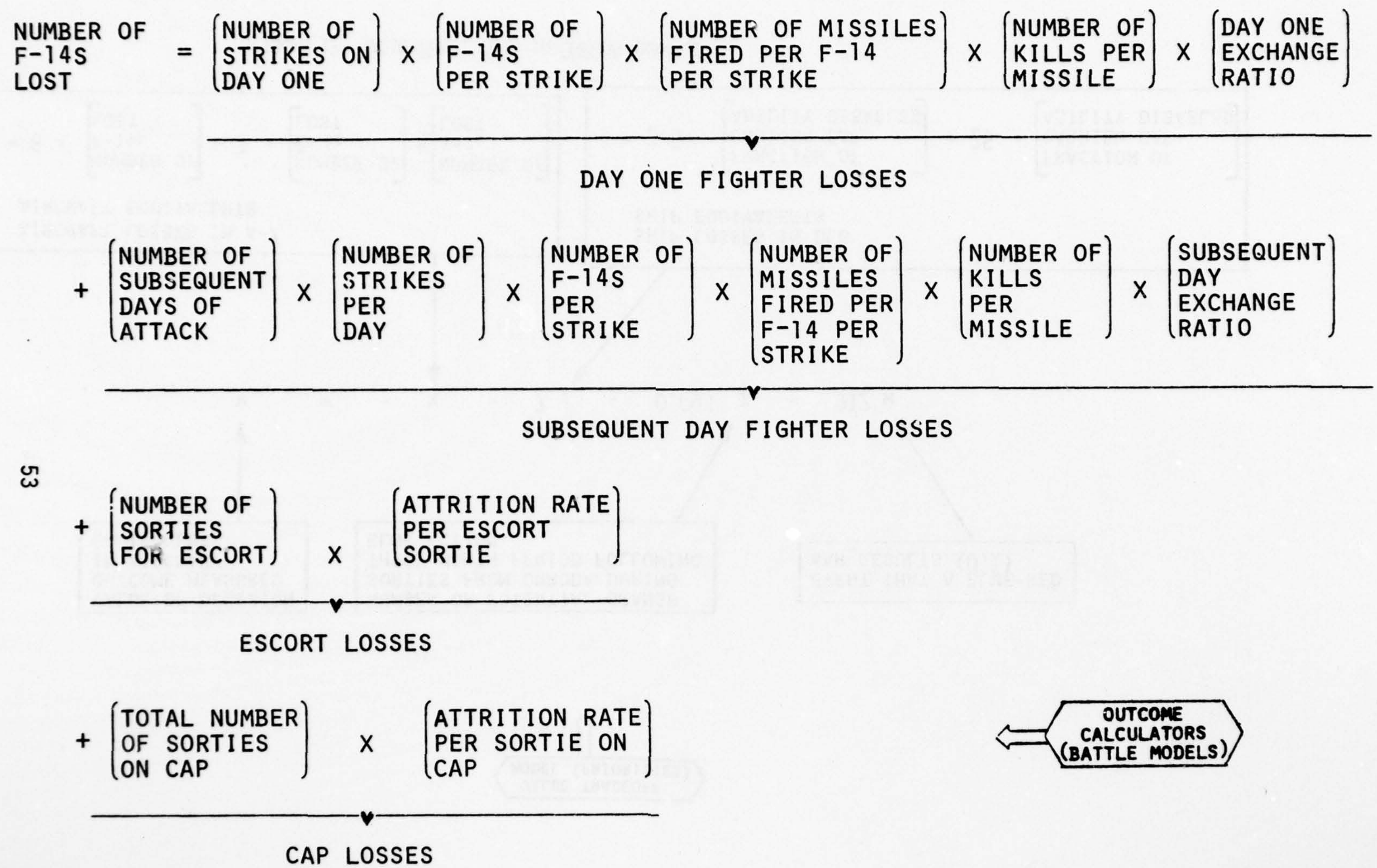


FIGURE 11: PART OF OUTCOME CALCULATOR USED IN EXAMPLE APPLICATION OF STRUCTURING PROCESS

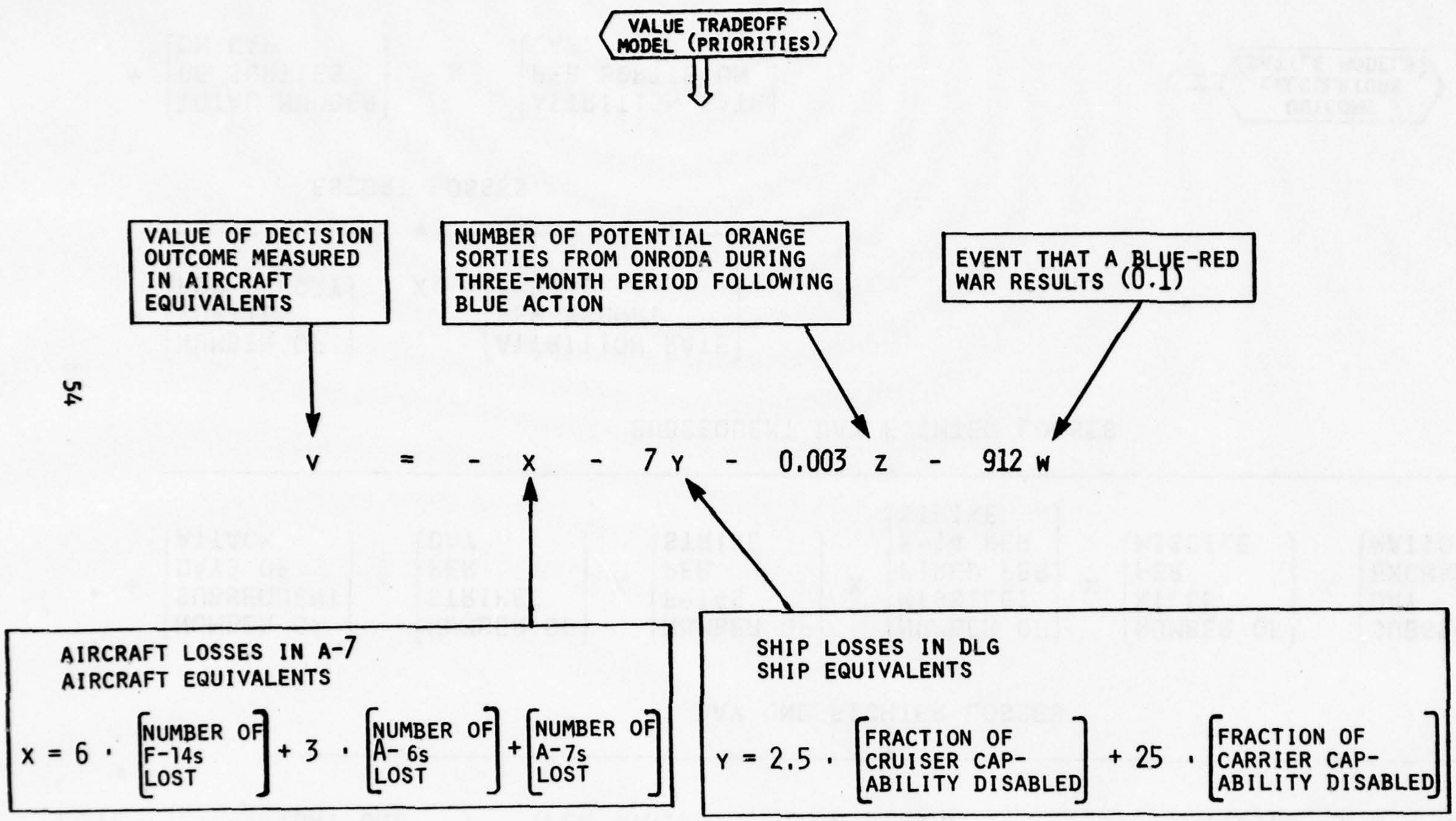


FIGURE 12: VALUE MODEL USED IN ONRODA EXAMPLE

outcome. For example, in this case an F-14 is judged to be worth about six times as much to the commander as an A-7.*

4.3.2.3 Identification of Model Areas for Expansion

Once outcome estimates have been specified, the computer can use the value model to estimate the value of each alternative. Figure 13 shows the output of the computation as it might be displayed on a screen for the member of the staff who is interviewing the commander. The estimated value of the airstrike is somewhat higher than the estimated value of the blockade: -60 compared with -99. The computer also indicates two other quantities of interest: delta, which is the amount by which the estimated value of each alternative would have to change to cause a switch in the optimal decision, and the value of resolving the current uncertainty in the outcome estimates. The computation of the value of resolving uncertainty in the outcome estimates is carried out as described in Steps 1 and 2 in Section 3.2. The rule used for directing the structuring process may be stated as follows: If further analysis is to be devoted to the decision, it should be directed to that area where resolving uncertainty has the greatest value. In other words, if time is to be devoted to expanding the decision tree, it should be expanded first from those nodes with the highest value, V, of resolving uncertainty. The value of resolving residual uncertainty of the airstrike alternative is 23 units. The value of resolving residual uncertainty of the blockade alternative is 11 units. Therefore, the staff member is directed to explore the airstrike alternative further.

+ The value model is such that values are expressed in units of "aircraft equivalents." An aircraft equivalent is equivalent in value to an A-7.

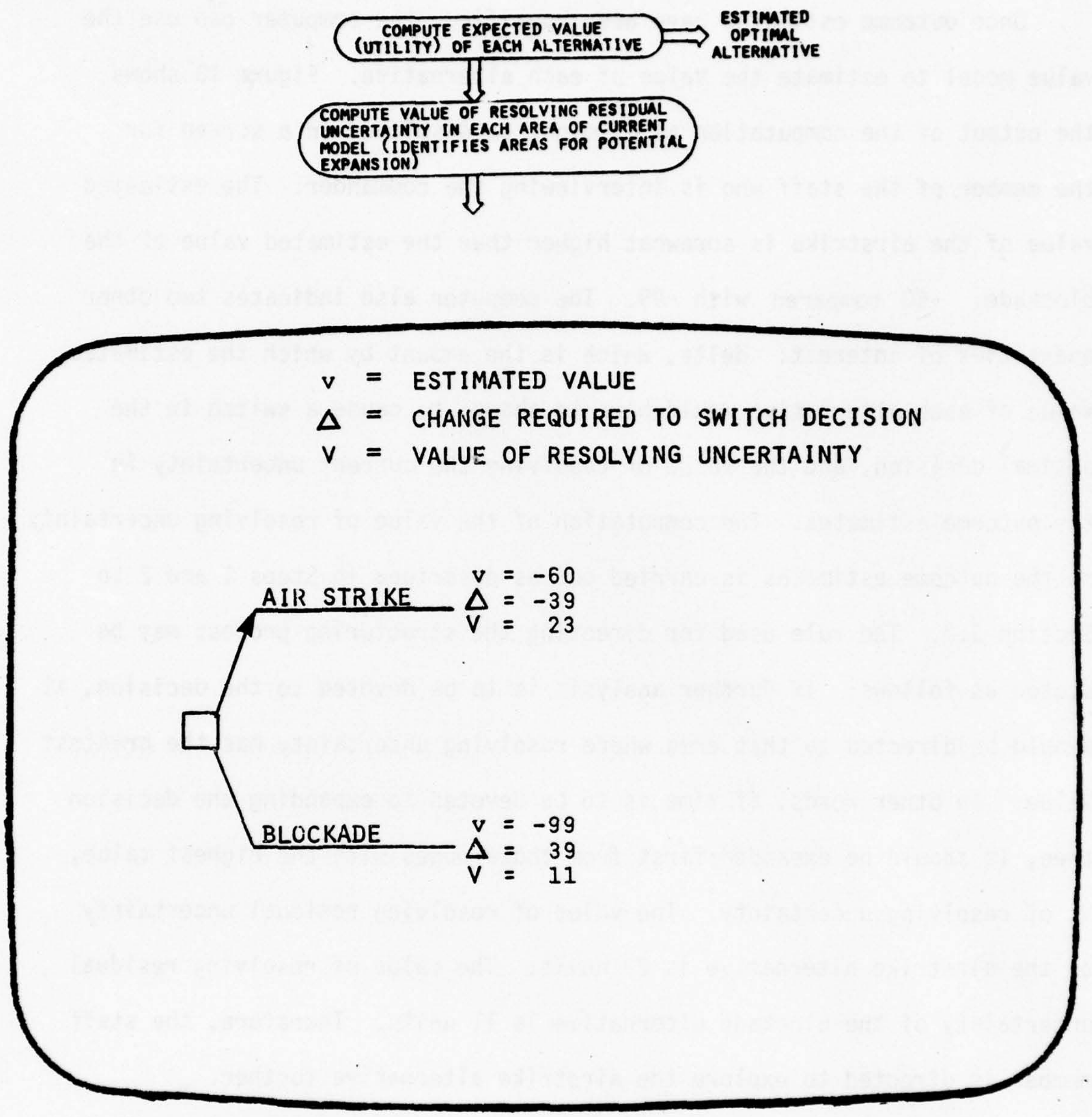


FIGURE 13: DISPLAY SHOWING INITIAL DECISION TREE

To assist in identifying events to add to the decision tree, the computer ranks the outcome variables according to how likely they are to cause a decision switch. This is Step 3 of the process. The results are illustrated in Figure 14. In this case, the computer finds that the number of aircraft lost under the airstrike alternative could range from 6 to 62 but that the estimated, or best guess value, is 19.2. The computer calculates that if 58.2 aircraft were lost, this would be enough to make the blockade alternative preferable, assuming everything else remains unchanged. The ratio of the maximum estimated change to the change required for a decision switch is largest for the outcome variable "aircraft lost." Therefore, this variable is ranked first. Similarly, "ships lost" is ranked second, probability of Blue-Red war is ranked third, and so forth.

4.3.2.3 Expanding the Existing Model

Based on outcome variable ranking, the computer generates a series of questions designed to identify additional factors to add to the decision tree model. Because aircraft losses was the outcome variable ranked first, the first question asked is: "Suppose you chose the airstrike alternative. Is there any event that could cause you to lose many more aircraft?" Figure 15 shows how this question might appear on the computer screen. As a bench mark to help staff judge whether events proposed are of sufficient importance, the computer indicates that a loss of 58 aircraft would be sufficient to produce a decision switch.

In this case, the commander is unable to think of any single event that could cause him to lose many more aircraft. Therefore, a similar question based on the outcome variable with second highest ranking, ship losses, is posed (Figure 16). In this case, the commander is able to define an event

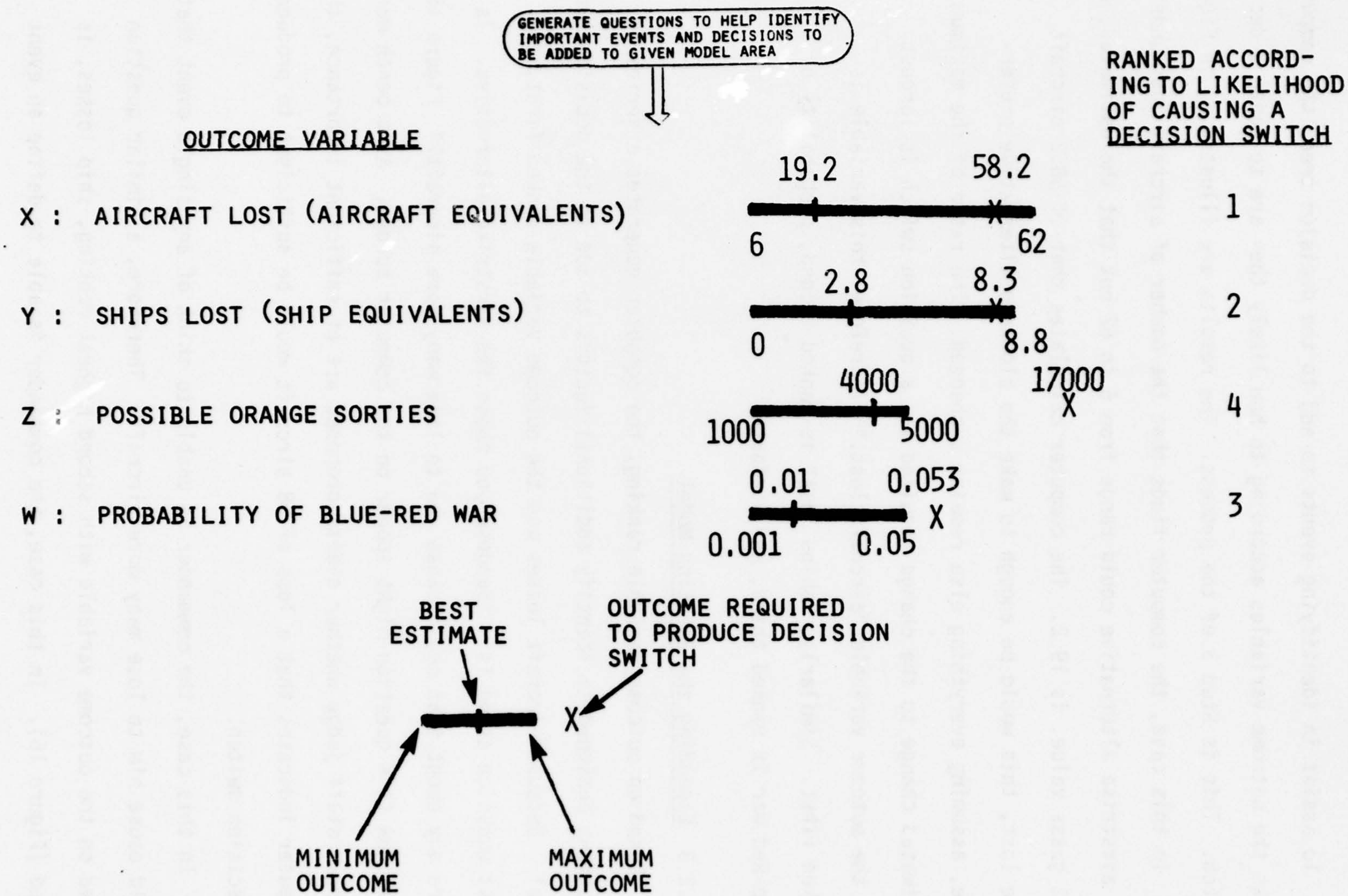


FIGURE 14: OUTCOME VARIABLES RANKED ACCORDING TO LIKELIHOOD OF CAUSING A DECISION SWITCH

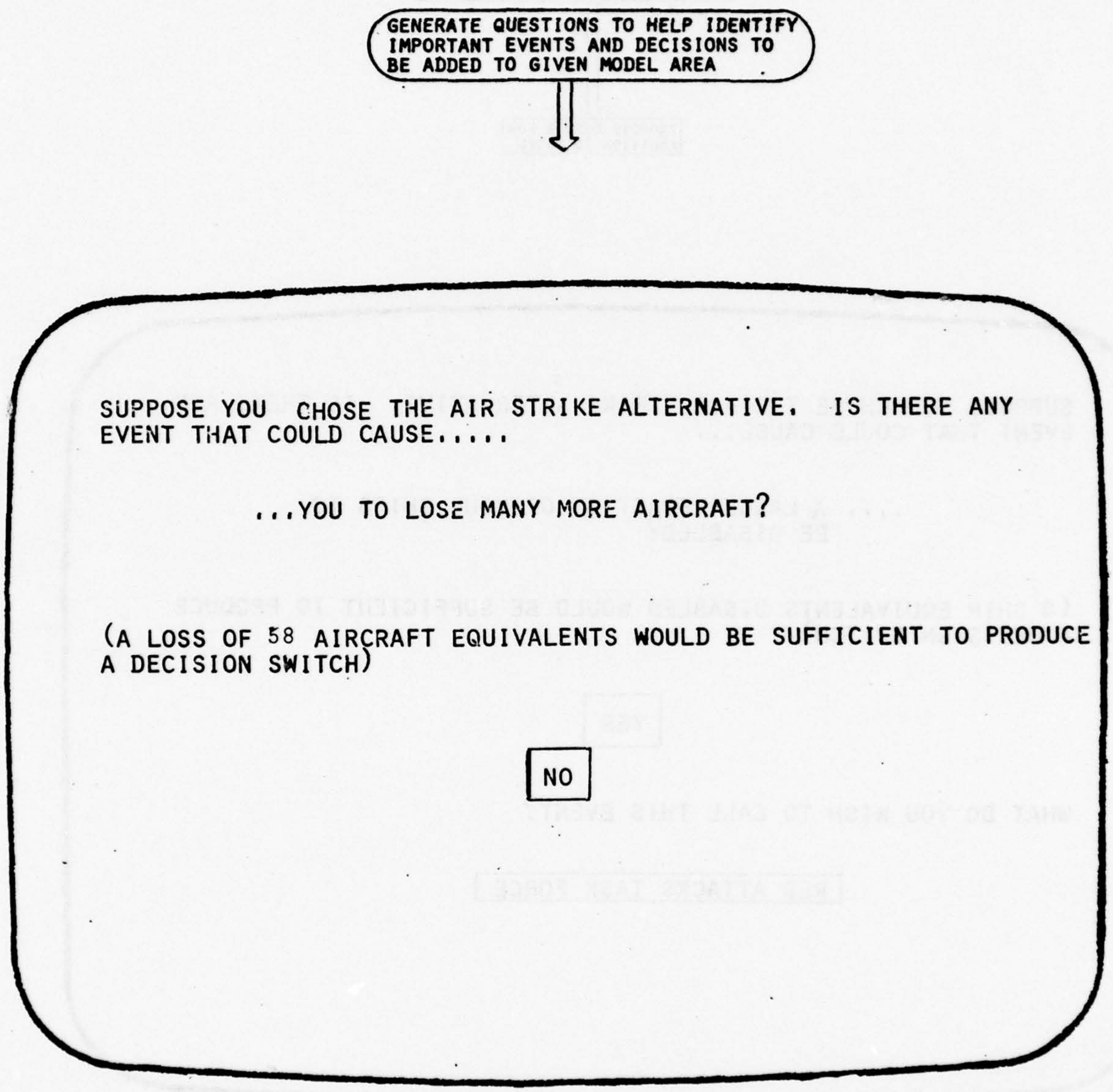


FIGURE 15: FIRST QUESTION DESIGNED TO UNCOVER FACTORS RELEVANT TO DECISION

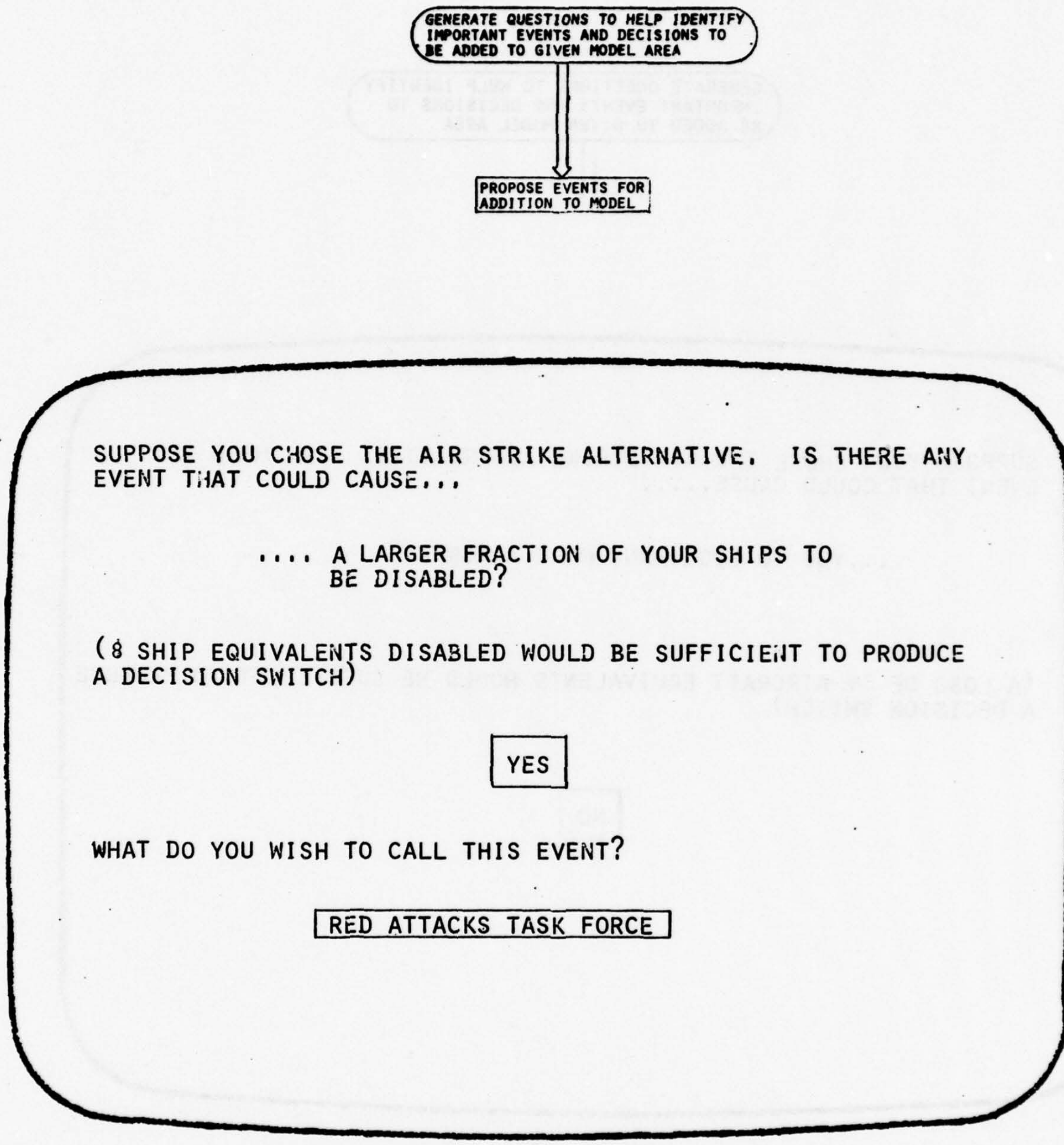


FIGURE 16: SECOND QUESTION DESIGNED TO UNCOVER FACTORS RELEVANT TO DECISION

that could result in the loss of a much larger number of ships, and that event is "Red attacks the task force."

Now that a potential event for addition to the analysis has been identified, the next step, Step 4, is to test whether including that event in the decision tree might affect the decision. The current indication is that the airstrike is the preferred alternative. It would be inefficient to include the possibility of a Red attack in the analysis if there is no chance that it will affect the decision. The first test is to see whether information that the event will occur causes the commander to choose the blockade alternative. This test is illustrated in Figure 17. If the event passes this test (i.e., a "Yes" answer is provided), there is still no reason to add it to the decision model unless the event has both a high enough probability of occurrence and a sufficient effect on outcome to have some chance of changing the decision. Thus, the second test is required to see if the event is sufficiently likely and important. The method described in Step 4 of Section 3.2 is one way of performing this test. The test consists of estimating the outcome that would result if the event were to occur, and then computing the probability the event would have to have for the commander to switch decisions. If, when the worst possible outcomes are estimated, the required probability of the event necessary to cause the decision to switch converges to a value below the estimated probability of the event, then that event should be added to the decision model.

This process is illustrated in Figure 18. The commander estimates the potential damage to his carriers under a Red attack. If this were the only outcome of a Red attack, the probability of attack required to cause a decision switch would be higher than the estimated probability.

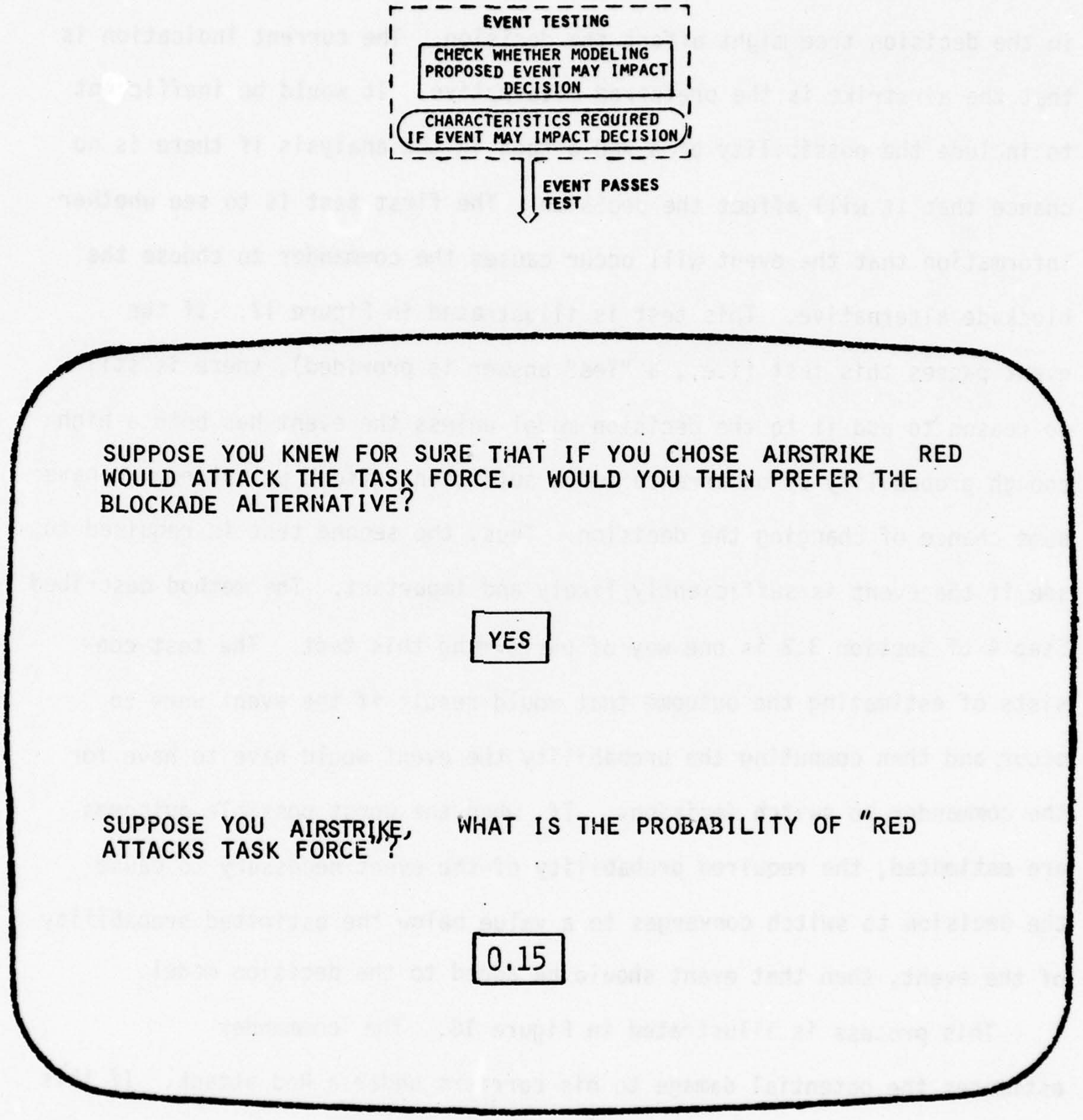
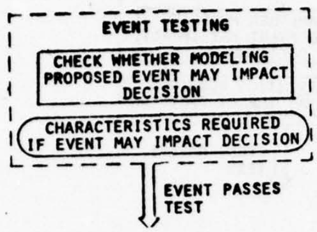


FIGURE 17: PRELIMINARY TESTING OF PROPOSED EVENT

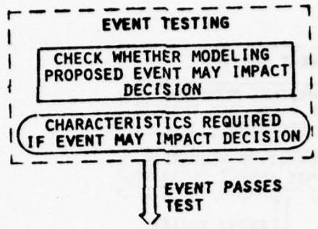


SUPPOSE THE ALTERNATIVE AIR STRIKE IS CHOSEN AND THE EVENT "RED ATTACKS TASK FORCE" OCCURS, WHAT IS THE WORST POSSIBLE OUTCOME YOU MIGHT EXPECT FOR EACH OF THE FOLLOWING?

		WORST POSSIBLE OUTCOME	
		PRIOR ESTIMATE	GIVEN RED ATTACKS TASK FORCE
SHIPS DISABLED	CV	0.5	[1]
	CG	0.5	
PROBABILITY OF BLUE-RED WAR		0.05	
POSSIBLE ORANGE SORTIES		5000	
AIRCRAFT LOST	F-14	8	
	A-6	3	
	A-7	5	

(REQUIRED EVENT PROBABILITY = 0.22)
(ESTIMATED EVENT PROBABILITY = 0.15)

FIGURE 18A: TESTING THE IMPORTANCE OF THE PROPOSED EVENT

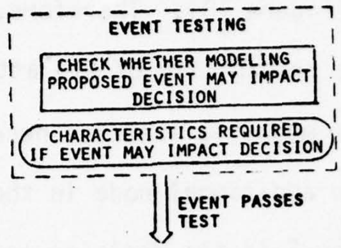


SUPPOSE THE ALTERNATIVE AIR STRIKE IS CHOSEN AND THE EVENT "RED ATTACKS TASK FORCE" OCCURS, WHAT IS THE WORST POSSIBLE OUTCOME YOU MIGHT EXPECT FOR EACH OF THE FOLLOWING?

		WORST POSSIBLE OUTCOME: PRIOR ESTIMATE	WORST POSSIBLE OUTCOME: GIVEN RED ATTACKS TASK FORCE
SHIPS DISABLED	CV	0.5	1
	CG	0.5	[1]
PROBABILITY OF BLUE-RED WAR		0.05	
POSSIBLE ORANGE SORTIES		5000	
AIRCRAFT LOST	F-14	8	
	A-6	3	
	A-7	5	

(REQUIRED EVENT PROBABILITY = 0.20)
(ESTIMATED EVENT PROBABILITY = 0.15)

FIGURE 18B: TESTING THE IMPORTANCE OF THE PROPOSED EVENT (CONTINUED)



SUPPOSE THE ALTERNATIVE AIR STRIKE IS CHOSEN AND THE EVENT "RED ATTACKS TASK FORCE" OCCURS, WHAT IS THE WORST POSSIBLE OUTCOME YOU MIGHT EXPECT FOR EACH OF THE FOLLOWING?

		WORST POSSIBLE OUTCOME	
		PRIOR ESTIMATE	GIVEN RED ATTACKS TASK FORCE
SHIPS DISABLED	CV	0.5	1
	CG	0.5	1
PROBABILITY OF BLUE-RED WAR		0.05	0.05
POSSIBLE ORANGE SORTIES		5000	
AIRCRAFT LOST	F-14	8	
	A-6	3	
	A-7	5	

(REQUIRED EVENT PROBABILITY = 0.15)
(ESTIMATED EVENT PROBABILITY = 0.15)

EVENT MAY IMPACT DECISION

FIGURE 18c: TESTING THE IMPORTANCE OF THE PROPOSED EVENT (CONCLUDED)

It would not be an event of sufficient probability to affect the decision. As additional outcomes are obtained, however, the event begins to look more serious, and probability of attack required for a decision switch approaches the estimated probability. In this example, the event is verified as potentially impacting the decision (Figure 18). Therefore, a decision is made to add to the decision tree the possibility of Red attacking the task force.

Step 5 is to carry out the modeling exercise necessary to represent the event of a Red attack as an additional node in the tree. The process used to conduct Step 5 is the decision analysis modeling process described in SRI's previous report on decision structuring (11). The objective of the modeling exercise is to develop one or more chance nodes to represent the event that is to be added to the tree. To do this, staff works with the commander (or expert designated by the commander to provide the probability estimates for the event) to establish a definition of the event under consideration that is meaningful, complete, and of the appropriate size. Meaningfulness requires that the event be unambiguously defined* and expressed in terms or units that are convenient for the individual providing the assessments. Completeness and appropriate size mean that all possible outcomes to the event are uniquely represented by a small number (2 to 5) of branches emanating from the node.

* A useful test to indicate whether an event is unambiguously defined is to ask whether a clairvoyant could reveal the outcome of the event without requesting additional clarification. For example, "weather conditions at time of attack" is ambiguous because the clairvoyant would need to know the geographical location, time, and date for which the information was requested.

For this example, the detailed modeling exercise was carried out via discussions between the analyst and the individual playing the part of the task force commander. Key results are summarized below:

- The estimated probability of the event of Red attacking the task force in the case of the airstrike alternative was revised from the initial probability of 0.15 to a probability of 0.04 after the event was defined more precisely.
- It was determined that Red might also attack in the case of the blockade alternative. The probability of Red attacking the task force in the case of the blockade alternative was assessed to be 0.01.

The modeling exercise is concluded by obtaining an assessment from the commander of the estimated values and ranges for expected aircraft and ship losses, possible Orange sorties, and the risk of Blue-Red war under the assumption that Red attacks the task force and under the assumption that Red does not attack. With these new outcome estimates, the computer has all the information it needs to expand the decision tree and to compute the value of resolving the remaining outcome uncertainty at each node in the tree (Figure 19). We see that airstrike still has the highest expected value (-39 compared with -62 for the blockade). Therefore, if the analysis were ended now, airstrike would be the recommended alternative. The computer also shows that there is now somewhat less value to resolving remaining outcome uncertainty, but that if additional analysis is conducted it should be devoted to resolving outcome uncertainty in the airstrike alternative (or for the specific case of an airstrike without a Red attack).

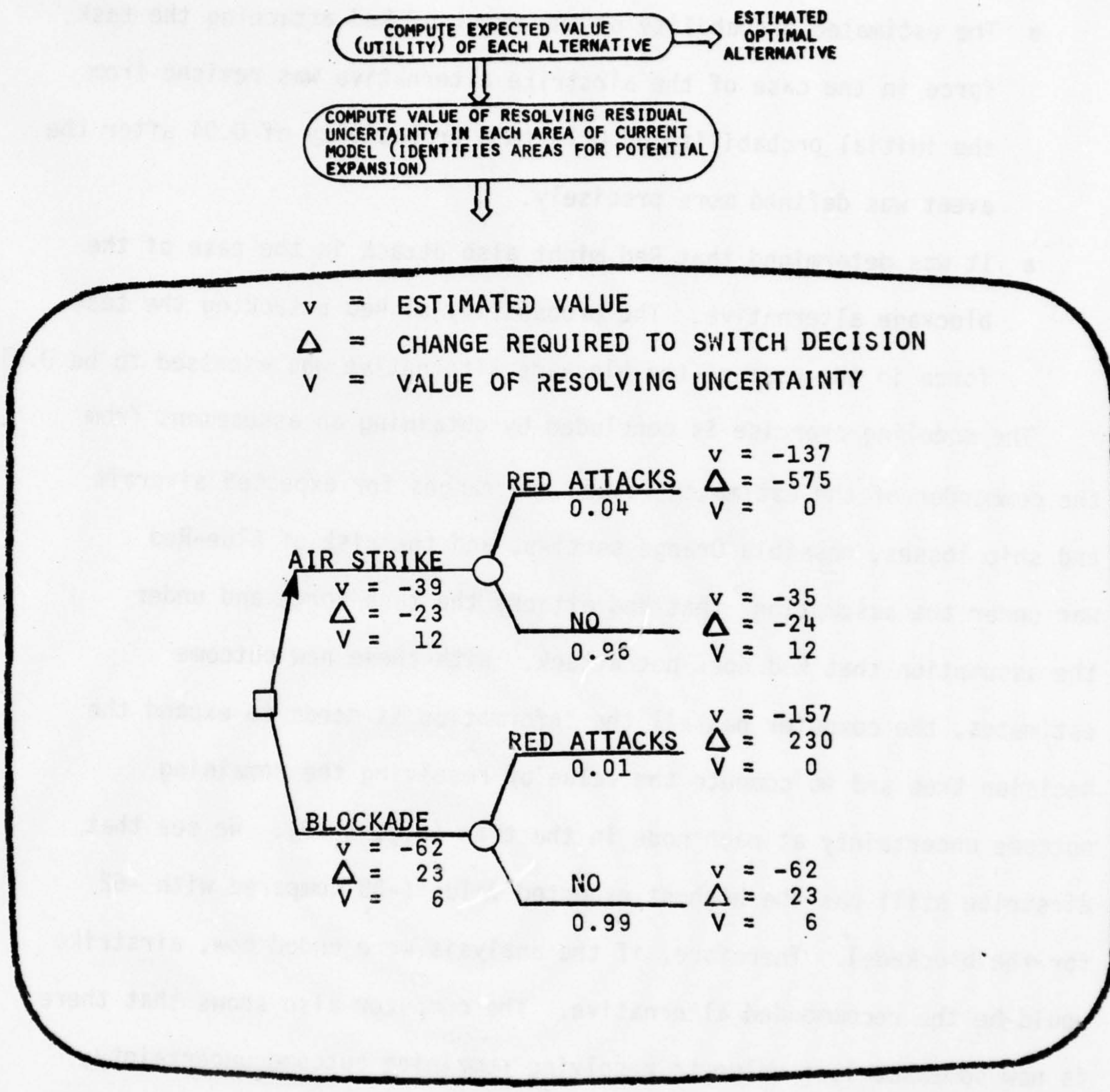


FIGURE 19: EXPANDED DECISION TREE

4.3.2.4 A Second Iteration

Exactly the same process is used to expand the tree further. This time, when we rank the outcome variables according to the likelihood that their uncertainty may cause a decision switch, the risk of Blue-Red war is the variable with highest ranking. Therefore, the computer poses the question shown in Figure 20. When staff asks the decision maker to identify an event that might significantly increase the risk of a Blue-Red war given the airstrike alternative, the possibility of Red landing hospital planes on ONRODA is suggested. It is likely that these planes would be hit during the Blue attack, and this would increase the risk of war. Testing the event of Red hospital planes verifies that it could potentially alter the decision, so the decision tree representation is expanded to include the new event. As this event is being modeled, the alternative of cancelling the airstrike if Red landed hospital planes is proposed. Therefore, this new decision is also added to the tree. The resulting decision tree is shown in Figure 21. As illustrated in Figure 21, the expected values associated with each alternative again show airstrike to be the superior alternative. The analysis also shows relatively low values for resolving the remaining uncertainty. Therefore, the analysis is stopped at this point.

4.4 Summary

The decision tree expansion algorithm is designed to help a decision maker identify the relevant factors influencing a decision. It accomplishes this by using approximate methods to compute the value of resolving uncertainty in various areas of an existing model. The illustrative application to the ONRODA scenario demonstrates how the algorithm could

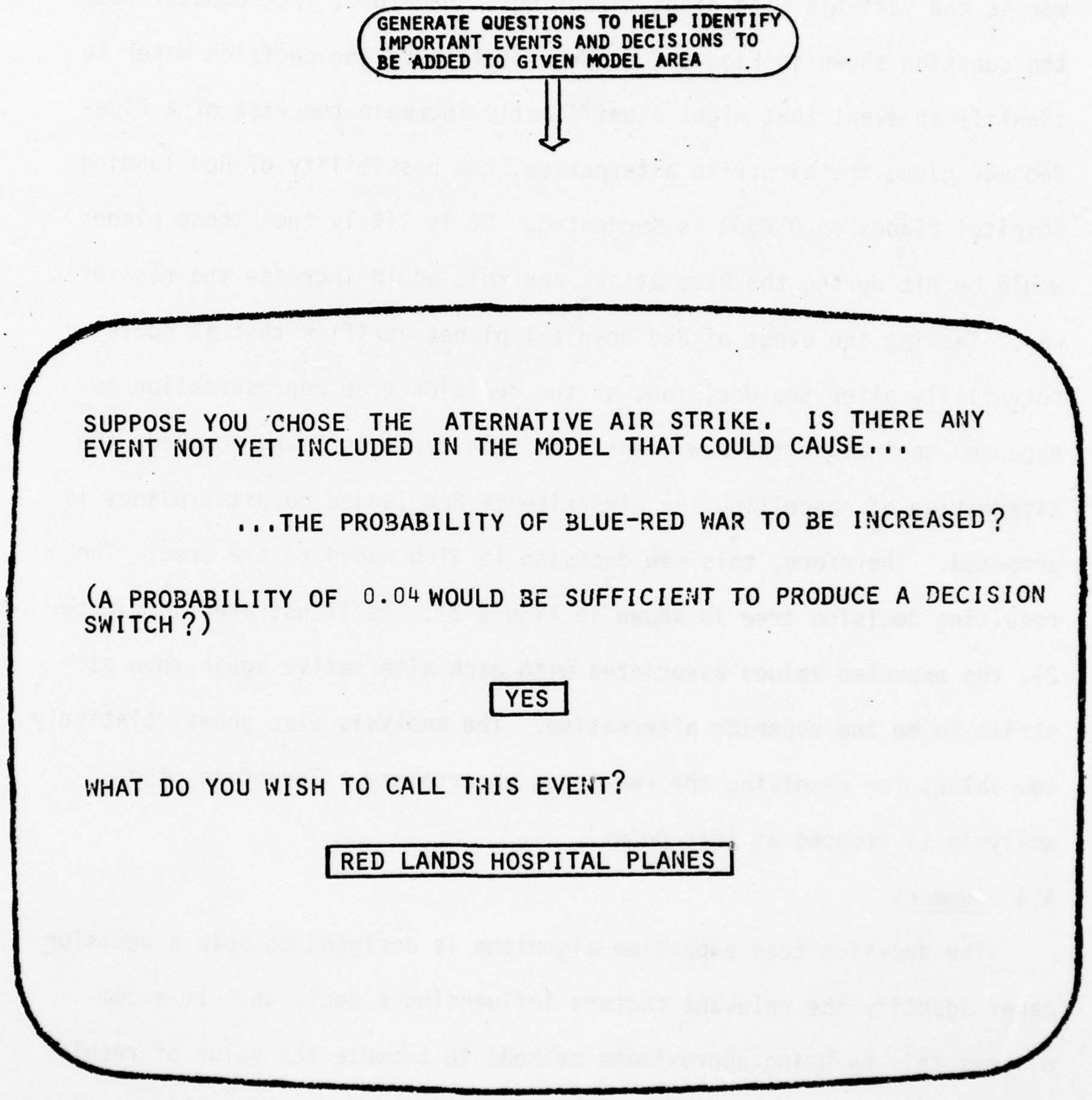
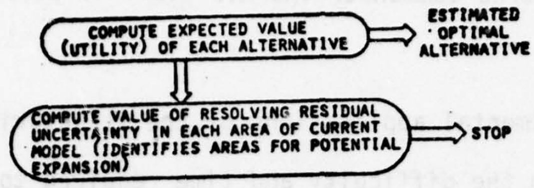


FIGURE 20: QUESTION DESIGNED TO UNCOVER FACTORS RELEVANT TO THE DECISION



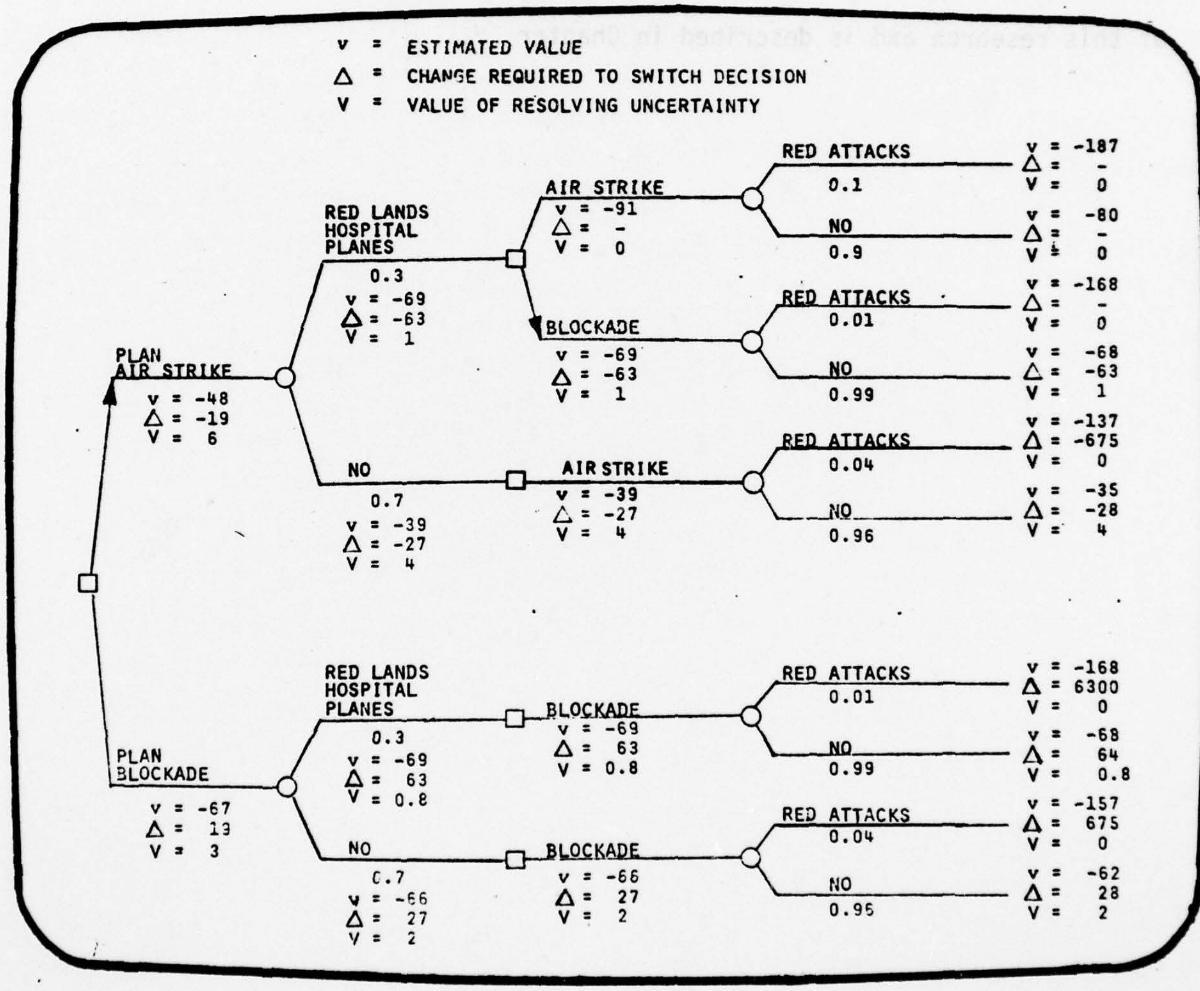


FIGURE 21: FINAL DECISION TREE MODEL

be used by a task force commander and his staff to structure a difficult decision problem.

Actual experimental applications of the structuring algorithm have been limited due to the difficulty and time required to perform the necessary calculations by hand. A computer implementation would greatly facilitate future testing and refinement of the algorithm. A preliminary computer implementation of the structuring algorithm has been accomplished as part of this research and is described in Chapter V.

V COMPUTER IMPLEMENTATION

A computer program for decision structuring has been developed as part of this research project and has been implemented on the ODA Program testbed at the University of Pennsylvania. This program demonstrates the feasibility of a computerized decision structuring aid based on the tree expansion algorithm. Although preliminary, the program implements many of the characteristics ascribed to the system conceptualized in the illustrative example of the last chapter. However, because of its preliminary nature and lack of a refined user interface, the implementation is currently suitable for use only by individuals familiar with computers and with the decision tree expansion algorithm. Further development will be required before it is in a form that may be easily used by untrained Naval personnel. The primary purpose of the program in its existing form is to serve as a mechanism for experimentally investigating the strengths and limitations of the expansion algorithm, but it will also serve as a base for directing future efforts to design and implement a refined user interface.

A short video tape with audio explanation has been prepared of a sample session in which the computer program was used to structure the ONRODA decision described in Chapter IV. This video tape demonstrates the manner in which a user interacts with the program to structure a decision model. The objective of this chapter is to provide an overview of the present status and capabilities of the program. Because it is anticipated that additional work will result in major revisions to the existing computer code, neither a user's manual nor a systems manual explaining the detailed characteristics of the computer program has been prepared.

5.1 Technical Description

The computer program was developed on the Burroughs 6700 computer at SRI International. The language of implementation is APL. This language was chosen to facilitate the development, enhance the interactive features of the code, and provide the necessarily extensive computational capabilities required for the implementation.

5.1.1 User Interface Subsystem

The user interface performs the following functions:

- User prompting
- Response checking, including
  - --Data type
  - --Number of responses
  - --Length of responses
  - --Domain checking
- Collecting and filing of user responses.

The user interface subsystem is designed to allow easy alteration of prompts and includes a separate prompt definition and editing system that allows the segregation of prompting messages from the actual program code. Reprompting in the event of inappropriate responses is automatic.

An important feature of the user interface subsystem that will simplify testing of the algorithm is an automatic prompt adjustment feature. Seven prompting formats are available:

- Yes/no questions
- Choose from a list of possible answers
- Fill in the blanks with alphabetic data
- Fill in the blanks with numeric data
- Respond with a character string of specified or unspecified length
- Print a message

The prompts are assigned levels according to their length and detail. The subsystems track the number of times each prompt has been viewed by the user. As the user becomes accustomed to a prompt, the prompt is automatically more concise. Once a prompt has been viewed three times, the level is decreased by one. This results in a simpler, shorter prompt message with the same meaning. Use of the more concise prompt streamlines the interactions between the computer and user and results in a more natural form of communication. At all times the user may override the automatic prompt adjustment feature in order to raise or lower the level of a prompt (or all prompts) at his or her discretion. This allows the user to adjust the prompting system to fit the needs of specific assessment situations.

5.1.2 <u>Tree Representation and Manipulation Subsystem</u>

Representation and manipulation of decision trees are handled by this second subsystem. The tree structure is represented via an automated numbering of the nodes in the decision tree. The structure is then stored in a matrix; that is, each branch of the tree under construction is held in a column consisting of the predecessor-successor pair. Functions that manipulate the tree are written in a recursive manner which facilitates calculation of rollback values, optimal decision policies, and probability distributions over outcome values associated with the optimal policy. External (user) reference to nodes in the tree is by a name (40 characters or less) or a shortened mnemonic reference (6 characters or less) that is defined by the user. Expansion or contraction of the tree is efficiently performed by operations that insert, delete, dip, or reproduce branches in the evolving tree structure.

5.1.3 Computational and Probability Distribution Fitting Subsystem

This subsystem converts estimated outcomes and ranges elicited from the decision maker into continuous probability distributions on outcome value. The system utilizes a curve-fitting technique based on a specialized set of piecewise cubic, positive polynomials. This method was chosen after other methods, such as spline and histogram techniques and expansion in terms of independent basis functions, were tried and found to be unacceptable. The subsystem also has functions for computing the moments and conditional moments of the fitted distributions and for combining independent distributions on terminal nodes to produce the distributions on rollback values for interior nodes.

5.2 Capabilities

In its present form, the computer implementation of the tree expansion algorithm already performs many of the functions desired of the fully developed system. Routines have been designed to estimate outcomes, calculate delta, determine the value of modeling, rank outcomes, inquire and verify the existence of new events that impact the decision model, and, finally, to extend the decision model to include these new events. The following paragraphs briefly describe the capabilities of the present computer implementation in each of these areas.

5.2.1 Estimation of Outcomes and Values

The outcome estimation routine is designed to produce an estimate of the minimum, estimated, and maximum value of the scenario associated with each terminal node of the decision tree. The routine accepts worst, estimated, and best case outcomes for each component of the outcome vector associated with each terminal node. A value function that is specified by the user as part of the initialization of the program is then used to convert outcome estimates to minimum, estimated, and maximum values.

5.2.2 Calculation of Delta

The delta associated with any node in the decision tree is the total value change at that node necessary to cause a switch in the recommended decision. Routines in the computer program calculate delta recursively from Equation 1 and the estimated expected values of the alternatives at the initial decision node.

5.2.3 Calculation of the Value of Modeling

For each node in the decision tree, the computer program calculates a value of modeling that represents the expected value of resolving the uncertainty in outcome value at that node. The uncertainty in rollback value at each terminal node in the tree is obtained by fitting probability distributions to the minimum, estimated, and maximum values associated with the node. Uncertainty in the rollback values at interior nodes is computed assuming probabilistic independence. Equations 2 and 3 are then used to obtain the value of resolving rollback value uncertainty.

5.2.4 Outcome Ranking

Once a node in the decision tree has been identified for investigation, outcome variables are ranked according to Equation 4. Thus, the outcome variable with highest ranking is such that resolution of its uncertainty at that node in the tree is most likely to produce a switch in the recommended decision.

5.2.5 Event Inquiry and Testing

Once the outcomes have been ranked, the inquiry routine in the computer program generates questions designed to prompt the identification of an event that could cause the outcome change needed to switch the initial decision. If the user cannot think of such an event for the highest ranked outcome, another question is generated based on the outcome variable with the next highest ranking. This is repeated until an event is identified.

After an event is identified, it must be verified potentially to impact the decision before it is modeled. This procedure involves asking the question, "Suppose you knew for sure that the event occurred, would you prefer another alternative?" If the answer is yes, the user is asked to estimate the probability of the event. If the node is on a path leading from the current optimal (nonoptimal) decision, worst (best) possible outcomes are assessed until the probability required for a decision switch is lower than or equal to the estimated probability. At this point, an alert is flashed on the screen, and the user is instructed to add the event as an additional node to the decision tree.

5.2.6 Modeling New Events and Decisions

The modeling routine currently has four functions that it can perform: adding a node to the tree, deleting a node from the tree, editing a node to make changes in the tree, or redefining a terminal node and continuing the tree without making any revisions in the structure. Editing allows for the possibility of revising probability estimates.

5.3 Limitations

The major limitation of the current computer implementation of the structuring aid is the lack of a refined user interface. The displays currently employed in the operation of the aid could be improved to reduce significantly data collection time and to improve information content.

In the current implementation, inputing the outcome assessments required for the algorithm takes considerable time. The user must type into the terminal worst, estimated, and best case numerical values for each outcome variable for each terminal node in the decision tree. Graphical techniques, such as use of a light pen on a cathode ray tube screen, would allow outcome ranges to be indicated with greater speed.

A noticeable difference between the current form of the computer aid and that envisioned in Chapter IV is the format in which the decision tree is displayed to the user. Currently, the decision tree that is constructed is indicated to the user in an abbreviated, symbolic form. It would be preferable to display the tree in standard format as a sequence of decisions and events that are revealed over time. Additional software must be developed to accomplish this. The value, however, is that the standard format is more easily interpreted by the user.

A serious problem that has not yet been addressed in the design of the computer aid is limited display space. Because of the limited display area available, video output must be designed to contain only essential information. Additional development of the computer program must solve the problem of what information should be displayed to the user when the model being developed expands beyond the limits of the video screen.

VI AREAS FOR FURTHER RESEARCH

Before the computer-assisted decision structuring process described in this report is ready for extensive experimental testing by Navy personnel, a number of improvements must be made to the computer program and to the structuring algorithm that makes use of this program. This section of the report briefly discusses additional research necessary to complete the development of the computer-assisted structuring process.

One of the most pressing needs for further development of the tree expansion algorithm is to complete the computer implementation of the current version of the algorithm to place it in a form that is suitable for preliminary testing and evaluation. As described in the previous chapter, the additional development needed is primarily refinement of the user interface. To date we have used the expansion algorithm in informal tests by carrying out the necessary calculations manually. This process is very time consuming and makes it impossible to conduct realistic evaluation of the usefulness of the algorithm for structuring. Manual computations also give little insight into the type of user interface that would be desirable for an automated system. Now that the necessary calculations are implemented in the computer program, further experimentation and refinement of the expansion algorithm will be facilitated greatly.

The next set of tests of the expansion algorithm should use an improved version of the computer program with a simplified user interface. This testing should be conducted using a variety of decisions from hypothetical Navy task force decisions taken, for example, from the ONRODA

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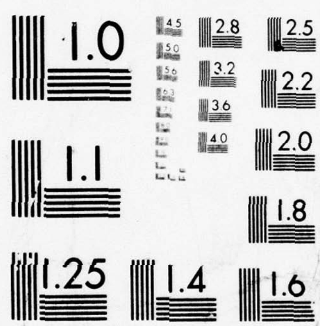

MICROCOPY RESOLUTION TEST CHART

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scenario. The experiments should be conducted with a variety of decision makers with different levels of experience and training in decision analysis. Because the decision aid is still in the developmental stage, it is probably not necessary or desirable at this time to teach a large number of Navy officers how to use the aid and then use them as experimental subjects. However, as the design of the aid is refined and a suitable user interface is developed, it may be desirable to have one or two individuals with experience in task force decision making experiment with the aid and comment on its usefulness in a task force environment. This round of testing should show us where further development is necessary, give us an indication of the feasibility of using an automated structuring aid given the equipment currently envisioned to support Navy task force decision making, and provide a guide for the relative amount of emphasis that should be placed on human intuition and computer-based algorithms.

Further testing and refinement of the expansion algorithm will enable us to strike the critical balance between theoretical completeness and the amount of time and effort required to use the aid. The algorithm for expanding a decision structure incorporates a number of approximations and assumptions. The acceptability of these assumptions depends on both the effect they have on the results of the analysis and the extent to which they simplify the use of the aid. We need to try the aid on a variety of representative problems to see whether the assumptions should be modified, expanded, or eliminated. Once experiments have indicated the appropriate level of approximation in the structuring process, we can redirect further development efforts accordingly.

It is doubtful that the expansion algorithm as it is now defined will be entirely suitable for the needs of task force commanders. The limited attempts that have been conducted to use the algorithm to structure various decision problems have pointed out areas where further development would be useful. For instance, the current version of the algorithm includes some questionable assumptions about the dependencies that exist among variables already included in the structure and variables under consideration for addition to the model. It would be desirable to find ways to give the user more control over the dependency assumptions, allowing him to substitute his own assumptions where necessary. Another area that appears likely to benefit from further development is the current procedure used to elicit the user's uncertainty about the outcomes associated with various possible scenarios. Although this assessment is limited to central values and ranges, it is still a time-consuming process. It may be possible to develop procedures that limit these assessments to only the most relevant scenarios or outcomes. Improvements such as these need to be both theoretically consistent with the underlying logic of the expansion algorithm and experimentally verified using an automated version of the algorithm.

It is clear that there are other aspects of the structuring process that are not currently captured by the algorithm for decision tree expansion described in this report, even though expansion may be the most important element of decision structuring. Furthermore, a review of the structuring procedure used intuitively by a decision analyst indicates that the boundaries between the various stages of decision structuring (identification of alternatives, preliminary value modeling, defining a preliminary decision structure, and expanding or contracting that structure) are not always well defined. In practice, decision analysts appear to move back and forth among the various elements of the structuring process -- especially between the processes of model expansion and contraction -- many times during the course of structuring a decision problem. This behavior indicates the importance of linking the expansion algorithm described in this report to other procedures capable of supporting other components of the structuring process, especially with procedures for defining a preliminary decision structure based on the user's intuition and a procedure for contracting a decision model.

Another area that deserves study is the tailoring of the structuring process to meet the varying needs and decision-making styles of potential users. At times a commander may wish to modify the structuring process because he finds it undesirable or impossible to explicitly perform certain structuring functions. For example, it is conceivable that in certain situations a commander may be reluctant to specify explicitly a value tradeoff function. The modular design of the structuring aid should be maintained to permit the development of shortcut structuring procedures that eliminate one or more of the structuring functions, yet still provide the commander with useful information.

Further work on decision structuring could lead to an automated aid that places either more or less reliance on the intuition of the task force commander or the members of his staff performing the analysis than the aid described in this report. In fact, the structuring aid that evolves from this work may be designed to allow the user to specify the amount of assistance he would like the aid to provide, ranging from a complete prompting system that leads him through the structuring process to an abbreviated set of calculations that leaves most of the structuring to his intuition. The structuring aid described in this report may evolve into a set of related aids dealing with the various elements of the structuring process, depending on the extent to which experiments show a need for automated aids in these areas.

Appendix

PROOF OF THE VALUE OF MODELING THEOREM

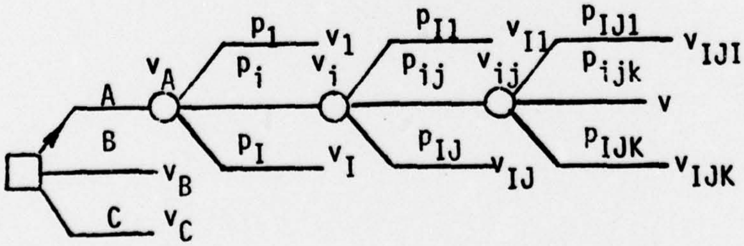
This appendix provides a proof of the value of modeling theorem referred to in Chapter III. To prove the theorem, we initially assume that the probability tree consists of a single decision node followed by probability nodes. Later we will show that including sequential decision nodes leads to the same conclusions.

<u>Theorem</u>

Let

v be the current rollback value of the node under consideration, and let v^* be the (uncertain) rollback value which would be computed for the node following expansion of the decision tree.

Delta (Δ) be the amount by which the node value would have to change to cause a switch in the current best initial decision. Further, let p_a be the path probability from the initial decision to the node with value v calculated as the product of the probabilities along the path,



$$p_a = (p_i)\,(p_{ij})\,(p_{ijk}).$$

Case 1: Node is along the path leading from the current best initial decision.

If $m = E[v^* | v^* \leq v + \Delta]$

and $P = \text{Prob}[v^* \leq v + \Delta]$,

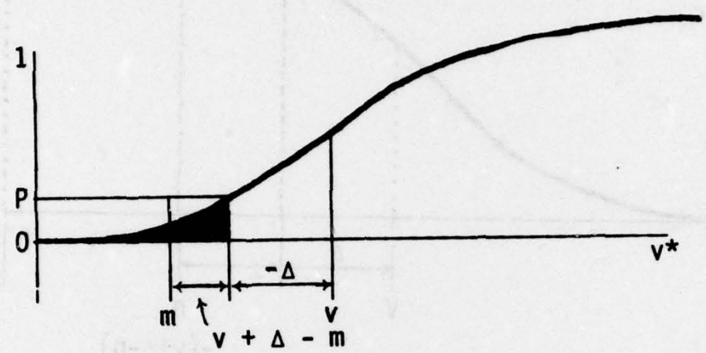


Figure A.1: Cumulative Distribution on Rollback Value Showing Quantities Used to Compute Value of Modeling for a Node Along a Path from the Current Best Decision

then the expected value of resolving uncertainty on v^* is

$$P\, p_a\, (v + \Delta - m).$$

Figure A.1 shows a graphical interpretation.

Case 2: V is not along the path leading from the current best initial decision.

If $Q = \text{Prob}[v^* > v + \Delta]$

and $n = E[v^* | v^* > v + \Delta]$

then the expected value of resolving uncertainty in v^* is

$$Q \cdot p_a \cdot (v + \Delta - n).$$

Figure A.2 shows a graphical interpretation.

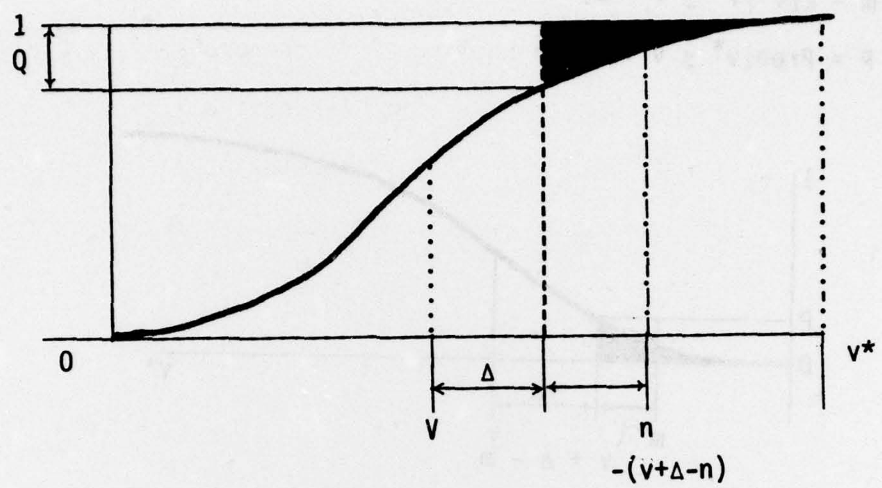
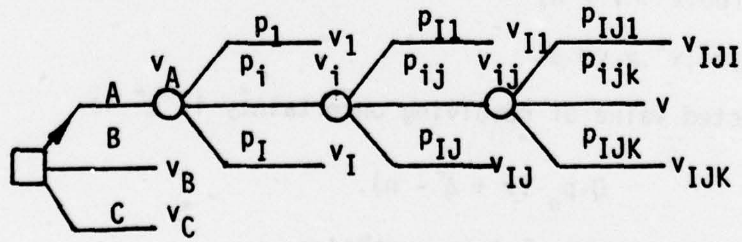


Figure A.2: Cumulative Distribution on Rollback Value Showing Quantities Used to Compute Value of Modeling for a Node Not Along a Path from the Current Best Decision

Proof: Let v_A be the rollback value of the current best initial decision (indicated by an arrow), v_B be the rollback value of the current second-best initial decision, and v_C be the rollback value of an alternative other than the current best initial decision.

Case 1: v is along the path leading from current best initial decision.



Expected Value of Resolving Uncertainty on v^*	=	EVRU	=	expected decision value knowing v^*	$- v_A$

The expected decision value knowing v^* is the probability that $v^* > (v+\Delta)$ times the expected value of alternative A given $v^* > (v+\Delta)$ plus the probability that $v^* \leq (v+\Delta)$ times the expected value of the current second-best initial decision. Thus, letting v_A^* denote the value of Alternative A,

$$\text{EVRU} = (1-P)\ E[v_A^* | v^* > v + \Delta] + Pv_B - v_A.$$

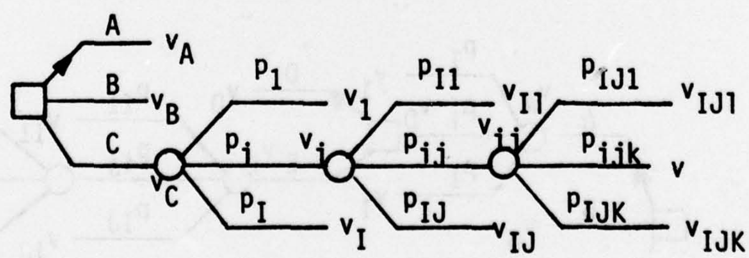
Since $v_A^* = v_A + p_a(v^* - v)$, this may be expressed as

$$\text{EVRU} = (1-P)\{v_A + p_a(E[v^*|v^* > v+\Delta] - v\} + Pv_B - v_A.$$

Using the relation $(1-P)\ E[v^*|v^* > v + \Delta] + Pm = v$

$$\begin{aligned}\text{EVRU} &= v_A - p_a v - Pv_A + Pp_a v + p_a v - Pp_a m + Pv_B - v_A \\ &= Pp_a(v-m) + P(v_B - v_A) \\ &= Pp_a(v + \Delta - m).\end{aligned}$$

Case 2: v is not along the path leading from the current best initial decision



Expected Value of Resolving Uncertainty on V	=	EVRU	=	expected decision value knowing v^*	-	v_A .

The expected decision value knowing v^* is the probability that $v^*>(v+\Delta)$ times the expected value of alternative C given $v^*>(v+\Delta)$ plus the probability that $v^*\leq(v+\Delta)$ times the expected value of the current best initial decision. Letting v_C^* denote the value of alternative C,

$$\text{EVRU} = Q\, E[v_C^* | v^*>v+\Delta] + (1-Q)v_A - v_A .$$

Substituting $v_C^* = v_C + p_a)v^*-v)$,

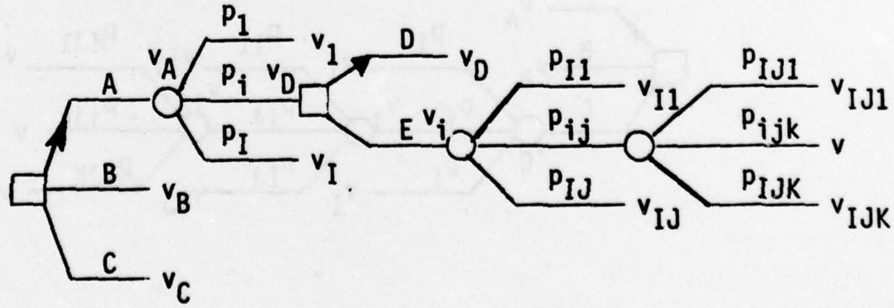
$$\text{EVRU} = Q\{v_C + p_a(E[v^*|v^*>v+\Delta]-v)\} + (1-Q)v_A - v_A .$$

By definition, $n = E[v^*|v^*>v+\Delta]$, so

$$\begin{aligned}\text{EVRU} &= Qv_C + Qp_a n - Qp_a v + v_A - Qv_A - v_A \\ &= Q[v_C - v_A + p_a(n-v)] \\ &= Qp_a(v + \Delta - n).\end{aligned}$$

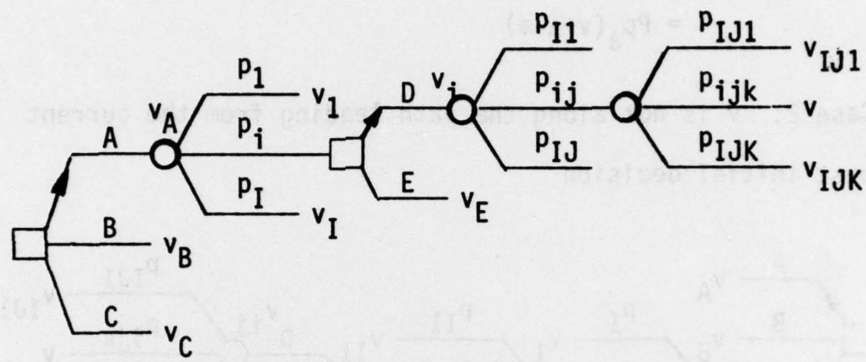
Now we relax the assumption of a single decision to show that including sequential decision nodes leads to the same conclusions.

<u>Proof</u>: <u>Case 1a</u>: v is along the path leading from the current best initial decision, but off the optimal strategy.



In this case there is no delta that would switch the decision because, no matter how much v is decreased, alternative D will be preferred and the value of alternative A will remain v_A.

<u>Case 1b</u>: v is along the path leading from the current best initial decision



In this case, if

$$p_i(v_i - v_E) \leq v_A - v_B$$

there is no delta that would switch the decision.

If

$$p_i(v_i - v_E) > v_A - v_B$$

then using

$$v_A^* = v_A + p_a(v^* - v)$$

Expected Value of Resolving Uncertainty on v = EVRU = expected decision value knowing v^* − v_A

$$= (1-P)E[v_A^* | v^* > v + \Delta] + Pv_B - v_A$$

$$= (1-P)v_A + (1-P)p_a E[v_A^* | v^* > v+\Delta]$$

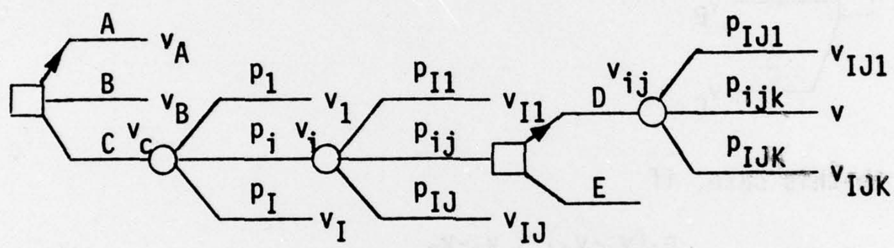
$$- (1-P)p_a v + Pv_B - v_A$$

$$= v_A - Pv_A + p_a v - Pp_a m - p_a v + Pp_a v$$

$$+ Pv_B - v_A$$

$$= Pp_a(v+\Delta-m)$$

Case 2: v is not along the path leading from the current best initial decision



With $v_c^* = v_C + p_a(v^*-v)$, then

Expected Value of Resolving Uncertainty on v = EVRU = expected decision value knowing v^* - v_A

$$= QE[v_C^* | v^* > v+\Delta] + (1-Q)v_A - v_A$$

$$= Qv_c + Qp_a n - Qp_a v - Qv_A$$

$$= -Qp_a(v+\Delta-n).$$

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