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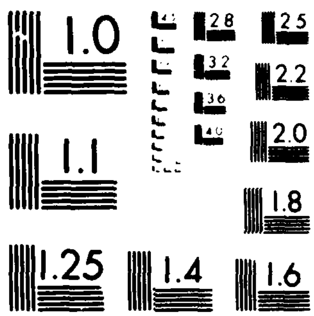

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OPERATIONAL DECISION AIDS: THE APPLICATION OF NOMOGRAPHY AND UNCERTAINTY ANALYSIS TO DECISION-AIDING SYSTEMS

S. Epstein
M. Strieb
R. Goldman
F. Glenn
R. Wherry

Analytics
2500 Maryland Road
Willow Grove, Pa. 19090

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Prepared for:
Mathematical and Information Sciences Division
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

ANALYTICS
2500 MARYLAND ROAD, WILLOW GROVE, PA. 19090

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This report describes analyses performed and conclusions obtained in applying nomography and uncertainty analyses to decision aiding systems. The models described here have been implemented for test and evaluation in the University of Pennsylvania ODA test facility.

Nomography is the art or science of constructing graphs that enable a dependent variable to be determined by the use of ortholinear projections

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given the values of one or more independent variables. Uncertainty is any imprecision in knowledge resulting from causes such as inaccuracy, lack of validity, or bias in the inputs to a decision.

The analysis focuses on the specific decision problem of air strike delay in the context of the ONRODA strike warfare scenario. The baseline approach from which study embarked is reported in Decision Analysis as an Element in an Operational Decision Aiding System (DDI Technical Report 75-13 for ONR, AD-A018109). While developed in a specific framework, the conclusions, methodology, and models are applicable to the broad class of decision problems which requires selection of the best time to initiate a specified action. With modification, the approach can be applied to the multiple-choice decision problem.

This is a report of work accomplished on one task in the project entitled, Operational Decision Aids, which was initiated in 1974 by the Office of Naval Research to develop aids for Navy command and control functions and make them available for incorporation in the design of future systems such as the Task Force Command Center (TFCC).

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I. INTRODUCTION

1.1 BACKGROUND

The Operational Decision Aids (ODA) project is sponsoring development of automated decision-aiding methodologies for introduction into the fleet. Many approaches and applicable technologies are being investigated, resulting in the development of decision aids which can be broadly divided into two classes: state models and outcome calculators. Analytics is addressing a subject which transcends this dichotomy; namely:

(1) How can nomograph-derived display techniques be employed to aid in presentation of results?

(2) How can uncertainty in inputs and modeled processes be best reflected in presentation of results?

In order to lead to practical results subject to test and evaluation, the effort has been directed at a particular class of decision problems, and within that class, at a specific problem. The results of this effort should nonetheless be interpreted for the broader range of decision problems to which they apply.

One possible classification of decision problems is:

(1) Those that require the selection of the "best" action to take at a specified time (also called multiple-choice problems).

(2) Those that require the "best" time at which to take a specified action.

Many other classifications are possible; however, it is relevant to note that, using this particular classification, the first area has received heavy attention both in the literature and the ODA project, while the second has received virtually none. Additionally, many military decisions specifically address the question of when to act. Consequently, our efforts have focused on this area.

Within this class of decision problems, we have concentrated on the question, "When is the best time to launch an air strike?" This problem has received some attention as noted in "Decision Analysis as an Element in an Operational Decision Aiding System" (Reference 1). The structure presented there serves as the foundation of our efforts. For purposes of demonstration and evaluation, a specific situation in the ONRODA strike warfare scenario, "ONRODA Strike Warfare Scenarios" (Reference 2), has been used. Figure 1 graphically depicts the decision situation employed in our implementation.

It is important to note that the methodology that Analytics has developed is applicable to other "when-to-act" decisions such as when to launch an amphibious assault, when to resupply a ship, and when to transit an ocean area. With

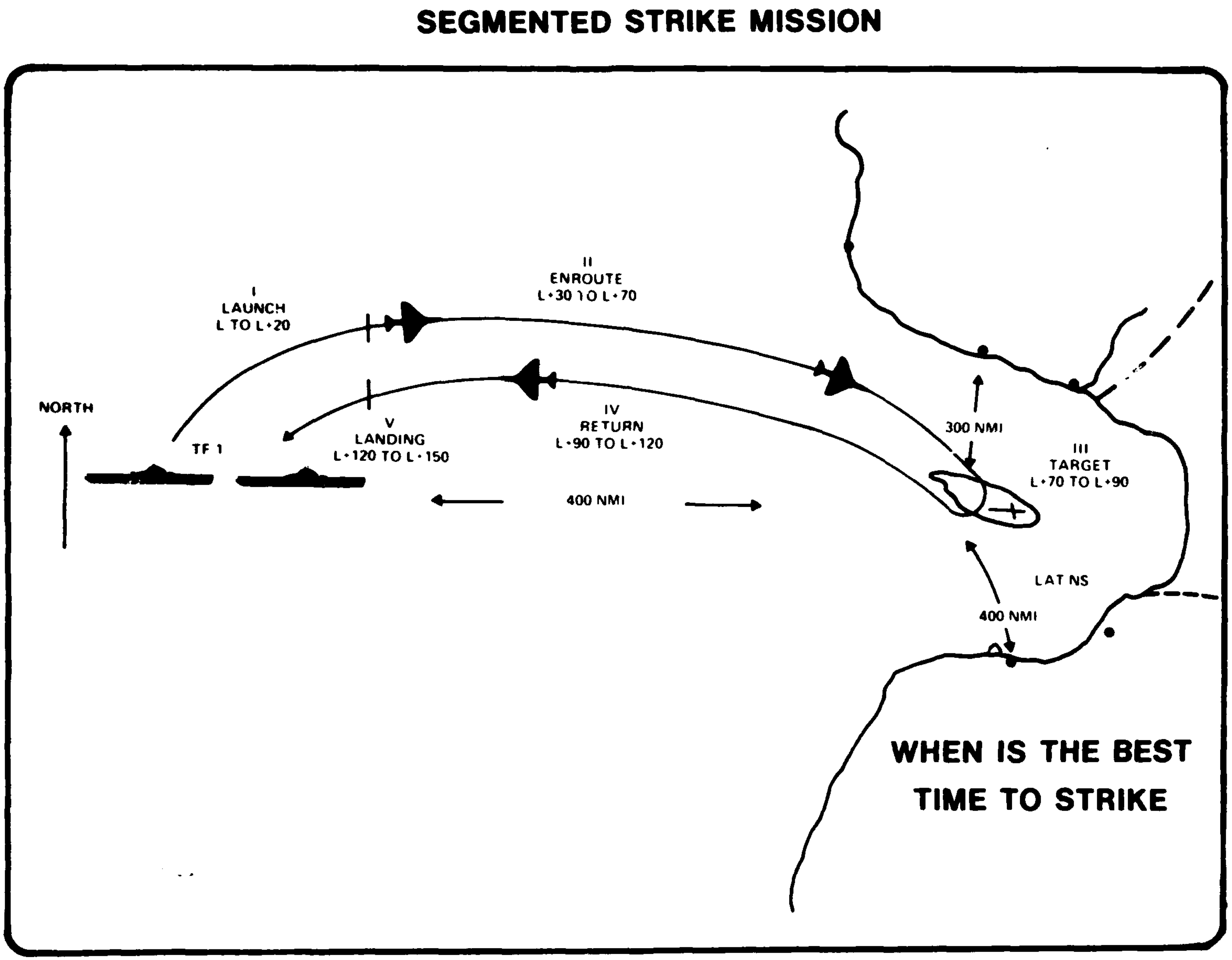


Figure 1. Implemented Decision Situation

modification, it can also be applied to conventional multiple-choice decision problems (choose the "best" action to take at a specified time), and is very appropriate to those types of problems in which the alternatives are time extensive (as in an air strike).

1.2 FEATURES OF THE DECISION AID

A decision problem can be described by a set of alternatives, criteria, conditioning elements, and a decision algorithm. These terms are defined as follows:

- Alternatives -- Available decision options from which a selection is to be made.
- Criteria -- Value measures upon which a selection is based.
- Conditioning Elements -- The inputs and assumptions about the conditions in the real world.
- Decision Algorithm -- Procedure that defines how to proceed from input to selection.

The nomograph decision aid allows for an unlimited number of alternatives, criteria, and conditioning elements. Furthermore, the conditioning elements can be continuous (e.g., range, altitude, or readiness), discrete (e.g., weather state, sea state, or enemy intent), or any combination of discrete and continuous. The value of a conditioning element can be expressed with a statement of uncertainty (e.g., circular error probable, variance, or standard error). Uncertainty is imprecise knowledge of the real world resulting from causes such as bias in a sensor, inaccuracy, estimation error, or any other phenomenon that manifests itself in imprecise knowledge of the real world.

The aid explicitly treats decisions that result in an action that unfolds over a time period during which the values of the conditioning elements vary. Thus, the aid specifically deals with time-varying statistics which are derived from conditioning elements defined as a function of time.

Additionally, the nomograph decision aid allows the user to define a time-dependent function that is used to discount the expected utilities achieved as the result of the occurrence of particular outcomes at particular times. This recognizes that there may be time constraints associated with meeting tactical objectives that must be factored into the algorithm to obtain a realistic evaluation of the alternative courses of action.

Finally, and most critically, the aid provides sufficient outputs and sensitivity analysis tools to allow the individual decision maker to explore his own risk/reward preferences and to confirm or refute the aid's "judgment." Specifically, the outputs allow use of various decision strategies such as maximum expected value, min-max, above threshold, etc.

1.3 STRUCTURE OF DECISION AID

The nomograph decision aid has been developed in the specific context of the ONRODA strike warfare scenario (Appendix A). It addresses a segmented mission (see Figure 1) consisting of five phases: (I) launch, (II) enroute to target, (III) over target, (IV) return, and (V) landing. Each phase is assigned a relative start time and completion time; these times are used by the algorithms for proper selection of time-dependent conditioning elements used in the computations.

The conditioning elements used are both continuous and discrete; some are applicable only in a single mission segment, while others affect two or more segments of the mission. The conditioning elements used in the current implementation are shown in Table 1.

TABLE 1. CONDITIONING ELEMENTS

NAME	ACRONYM	SEGMENTS AFFECTED
OWN FORCE READINESS (3 Aircraft Types)	OFR	ALL
ENEMY AIR DEFENSE	EAD	II, III, IV
ENEMY GROUND DEFENSE	EGD	III
WEATHER AT TARGET	WAT	III
WEATHER AT CARRIER	WAC	V

Two criteria with associated weighting factors are incorporated in the algorithm: target destruction (aircraft and ground defenses) and own force losses (aircraft and crew, both killed and damaged).

As noted earlier, Analytics' work transcends the distinction between state and outcome calculator approaches by incorporating two algorithms, one based upon each approach and designated as the state and outcome models, respectively. Both algorithms fit into the same formulation of the nomograph decision aid (see Figure 2), using the same inputs and providing the same outputs.

Both algorithms provide expected utility and a spread of realizable values (due to uncertainty in the value of conditioning elements and in variations in underlying processes) for each possible launch time. Additionally, the outcome calculation provides own force losses in numbers of aircraft on a mission segment basis. Furthermore, it can provide target destruction achieved in numbers of enemy assets destroyed.

Each algorithm is supplemented by a sensitivity analysis procedure which yields outputs as a function of any one of the conditioning elements varied independently.

Particularly with regard to the outcome model, the use of an abstract measure, such as utility, supplements specific physical achievements by providing a multi-attribute trade-off among achievements according to each separate criterion. Other common scales, such as equivalent units or money, could be used to effect the presentation of a single measure of merit to the decision maker.

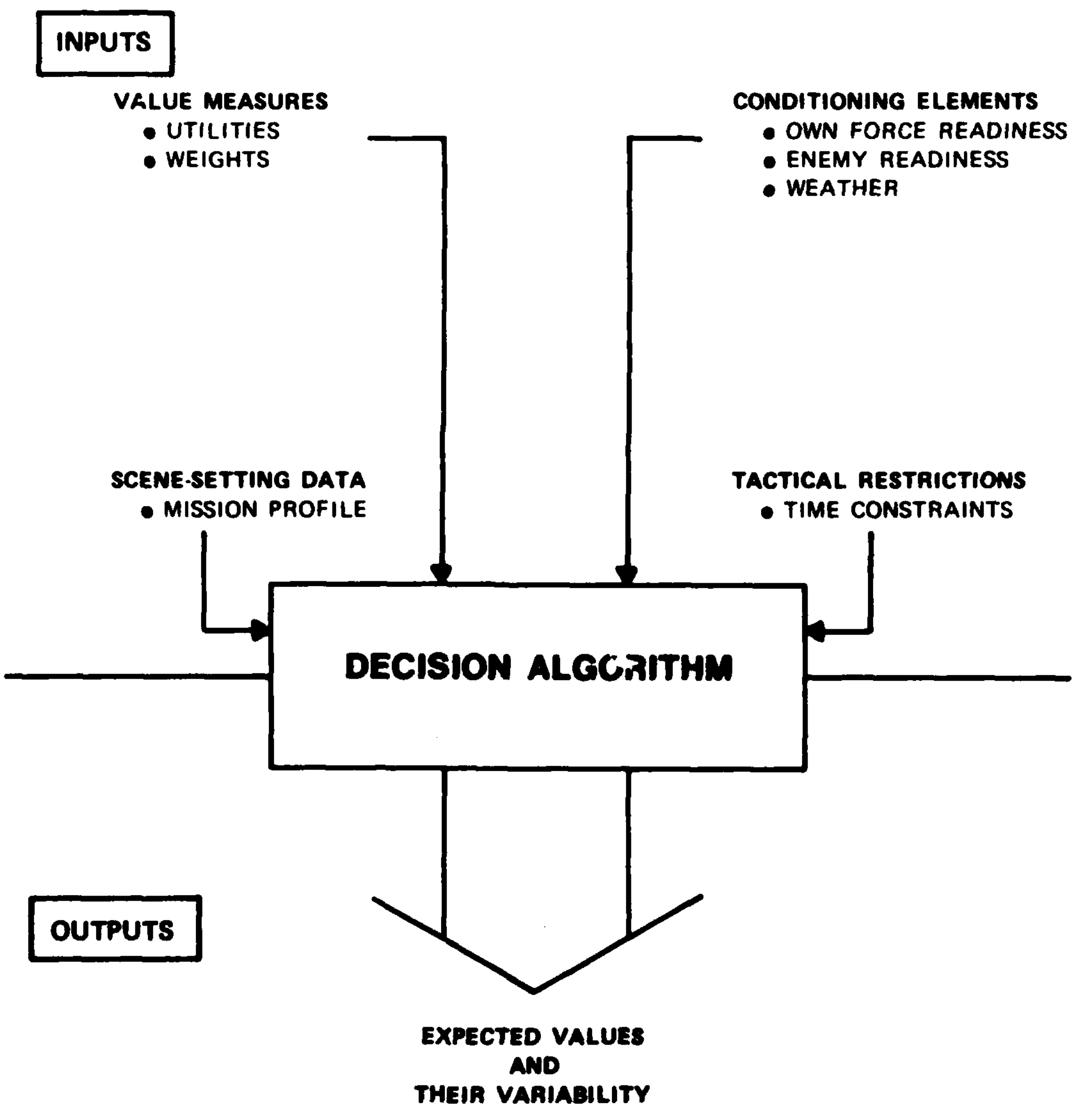


Figure 2. Nomograph Decision Aid Formulation

1.4 GRAPHICAL FEATURES

The nomograph decision aid has been implemented to take advantage of paired alphanumeric and graphical displays available in the test facility. Each tabular data entry display is complemented by a color display that presents the data graphically. The decision aid outputs and sensitivity analyses are presented in color nomographs. Finally, the attrition outputs of the outcome calculator are presented in a multi-quadrant color nomograph, useful for examination of "what if" questions. Plates 1 through 15 give examples of the input and output graphic displays.

Many of the displays provided in the aid are intended for use by those staff officers (other than the decision maker) who provide inputs to the system. Other displays (those showing results and sensitivity analyses) are directed at the decision maker. It is envisioned that the decision maker would have access to the graphical displays (e.g., Plate 11) used by his staff to examine the inputs to the model if he so chooses; however, the tabular displays provided to enter inputs are not expected to be used by the decision maker.

Several graphic displays have been designed to take specific advantage of the color display capabilities available in the test bed, while other displays (though in color) have been designed for equal interpretability in a black and white presentation. In particular, color has been used primarily as a discriminant, allowing a significant amount of information to be shown in one display where a monochromatic presentation would require several displays (or one display composed of several sub-displays). Alternate black and white formulations can readily be achieved, opening the door to a cost benefit analysis of color versus black and white in this particular situation.

1.5 SUMMARY

The aid has been developed and implemented to incorporate significant capabilities in dealing with uncertainty in the decision process and to apply state-of-the-art graphical display techniques. No limitations are placed on the number of alternatives, criteria, and conditioning elements that can be accommodated. Further, any restriction on the form of the conditioning elements has been removed by incorporating the ability to deal with both continuous and discrete cases -- the discrete conditioning elements having any arbitrary number of states.

The developed methodology has been shown to be compatible with both state and outcome calculator algorithms. At the same time, our work has shown that the outcome calculator approach has some significant advantages:

(1) It is able to output physically meaningful results.

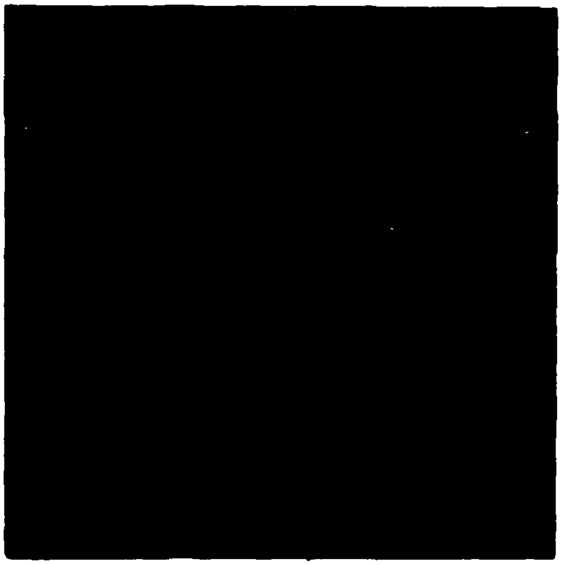
(2) It is more easily adapted to specific situations and generalized to other decision problems.

(3) It allows the decision problem to be treated without certain oversimplifications required to make the state model tractable.

However, it is also recognized that for those decisions where development of an outcome calculator is beyond our present knowledge, the state model can provide a logical and organized approach to attacking the problem, where there would otherwise be a void.

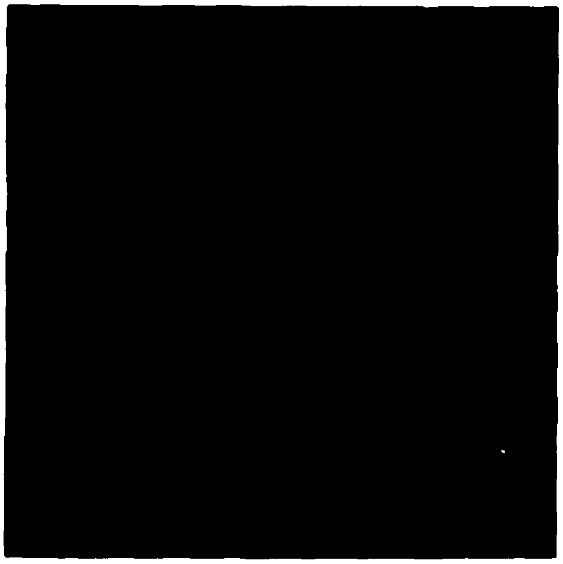
As implemented, the system provides the opportunity for a wide variety of tests directed at presentation alternatives,

PLATE 1.



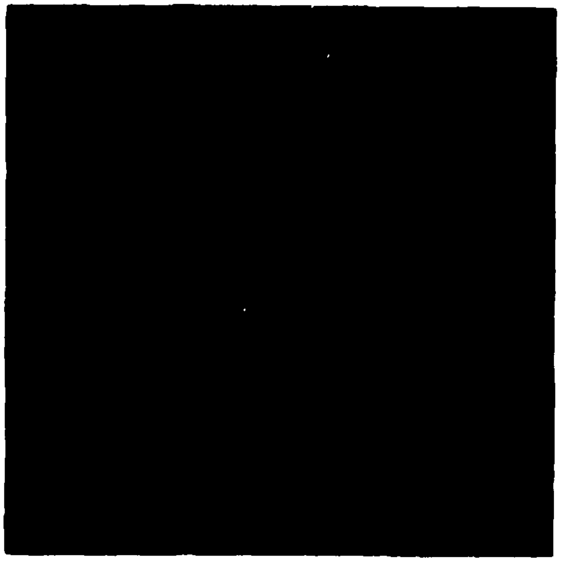
UTILITY VS. TIME — STATE MODEL

PLATE 2.



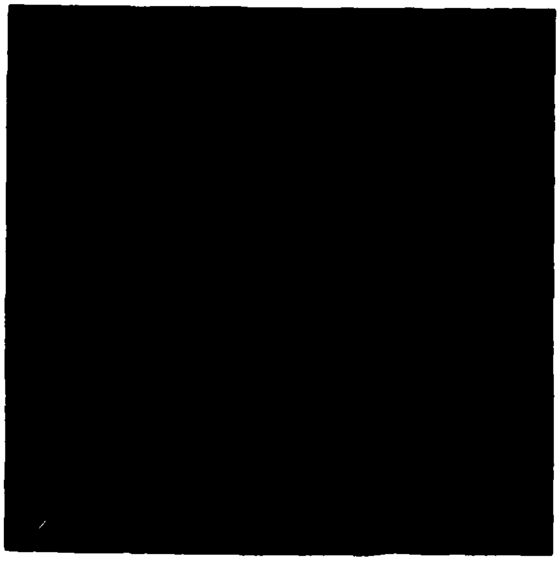
UTILITY VS. TIME — OUTCOME MODEL

PLATE 3.



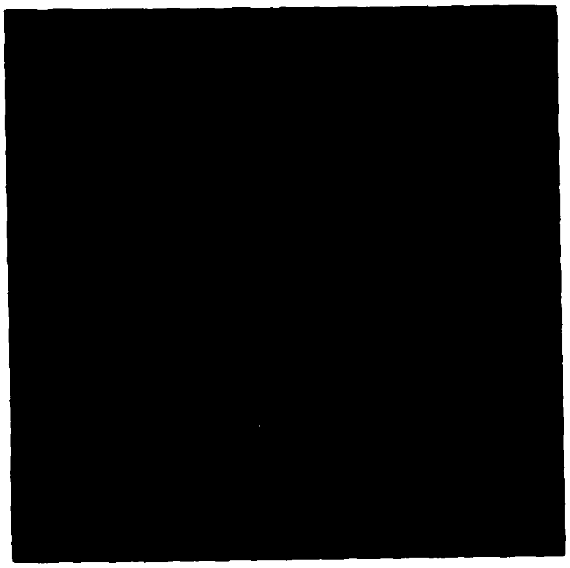
THE LOSS NOMOGRAPH

PLATE 4.



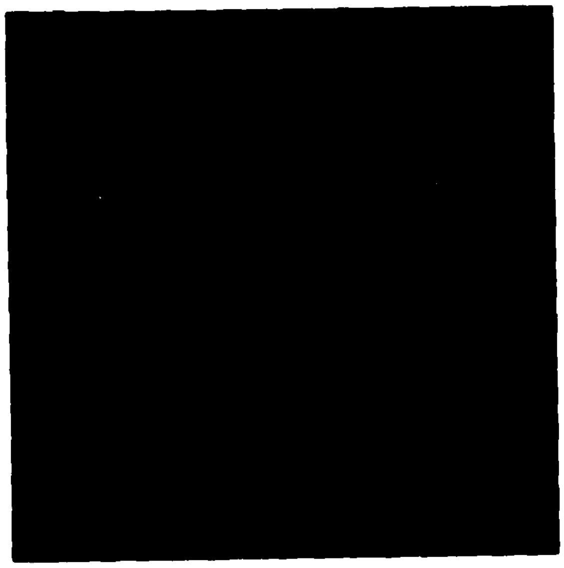
AIRCRAFT LOSSES BY SEGMENT

PLATE 5.



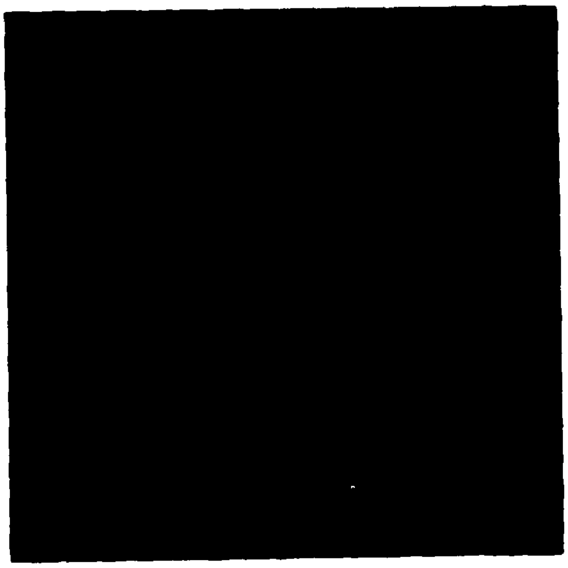
A-6 SENSITIVITY ANALYSIS

PLATE 6.



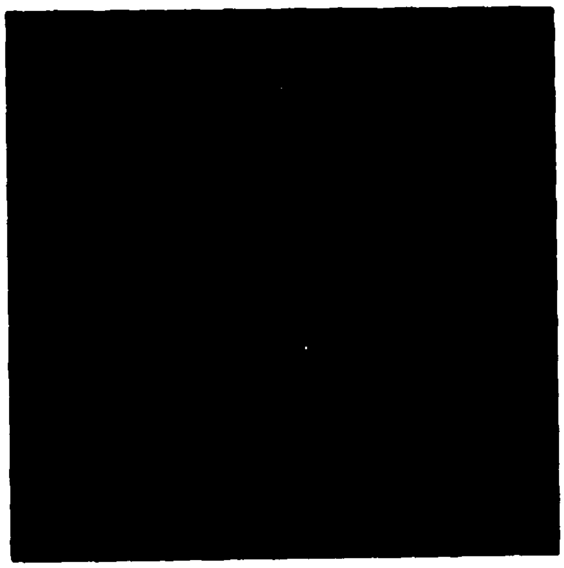
A-7 SENSITIVITY ANALYSIS

PLATE 7.



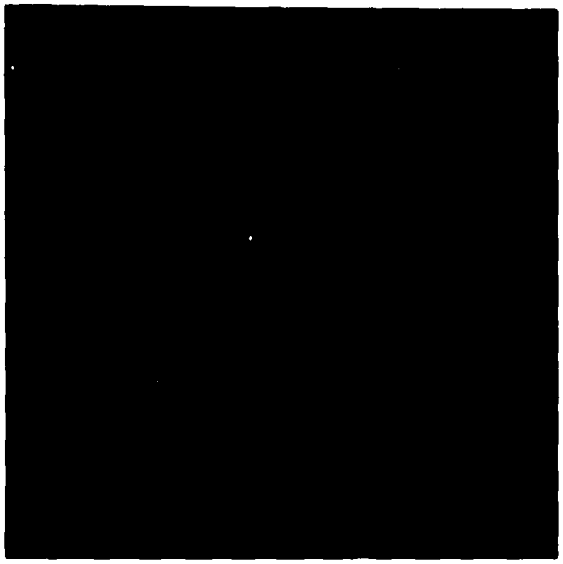
F-14 SENSITIVITY ANALYSIS

PLATE 8.



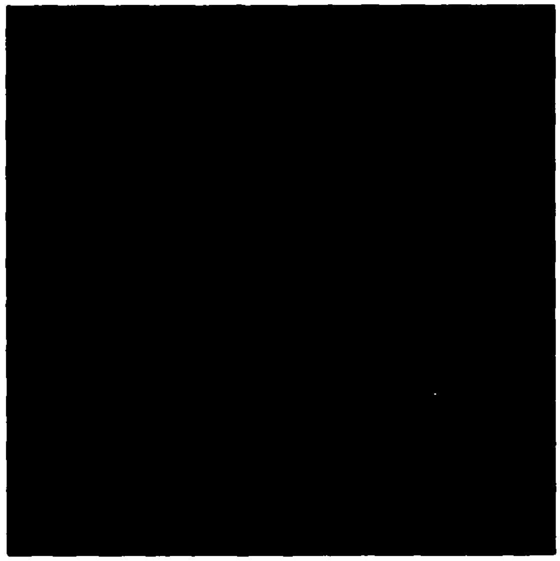
EAD SENSITIVITY ANALYSIS

PLATE 9.



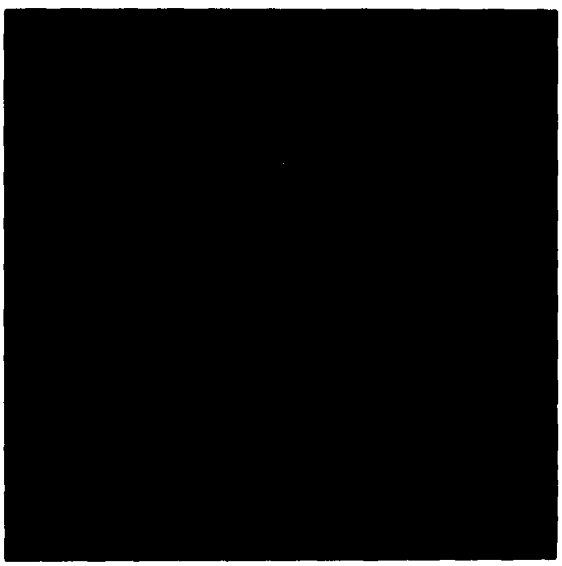
WAT SENSITIVITY ANALYSIS

PLATE 10.



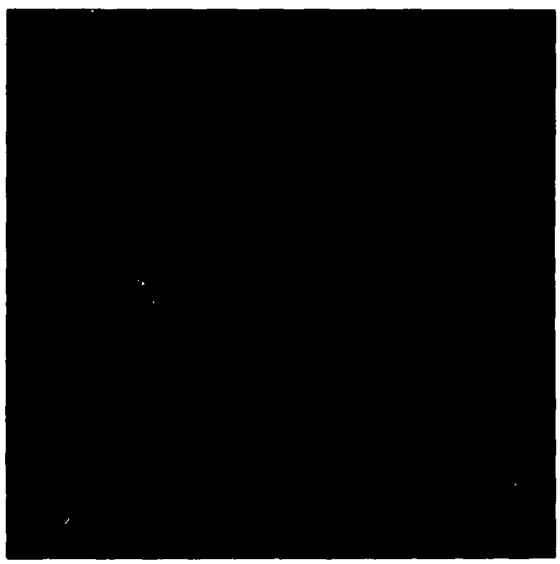
WAC SENSITIVITY ANALYSIS

PLATE 11.



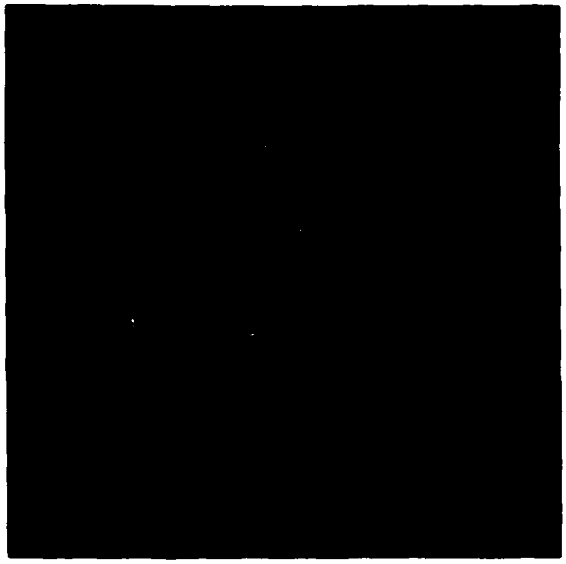
OFR INPUT DISPLAY

PLATE 12.



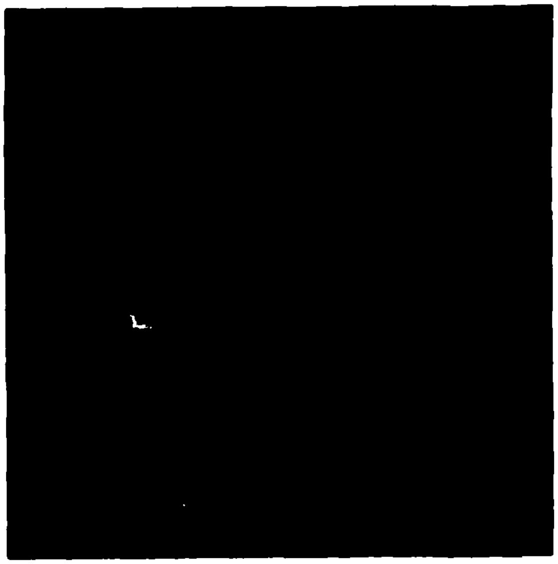
EAD INPUT DISPLAY

PLATE 13.



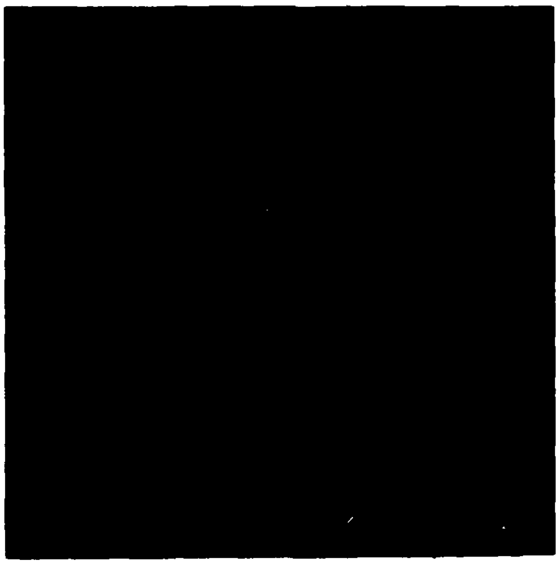
EGD INPUT DISPLAY

PLATE 14.



WAT INPUT DISPLAY

PLATE 15.



WAC INPUT DISPLAY

classes of algorithms, and display methodologies. The ground has been broken to examine the applicability of the aid to practical Naval decision situations and, as a consequence, its cost-effectiveness as a multi-purpose tool to the Navy of the future.

II. THEORETIC FOUNDATION AND PRINCIPLES OF APPLICATION

2.1 INTRODUCTION

Before applying nomograph techniques to and incorporating uncertainty features in decision aiding systems, the general structure of decision models was studied in order to ensure that the aid that would ultimately be designed would not be unnecessarily limited in application.

The properties of the decision aid described in the DDI Phase III report (Reference 1) and the literature on utility-based decision models was examined. From this examination, certain specific properties required to treat generalized decision problems were derived and incorporated into a generalized utility-based decision model. The model was then restricted to the specific implementation reported here. An outcome calculator analog was developed to test transportability of our concepts.

2.2 DEVELOPING A GENERALIZED STATE-BASED DECISION MODEL

2.2.1 General Formulation of Current Models

Alternatives (as defined in Section I) are denoted as A_i, where i varies from 1 to d. An A_i is selected by maximizing the expected payoff, or utility, associated with it according to specified criteria for evaluation. Criteria are denoted as C_j, where j varies from 1 to c. In the evaluation, criteria potentially have different importance, or weight (W). Thus, associated with each C_j is a W_j, where

$$1 \geq W_j \geq 0 \text{ for } j = 1, \ldots, c$$

and

$$\sum_{1}^{c} W_j = 1$$

The selection of A_i also depends upon the state of the world (observed, hypothesized, guessed, etc.). The state of the world relevant to the decision at hand is defined in terms of conditioning elements, which are denoted by CE_k, where k varies from 1 to ce. Each CE_k is divided into a discrete set of mutually exclusive and exhaustive states. The states of a particular CE_k are denoted $CE_{k,\ell}$, where ℓ may vary from 1 to s.

To each element of a matrix whose rows are specified by A_i and whose columns are specified by C_j and $CE_{k,\ell}$, a utility $U_{ijk\ell}$ is assigned (Figure 3).

		STATES			
		S_1	S_2	...	S_{ss}
VALUE OF CONDITIONING ELEMENTS THAT DEFINE EACH STATE	CE_1	$CE_{1,1}$			
	CE_2	$CE_{2,1}$			
	⋮	⋮		...	
	CE_k	$CE_{k,1}$			
	⋮	⋮			
	CE_{ce}	$CE_{ce,1}$			
ALTERNATIVES	A_1	U_{11}		...	
	A_2	U_{21}			
	⋮	⋮			
	A_i	U_{i1}		...	
	⋮	⋮			
	A_d	U_{d1}			

CRITERIA	C_j
WEIGHT	W_j

Figure 3. The Value Table

This matrix of alternatives and utilities is a value table (VT). The most general form of a VT is one in which each column is defined by every CE_k and the U's are assigned with implicit combination of criteria and weights; this generalization obviates the limitation of allowing only a weighted sum across criteria. DDI did not use this approach, nor will Analytics; the user burden and reduced flexibility in altering weights outweighs the nicety of generality. Within this constraint, the most general form of a VT is one in which one column is defined by every CE_k for each C_j.

Figure 3 summarizes the family of VTs in our approach, one for each C_j, where the $\{CE_{k,\ell}\}$ map into states of the world, S_m, with m varying from 1 to ss. Note that the S_m must be exhaustive and mutually exclusive with respect to the $\{CE_{k,\ell}\}$. *This does not imply* the value of ss in any way; however, for the decision to be non-trivial, ss ≥ 2.

To select among the A_i, we must compute the expected utility of each A_i, namely

$$EU(A_i) \equiv EU_i = \sum_m p\ (S_m)\ U_{im}$$

where

$$U_{im} = \sum_j W_j\ U_{ijm}$$

(remembering m defines $\{k,\ell\}$), and select the maximum. To do this, we must know $p(S_m)$.

The $p(S_m)$ may be obtained from the model user, or they may be generated by a simulation or analytic evaluation of the real world.

DDI introduces the likelihood table (LT) to enable computation of the $p(S_m)$. One LT exists for each CE_k. Further, for each state $CE_{k,\ell}$ of that CE_k a prior probability is stated, which is labeled $p_{pr}(CE_{k,\ell})$ such that

$$\sum_{\ell} p_{pr}(CE_{k,\ell}) = 1$$

Next, we construct a set of indicators, I_n, where n varies from 1 to N, and associate with each I_n likelihood ratios that I_n would be observed, given that $CE_{k,\ell}$ obtained. These ratios are used to calculate posterior probabilities of the $CE_{k,\ell}$ which are labeled $p_{po}(CE_{k,\ell})$, also such that

$$\sum_{\ell} p_{po}(CE_{k,\ell}) = 1$$

Indicators are required to be independent so that successive Bayesian updates can be computed validly.

Upon receipt of any I_n, a $\{p_{po}(CE_{k,\ell})\}$ results which combined with all other sets for remaining CE_k produces a $p(S_m)$ for all states. Obviously, if the VTs are segmented for each CE_k, as DDI has done, then partial evaluation of EU_i can be made without completely determining which S_m exists. However, all such partial evaluations must be made before an A_i can be selected.

Clearly, $p(S_m)$ can be computed as the joint probability of all the $CE_{k,\ell}$ that define S_m by multiplying the individual $p(CE_{k,\ell})$ as long as the CE_k are independent. We chose to restrict the formulation to such CE_k even though we can accommodate dependence in either of two ways:

- Knowledge of the covariance.
- Construction of a composite LT or input of a composite $p(CE_{k,\ell}, CE_{k',\ell})$.

2.2.1.1 Making Utility Assignments

For any expected utility model for decision making to be valid, utility must be defined on an interval scale. That such a utility assignment is possible at all is ensured only if some fairly restrictive conditions apply to the preference ordering of the outcomes of the action-state combinations. Such combinations were first described by von Neumann and Morgenstern (Reference 3). Basically, they require that there be not only a fixed preference ordering of the outcomes but also a reasonably continuous ordering of all probability mixtures of the outcomes. (A probability mixture of outcomes A and B refers to the situation where A obtains with some probability p and B obtains with probability 1 - p.) People are never totally consistent with the von Neumann and Morgenstern axioms because they invariably exhibit vacillation in preferences between alternatives for which they are nearly indifferent. This difficulty can be overcome by using a statistical criterion for preference. Still, the axioms tell us only that a utility assignment is possible, not how to make it.

An acceptable utility function must generate utilities whose numerical ordering mirrors the preference ordering of the outcomes. Experimental studies that have attempted to derive utility functions from observations of preferences have mainly been concerned with the monetary value of gambles (e.g., Mosteller and Nogee (Reference 4) and Tversky (Reference 5)), thus simplifying the comparison task of the subject. One interesting exercise in the estimation of utility was reported by Davidson, Suppes, Siegel (Reference 6), using a linear programming model to d rive utilities from stated preferences between musical selections. Although it is interesting to try to apply the linear programming technique to determine utilities, the utility assignments ultimately tend to rely on authoritative subjective estimates. Therefore, it is imperative to demonstrate that the utilities are consistent with preferences between outcomes and, perhaps, even between probability mixtures of outcomes. Wherever inconsistencies are observed, it might be possible to revise the utilities by applying some predefined mathematical operator.

Utility assignments are generally made using a scale spanning 100 units. Often in comparing relative values among decision options, given a state of the world (a column in the table), the "best" value is assigned a value of 0 and all others are assigned negative values up to -100. Thus, each column always has a 0, and relative values within rows have no significance. Such value assignments are termed "regrets" and are used because they are easier to assign than utilities. Each entry represents how much the decision maker would regret the consequence of that decision relative to the best decision under the circumstances depicted by that column. Regrets are derived from true utilities and are relative rather than absolute numbers. Regrets have significance only within a column, e.g., within a single state of the world.

One can derive regrets from utilities, but not vice versa. The ranking of decisions using regrets is the same as if utilities were used, providing that the same probabilities of states are used to evaluate each alternative. This is usually the case, but in time-varying problems, it may not be. Therefore, this restriction must be recognized. If utilities are used, there is no problem in applying time-varying statistics.

2.2.1.2 Combining Value Tables

When a decision is affected by multiple attributes (either criteria or conditioning elements), VTs must be combined to arrive at a composite expected utility. If VTs are constructed separately for each criterion with all conditioning elements being represented in each table, then the general form of the EU calculation can be described as

$$EU_i = \sum_{m=1}^{ss} p(S_m) \left[\sum_{j=1}^{c} W_j \, U_{ijm} \right]$$

In cases where the U_{ijm} are not assigned to all conditioning elements jointly (as is the case in Reference 1), we instead compute

$$EU_i = \sum_{m=1}^{ss} p(S_m) \left[\sum_{j=1}^{c} W_j \left(U_{ijm_1} + U_{ijm_2} + \cdots \right) \right]$$

The principal ground rule for utilities is that they must represent monotonic measures of preferences for the outcomes of decision actions -- bigger is better. Any rules for combining must be consistent with this; in other words, it must not be possible after combination over elements of one case to arrive at a utility value lower than that for a second case in which the preference for the outcome is the same or higher.

2.2.1.3 Time-Dependency

Consider some simple possibilities where the $p(S_m)$ are time-dependent. Mission A has three phases:

(1) Navigate successfully to target.

(2) Destroy target.

(3) Return safely.

Let all elemental utilities be in the range 0 (failure) to 1 (success). As a trial, let the overall utility for the mission be the weighted sum of the individual utilities U_1, U_2, U_3, with weights W_1, W_2, W_3 (assigned 0.25, 0.5, 0.25). For the example, allow only full success or full failure as illustrated below:

UTILITY ASSIGNMENTS

		POSSIBLE OUTCOME COMBINATIONS				
PHASE	WEIGHT	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
1 (enroute)	0.25	0	1	1	1	1
2 (at target)	0.5	0	0	0	1	1
3 (return)	0.25	0	0	1	0	1
Overall		0	0.25	0.5	0.75	1
		mission failure, no survival		mission failure, survival	mission success, no survival	mission success, survival

A fully successful mission in all phases produces a utility equal to 1, and an unsuccessful mission yields:

$$U = (W_1U_1 + W_2U_2 + W_3U_3) = 0$$

The outcomes of Phases 2 and 3 are, however, dependent on earlier phases so that not all combinations are possible.

Successful destruction of the target without returning safely yields a utility of 0.75. But higher utility is assigned to successful navigation to target without target destruction and without returning safely (0.25) than if all phases were unsuccessful (0). While this is arguable, the outcomes are effectively the same and should receive the same utility. The significance is that the assignment of elemental utilities makes sense only if such assignments are associated with entities that are independent in terms of value (rather than probability), such as enemy destruction and survival. Here, weighted sums of utilities have useful interpretations.

Consider another method for combining elemental utilities -- a product rule. We can define $U = U_1 \times U_2 \times U_3$ and obtain the following table of utility assignments:

UTILITY ASSIGNMENTS

	POSSIBLE OUTCOME COMBINATIONS				
PHASE	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
1 (enroute)	0	1	1	1	1
2 (at target)	0	0	0	1	1
3 (return)	0	0	1	0	1
Overall	0	0	0	0	1

If all U_i's are one, $U = 1$ as desired; if any U_i is 0, then $U = 0$. But that gives the same utility if Phase 3 fails whether or not the target is destroyed. It also gives no preference to survival over non-survival if the target is not destroyed.

Other combinations might be conceived, such as a sum whose terms contain some products of elemental utilities, as seen in the following example. Let

$$U = W_{12}U_1U_2 + W_3U_3$$

and assign

$$W_{12} = 0.75$$

$$W_3 = 0.25$$

Then

UTILITY ASSIGNMENTS

	POSSIBLE OUTCOME COMBINATIONS				
PHASE	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
1 (enroute)	0	1	1	1	1
2 (at target)	0	0	0	1	1
3 (return)	0	0	1	0	1
Overall	0	0	0.25	0.75	1.0
	mission failure, no survival		mission failure, survival	mission success, no survival	mission success, survival

or, with $W_{12} = 0.5$; $W_3 = 0.5$, we have

UTILITY ASSIGNMENTS

POSSIBLE OUTCOME COMBINATIONS

PHASE	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
1 (enroute)	0	1	1	1	1
2 (at target)	0	0	0	1	1
3 (return)	0	0	1	0	1
Overall	0	0	0.5	0.5	1.0
	mission failure, no survival		mission failure, survival	mission success, no survival	mission success, survival

Both weighting assignments yield a plausible ordered utility. However, the approach which guarantees preserving preference ordering is one of assigning utilities to the allowable states associated with the various applicable conditioning elements without segmenting by mission phases.

In short, it may be possible to construct consistent and combinable utility functions for mission phases, but the final test is whether the overall values meet the conditions required of utilities. The procedure of separate valuation is not recommended as a general one.

2.2.2 Requirements for a Generalized Formulation

The preceding discussion shows that the dependent properties of sequences of events resulting from the decision to initiate a time-extensive action place certain requirements on a generalized decision procedure. Additional requirements are imposed if the $p(S_m)$ are defined by conditioning elements which are functions of time. These observations, although related, are not identical; furthermore, they apply to <u>any</u> such decision whether of the "best" time or the "best" alternative types, as described in Section I.

There are four different ways that time can enter decision problems:

(1) Decisions which result in time-extensive actions.

(2) Decisions which are truly the same except for the time the action is effected.

(3) Decisions as above except the action must be implemented within a certain range of times.

(4) Decisions for which a choice must be made within a certain time irrespective of when the action is taken.

The last category is dismissed immediately since it applies to the speed of reaching a selection, which can be segregated from the selection optimization in a multi-decision structure.

Decisions which result in time-extensive actions generally depend on CEs which are time-dependent as well. This need not always be the case; however, generality demands the capability to handle such cases. Thus, generally, a CE must be defined as time-extensive. Likewise, definition of an S must include specification of CEs that are time-extensive.

Decisions which are truly the same except for the time the action is implemented also require consideration of time-extensive CEs. If the decisions are truly the same, then in reality only a single alternative is available. If time is isolated as a criterion, then other criteria can be restricted to showing time-independent utilities. Thus, all A_i which truly represent a single alternative can be considered as a single A_i for all criteria except timeliness.

The third class addresses the time domain of interest within which a single predetermined alternative must be selected to optimize EU locally. This construct requires no special treatment other than to recognize that not all $A_i(t)$ may be candidates for selection due to external constraints.

To summarize, a generalized model capable of handling time-extensive/non-time-extensive actions, time-dependent/non-time-dependent parameters, and unlimited numbers of criteria must possess the following properties:

(1) Utilities rather than regrets must be used as the value measure.

(2) Values must be assigned to each alternative for each criterion, but for all conditioning elements specified.

(3) Probabilities of states must be allowed to be time-dependent.

(4) The interdependence of time-sequenced events must be considered in computing $p(S_m)$.

2.3 EXTENSION TO THE GENERALIZED OUTCOME CALCULATOR

Fortunately, the lessons learned in examining state-based models easily extend to outcome calculator models. The last two requirements above simply imply that the outcome calculator must have the capability to treat dynamic variables and must derive inputs to time-sequenced events from outputs of precedent events. The second requirement readily translates to assigning values to outcomes for each criterion. The first requirement stands unchanged.

2.4 APPLICATION OF THE AID TO OTHER PROBLEMS

2.4.1 The State Model

The state model, developed for the decision aid described in the following sections, provides a framework capable of handling any "best time to" decision which involves five conditioning elements, two criteria, six possible times, and twelve states of the world. By changing the input data and the stored data that define the meaning and values of these elements, the decision situation being addressed can be readily changed. Only modest programming changes would be required to vary the number of conditioning elements, criteria, and states.

The use of breakpoints as model inputs in defining subjective terms such as "good," "bad," "superior," etc., provides a ready means to adapt the model to specific aircraft, crew, ordnance, fatigue, morale, etc., capabilities. Analogously, if an amphibious assault were modeled, similar variabilities in asset performance could be accommodated.

Both breakpoints and utilities provide a means to tune the model based on experience, either manually or automatically, by use of an adaptive feedback program such as those considered in other decision aiding studies.

The most severe limitation in generalizing the state model results from maintaining a tractable number of states. This observation is true of <u>all</u> state models.

Extension of the model to multiple-choice decisions, either conventional or time-extensive, can be achieved by providing additional VTs and iterating the final expected utility calculations described in Section 2.2. Significant programming changes would be required in input, algorithm, and display portions of the code.

2.4.2 The Outcome Calculator

Like the state model, the outcome calculator provides a framework capable of similar quantitative and qualitative expansion. The outcome calculator has been implemented as a general transfer function model with the functions represented by stored tables of values. Modification of the transfer functions provide the same flexibility as breakpoint changes in the state model, although their complexity makes the process far more time and thought consuming.

The transfer function tables could easily be generated by static or dynamic use of engagement models specifically suited to the scenario, force mix, environment, and other factors available to the aid. As reported in "Augmentation of the Naval Task Force Decision Aiding System: The Outcome Calculator" (Reference 7), dynamic use of models may be unrealistic in light of the inputs present models require and the cost, in time and money, of using them.

Extension of the outcome model to multiple-choice decisions is far easier than extension of the state model since the internal logic of the model is unaffected; extension is achieved by posing additional VTs to map expected outcomes into composite expected utilities.

2.4.3 Multiple-Choice Extension

To draw an example of the ability to extend the model to multiple-choice problems, let us consider the fairly complex set of alternatives

- Launch
- Prepare to launch
- Wait and examine decision later

with the assumption that preparing to launch requires one hour, and launching cannot take place for one hour after deciding to launch a prepared force (therefore, two hours later for an unprepared force). Let us consider one criterion, namely target destruction, applied to the state model. For simplicity, we presume the states of the world are defined as

- S_1 -- we have superior air power
- S_2 -- We have equal air power
- S_3 -- We have inferior air power

with air power being the only parameter of consequence in our decision.

We now ask for utility assignments (on the 0 to 100 scale) for each combination of A_i and S_m and obtain, for example,

	State		
Alternative	S_1	S_2	S_3
Launch	100	80	40
Prepare to Launch	90	70	30
Wait	60	60	60

Let us suppose we execute the algorithm and obtain the $p(S_m)$ which are necessarily time-dependent with reference to the A_i; for example, the $p(S_m)$ for A_1 are for time now plus 1 hour, for A_2 they are for time now plus 2 hours, and for A_3 they are for time now plus 0 hours (though, for A_3, the utilities are independent of the state that occurs and, hence, are unaffected by the time for which the probabilities are computed).

Applying the proper $p(S_m)$ to the U_{im} using

$$EU_i = \sum_m p(S_m)\, U_{im}$$

we obtain EU_1, EU_2, and EU_3. This allows us to select among A_1, A_2, and A_3 as in a conventional decision situation.

Furthermore, we can, in complete analogy to the present implementation, provide $EU_1(t)$, $EU_2(t)$, and $EU_3(t)$, allowing selection of the maximum $EU_i(t_j)$ -- the best action and the best time.

III. SELECTION OF GRAPHIC DESIGN

3.1 NOMOGRAPHY

Nomography is the art or science of constructing graphs that enable a user to determine the value of a dependent variable from the value(s) of one or more independent variables by use of an ortholinear projection. For the purposes of this discussion, a nomograph will be understood to be a CRT graphical display which presents to the decision maker information that relates the values of the inputs to a decision algorithm to the values of the outputs of the algorithm. It, thus, allows the decision maker to examine the relationship between input and output, to study the sensitivity of the outputs to changes in the inputs, and to conduct "what if" exercises.

A nomograph is generally inapplicable to merely displaying the values of an input, since no rule of a predictive nature is implied. Although one could argue that causality and trends in the real world are, in fact, the "rules" which produce perceived inputs as representations of underlying elemental processes, this is nonetheless totally useless to the decision maker. His concern is reaching a decision for which the outputs of the decision algorithm provide him some aid. If the outputs can be provided with a rule of a predictive nature, then a service is being provided to the decision maker.

Thus, the term nomography, as we will use it, refers to a method of displaying the results of an algorithm, where there is a predictive rule that converts input data to output results.

The term nomograph is usually reserved for those graphical presentations in which the values of two or more variables are required to select the resulting dependent variable. However, it is not necessary for all independent variables to appear physically in the nomograph. In machine-supported displays, the values of additional variables, though not explicitly shown, can be used to determine the functional relationship between those independent variables which are input to the nomograph and the dependent variable which is extracted from the nomograph. Classical definitions of nomography would typically exclude a two-axis graph in which an output can be determined by specifying one input. However, in the case of computer-supported displays, where the functional relationship between these two variables is dependent on a number of independent variables which have been set previously, the resulting graphical presentation is nonetheless a nomograph.

Thus, two of the displays used in the decision aid can be appropriately termed nomographs: the sensitivity analysis display, an example of which is presented in Plate 5 and the aircraft lost by strike display, depicted in Plate 4. The former is a one-quadrant nomograph entered by specifying a single variable -- specifically, the selected conditioning element for the sensitivity analysis. The aircraft loss nomograph uses a multiple quadrant presentation to provide own force losses as a function of the segments of an air strike for a single presumed launch time. Both analyses assume that all other variables input to the decision algorithm have the time-dependent distributions specified in their corresponding input displays.

The sensitivity display provides the decision maker with the ability to correlate the range of variability of the expected outcome utilities with the domain of variability of an independent variable. It allows a decision maker to examine how dependent his expected outcome is on variations in that input parameter. For those inputs which represent factors under the decision maker's control, such as number of aircraft launched, the sensitivity analysis provides a means to determine the value of launching more or less than the desired number of aircraft, as well as the change in utility that would be expected should the number of aircraft actually launched be fewer than the number predicted to be available for launch by the maintenance or readiness officer. For those inputs which represent factors beyond the control of the decision maker, such as enemy ground defenses, the decision maker is provided with a measure of the impact upon expected outcome that lack of knowledge, error in observation, or misjudgment of enemy readiness will have upon the consequences of a strike decision. Thus, the sensitivity analysis is a predictive tool that supports the decision maker's analysis by informing him of the risks inherent with each available alternative.

The loss nomograph provides information which cannot be provided by the sensitivity analyses. Specifically, it indicates in which mission segment losses are occurring. Therefore, if the decision maker is able to increase his strike force, he will be able to decide whether to increase air superiority fighters, EW escorts, bombers, etc. Further, unlike a gross loss number, the segment-dependent indication of loss provides further confirmation to the decision maker that the expected outcomes produced by the model are realistic with respect to each segment of the mission. For example, in an evaluation in which the decision maker has placed greater weight on target destruction than on own force losses, he may be concerned about whether target destruction is achieved, principally in the air-to-air combat prior to reaching the target, over the target or during the return leg, or by bombing aircraft on the ground. Although in either case his own losses may be equally high, his confidence in the aid may be reinforced if he sees that the losses occur early in the mission rather than later when high losses would tend to reduce his combat effectiveness.

Of course, all these considerations may ascribe too much introspection to the decision maker -- he may neither have the time nor the propensity to conduct such an evaluation. This, however, is a point which can only be answered experimentally.

3.2 PHYSICAL APPEARANCE

All of the graphical displays used in the aid have been designed to take advantage of the RAMTEK color display capability at the University of Pennsylvania test bed. Color has been used primarily as a discriminant, to aid the decision maker in spotting the important information in the display (see Appendix E). Color has also been used to indicate criticality in the enemy ground defenses display, where the ratio of red to blue colors serves as a quick indicator of the intensity of expected ground defenses. However, except for those displays where color is employed as a discriminant to compact more information than would be conveniently displayed in a single black and white presentation, all displays would be equally interpretable in black and white based on simple geometric considerations.

Scaling, letter size selection, screen size, and other symbology have been selected in accordance with the capabilities of the test bed. No further basis is claimed here for the selections made in the design of the graphical displays used in the system.

With the exception of the loss nomograph, all system displays have been designed with the independent variables on the abscissa of the graph and the dependent variables on the ordinate. This complies with standard mathematical conventions and the customary form in which graphs are presented in Naval publications and manuals. Trial implementations in which the dependent and independent variables were reversed led to disorientation or confusion on the part of observers, confirming the desire to maintain a conventional scale orientation.

The loss nomograph provides a display of the cumulative effects of the engagement as a function of time. The display has been designed so that later mission segments progress in a clockwise direction. Again, this selection has been made in accordance with normal conventions for graphical presentation. The upper left quadrant was selected as the initial point for entering the nomograph because the eye, accustomed to reading a page, will naturally tend to fixate there first. One could also argue that this should result in a nomograph that is best entered at the left edge of the upper right quadrant; this hypothesis can be evaluated experimentally.

Orange has been used for scale indicators, axes, and labels on all displays because it draws attention and at the same time is not an indicator of criticality. In those displays in which only one additional color is employed, blue has been used based on studies of color radar displays that indicate that it tends to minimize eye strain, while still attracting attention, and being readily perceptible against a black background.

Both the sensitivity analysis and the loss by segment nomographs have been designed so that projections from the value of an independent variable to the value of the dependent variable are consistently performed perpendicular or parallel to the axes presented in the graph. Although a large number of nomographs in the literature use projections oblique to an axis, an examination of the nomographs in several Naval operational manuals has indicated that parallel or perpendicular projections predominate. Without the aid of additional instruments to determine the correct value of the dependent variable, rectilinear projections can be more accurately made visually than oblique projections.

3.3 DISPLAY OF UNCERTAINTY

As was noted earlier, uncertainty as used in this report, represents all those effects that lead to an imprecise knowledge of the real world. Thus, uncertainty can result from bias, estimation error, statistical variability, imprecise observation and confidence (or the lack thereof) in the use of reported information. While knowledge of the specific reasons for the uncertainty or its distribution are not intrinsic to the aid itself, performing statistical operations on inputs with uncertainties can be extremely difficult unless some a priori assumptions about the shape of the distribution functions of the inputs are made.

In general, the decision aid treats the inputs as expected values and standard deviations of normal distributions. Based on this assumption, outputs with both expected values and interquartile ranges can be presented.

There is at present no experimental justification for assuming that the values input by an observer would, in fact, be the mean and standard deviation of a pre-known distribution. Without making these assumptions, it would be difficult to describe statistically what has been calculated as a result of the mathematical operations performed on the inputs in any sense other than an expected value and its perturbation. Appendix D presents a more detailed discussion of this problem. Since the problem can be resolved by experimentation and its results incorporated in place of present assumptions, no further concern is warranted at this time.

IV. USING THE DECISION AID

4.1 GENERAL FEATURES*

The Analytics Decision Aid (ADA) has been designed to minimize the difficulties that individuals who are unfamiliar with computers typically experience when attempting to run a complex program. ADA automatically prompts the user for the appropriate information, supplies help if the user does not understand available options, issues error messages when the user enters invalid data, and warns the user if calculations are being performed with suspect data. The user need not enter all data every time the aid is used -- default data is automatically supplied or the user can save the data from a previous run for use at a later time. Each of the arrays of data values used in the aid are individually accessible and modifiable, obviating the need to enter all data items in order to modify a single table or even a single number within a table.

* ADA is currently being revised and expanded to support testing now underway under ONR sponsorship.

4.2 ACCESSING THE DECISION AID

ADA resides on the University of Pennsylvania's DEC System 10, in two versions. One version uses both a standard alphanumeric display and the RAMTEK color graphic display, the other uses only the alphanumeric display. To use the RAMTEK color graphic version, the user must be at the University of Pennsylvania and connected to the RAMTEK color display system. The alphanumeric version can be used at any location having access to the DEC-10 via a standard teletype or CRT display.

The RAMTEK version is run* by entering

RUN ADARAM [4010,201]†

after signing on to the system. The tabular version is run by entering

RUN ADATAB [4010,201]

ADA will respond with the message

```
ENTER 'READ' TO USE DATA FROM LAST RUN,
'DEF' TO RUN WITH DEFAULT DATA -
```

---

* In the instructions that follow, a "carriage return" is implied after every line input by the user.

† If signed on under account 4010,201, the entry in brackets is not necessary. The RAMTEK must also have been previously assigned to the job by entering

ASSIGN TTYXXX 8

where XXX represents the unit number currently assigned to the RAMTEK.

The decision maker must then type in either DEF or READ. If DEF is entered, the default data set (shown in Figures 5 through 14) will be used. If READ is entered, the user must have stored data during a previous ADA run on a file named FOR20.DAT (or otherwise identified the file to the system). This data will then be used instead of the default data. ADA will respond with the message:

```
ENTER 'HELP' TO OBTAIN ASSISTANCE
'RUN' TO BEGIN EXECUTION-
```

A novice decision maker will, at this point, probably enter HELP, even though entering RUN will sequence him through operations that are generally self-explanatory. The operations that result from typing RUN are described in Section 4.3.

If HELP is entered, the system will display the table shown in Figure 4. This table lists the various input and output tables available to the decision maker. The table indicates that by entering the appropriate code in response to the SELECT DISPLAY cue, the decision maker can examine the inputs to the aid, run the models to obtain the decision aid outputs, and run sensitivity analyses to examine the sensitivity of the results to changes in each of the input parameters.

4.3 THE PREFERRED STRIKE TIME DISPLAY

The PST display (see Figure 5) provides information to the decision maker on the times at which the task force commander's subordinate officers last provided updates to the conditioning elements used in the decision aid calculations and enables the commander to request that this information be updated before the decision aid is run. It also enables the decision maker to specify the earliest and latest times

```
ENTER 'HELP' TO OBTAIN ASSISTANCE
'RUN' TO BEGIN EXECUTION-HELP

WHENEVER THE CUE 'SELECT DISPLAY-' APPEARS, SELECT
A DISPLAY FROM THE FOLLOWING LIST BY ENTERING THE
APPROPRIATE ABBREVIATION

      DISPLAY                    ABBREVIATION

OWN FORCE READINESS                  OFR
ENEMY GROUND DEFENSES                EGD
ENEMY AIR DEFENSES                   EAD
WEATHER AT TARGET                    WAT
WEATHER AT CARRIER                   WAC
STATE MODEL UTILITIES                STATE
OUTCOME MODEL UTILITIES              OUTCOME
LIKELIHOOD RATIOS FOR ENEMY
  GROUND DEFENSES                    LEGD
LIKELIHOOD RATIOS FOR ENEMY
  AIR DEFENSES                       LEAD
PREFERRED STRIKE TIMES               PST
SENSITIVITY ANALYSES                 SENS
TO RUN STATE MODEL                   RUNS
TO RUN OUTCOME MODEL                 RUNO
TO COMPUTE AIRCRAFT LOSSES           LOSS
STOP RUN                             STOP
TO REDISPLAY THIS TABLE              HELP
```

Figure 4. The HELP Display

Note: Information entered by the decision maker is underlined.

```
SELECT DISPLAY (OFR,EGD,EAD,WAT,WAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-PST

LAST INTELLIGENCE REPORT AT
  ENEMY AIR DEFENSES     0600
  ENEMY GROUND DEFENSES  0600

LAST WEATHER REPORTS AT
  CARRIER                0600
  TARGET                 0600

LAST READINESS REPORT AT     0600

DOES THIS INFORMATION REQUIRE UPDATING BEFORE THE DECISION AID IS RUN?-
NO

EARLIEST POSSIBLE STRIKE TIME     0600
LATEST POSSIBLE STRIKE TIME       1100
ALL STRIKE TIMES ARE ASSUMED TO BE EQUALLY ACCEPTABLE

DO YOU WISH TO CHANGE STRIKE TIMES? NO
DO YOU WANT TO CHANGE THE PREFERENCE FACTORS? YES
ENTER WEIGHTS TO BE ASSIGNED TO EACH ONE HOUR INTERVAL
        0600=.0
        0700=.2
        0800=.8
        0900=1.0
        1000=.8
        1100=.2
DO YOU WISH TO CHANGE ANY PREFERENCE FACTORS? NO
```

Figure 5. The PST Display

NOTE: Information entered by the decision maker is underlined.

at which the strike can be made and permits the assignment of weights to each strike time to accommodate his personal preferences or to incorporate dynamic time-dependent factors relevant to the problem that have not been explicitly included in the decision model.

In a typical decision process, inputs to the aid would have been supplied by the task force commander's subordinate officers, e.g., the intelligence officer would have supplied information on the enemy ground and air defenses, the weather officer would have supplied weather predictions at the target and at the carrier, and the maintenance or readiness officer would have supplied own force readiness estimates. The task force commander's primary interest is, therefore, likely to be in the time at which these data were supplied, relative to the current time. This summary information is available in the preferred strike time display. This display would have appeared if RUN rather than HELP had been entered when the decision aid was originally accessed.

Initially, the information shown in Figure 5, the times of the last intelligence, readiness, and weather reports, are displayed together with the question

DOES THIS INFORMATION REQUIRE UPDATING
BEFORE THE DECISION AID IS RUN?-

If the decision maker feels that any of the data requires updating, he can enter YES. The system will then ask him to enter the name(s) of the conditioning element(s) requiring updates. After this information has been entered, or if no updates were required, the system will display the additional information shown in Figure 5, along with the question

DO YOU WISH TO CHANGE STRIKE TIMES?-

If the decision maker enters YES in response to this question, he will be allowed to enter new earliest and latest strike times. Whether or not he chooses to change the strike times, he will be able to assign weights to each one-hour interval or to weight each strike time equally so that tactical objectives which are time-critical in destroying enemy assets can impact evaluation of alternatives.

Typically, once the decision maker has examined this table, he will proceed to run either the state model (by entering either STATE or RUNS in response to the SELECT DISPLAY cue) or the outcome model (by entering either OUTCOME or RUNO). Entering STATE or OUTCOME ultimately causes the same calculations to be performed as RUNS and RUNO, respectively. The difference between the options is that STATE and OUTCOME provide an initial display of the state and outcome model utilities and permit the decision maker to modify these utilities, the weights assigned to the two criteria (target destruction and own force loss) and, in the case of the STATE model, to change the "breakpoints" associated with the state definitions. Therefore, in the following discussion, the STATE and OUTCOME displays will be described, followed by the RUNS and RUNO displays.

4.4 THE STATE DISPLAY

State models require the definition of a set of states, characterized by specific values for each of the conditioning elements. The ADA state model currently defines 12 states (Figure 6a), based upon the values of the following conditioning elements: weather at target, weather at carrier, enemy ground defenses, and relative readiness. (The readiness

```
SELECT DISPLAY (OFR,EGD,EAD,VAT,VAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-STATE
```

STATE MODEL UTILITIES

STATE	RR	VAT	VAC	EGD	TD	LOSS	
1	I	ANY	B	ANY	20	10	
2	I	ANY	G	ANY	20	30	
3	E,S	ANY	B	N,L	50	40	I=INFERIOR
4	E,S	ANY	B	M,H	30	30	E=EQUAL
5	E	B	G	N,L	35	70	S=SUPERIOR
6	E	G	G	N,L	50	70	B=BAD
7	E	B	G	M,H	25	50	G=GOOD
8	E	G	G	M,H	40	50	N=NONE
9	S	B	G	N,L	70	100	L=LOW
10	S	G	G	N,L	90	100	M=MEDIUM
11	S	B	G	M,H	60	80	H=HIGH
12	S	G	G	M,H	80	80	

```
WEIGHT ASSIGNED TO TARGET DESTRUCTION=.75
WEIGHT ASSIGNED TO OWN FORCE LOSSES=.25

BREAKPOINTS VAC=.40  VAT=.30  OFR=.55  .85
DO YOU WISH TO CHANGE ANY UTILITIES? NO
DO YOU WISH TO CHANGE THE WEIGHTS? NO
DO YOU WISH TO CHANGE THE BREAKPOINTS? NO
```

Figure 6(a). The STATE Display

EXPECTED UTILITIES (STATE MODEL)

0600	EU=	20	SIG=	1
0700	EU=	32	SIG=	1
0800	EU=	65	SIG=	3
0900	EU=	61	SIG=	3
1000	EU=	65	SIG=	3
1100	EU=	32	SIG=	1

Figure 6(b). The RUNS Display

NOTE: Information entered by the decision maker is underlined.

ratio is a combined estimate of own force readiness and enemy force readiness [see Appendix B]). Since several of these quantities, as used in the model, are continuous variables, defining 12 states requires partitioning the ranges of the variables into discrete values and forming the appropriate permutations of each variable with every other variable. As shown in Figure 6a, ADA partitions

- The continuous variable relative readiness into the discrete values inferior, equal, and superior, i.e., Blue's expected force level is inferior, equal, or superior, relative to the expected Orange force level.
- The continuous variable weather at target into good and bad, i.e., the weather at the target is expected to be either good or bad with respect to attaining the mission objectives (destroying the enemy's defensive/offensive capability).
- The continuous variable weather at carrier into good and bad, i.e., the weather at the carrier is expected to be either good or bad with respect to Blue's ability to land its planes safely.

The values of the conditioning elements that partition the ranges are termed "breakpoints" and are shown in Figure 6a.

The variable enemy ground defenses, as defined in the model, is already a discrete variable with values of none, low, medium, or high. Thus, as indicated in Figure 6a, state 12 can be described by the statements:

- Our air power is superior to the enemy's.
- The weather at the target is good.
- The weather at the carrier is good.
- The enemy has either medium or high defenses.

To each state defined in this way, utilities for target destruction and own force losses are assigned that are interpreted to mean:

> "If the conditions defining this state pertain at the time the strike occurs, the target destruction utility that will be obtained will be _____ and the own force loss utility that will be obtained will be _____."

Thus, for example, if the real world is in state 12 when the strike takes place, a target destruction utility of 80 will be obtained and an own force losses utility of 80 will be obtained, according to Figure 6a.

The state definitions must be mutually exclusive and exhaustive,* and the values of utilities assigned to the states must make sense. For example, it is clear that target destruction will be less and losses are likely to be worse (i.e., have a lower utility) if own forces are inferior rather than equal or superior. Therefore, for the utility assignments to make sense, states that have an inferior relative readiness must have lower target destruction and own force loss utilities. This ordering has been preserved in, for example, the utility assignments for states 1 and 2 versus states 3 and 4 in the sample set of utilities shown in Figure 6a.

The state model calculates the probability of being in each of the 12 states at each of the specified launch times. From these probabilities, it determines an expected utility for launching the attack at each time by multiplying the

---

* The real world must be in one and only one of the states.

probabilities by the associated utilities for target destruction and own force losses. Before performing these calculations, however, the decision maker is given the opportunity to modify the utilities associated with any state, the breakpoints that "discretize" relative readiness, weather at target, and weather at the carrier, and the weights assigned to target destruction and own force losses.

4.5 THE OUTCOME DISPLAY

In the outcome model, utilities are assigned to specific target destruction and own force loss outcomes. For example, as shown in Figure 7a, if an engagement with the enemy results in 10 percent of the target being destroyed and three of our own aircraft being lost, then a target destruction utility of 50 and an own force loss utility of 65 will be obtained. The outcome model (Appendix C) then predicts from these utilities and the probable distributions of input values, the probable distribution of outcomes and the expected utility distributions for striking at each of the possible strike times. Prior to running the outcome model, the decision maker is given the opportunity to modify the utilities associated with the various outcomes and the weights assigned to target destruction and own force losses.

4.6 EVALUATING THE DECISION ALTERNATIVES (RUNS AND RUNO)

If the decision maker requests either the state or outcome model utility displays, ADA allows the decision maker to modify the assigned state or outcome utilities and the weights assigned to the criteria of target destruction and own force losses. It will then automatically calculate the expected utilities and standard deviations for all allowable strike times. Alternatively, the decision maker can obtain the state or outcome model expected utilities directly (without reviewing the assigned state or outcome utilities) by

SELECT DISPLAY (OFR, EGD, EAD, VAT, VAC, STATE, OUTCOME, LEGD, LEAD,
PST, SENS, RUNS, RUNO, LOSS, STOP, OR HELP)-OUTCOME

OUTCOME MODEL UTILITIES

TARGET DESTRUCTION	UTILITY	OWN A/C LOST	UTILITY
0%	0	0	100
2%	5	1	95
5%	25	3	75
10%	50	5	50
15%	75	7	40
20%	100	9	25
		11	10
		13	5
		15	0

WEIGHT ASSIGNED TO TARGET DESTRUCTION=.75
WEIGHT ASSIGNED TO OWN FORCE LOSSES=.25

DO YOU WISH TO CHANGE TD UTILITIES? NO
DO YOU WISH TO CHANGE LOSS UTILITIES? NO
DO YOU WISH TO CHANGE WEIGHTS? NO

Figure 7(a). The OUTCOME Display

EXPECTED UTILITIES (OUTCOME MODEL)

TIME=0600	EU=	11	SIG=	0
TIME=0700	EU=	10	SIG=	1
TIME=0800	EU=	46	SIG=	3
TIME=0900	EU=	60	SIG=	3
TIME=1000	EU=	51	SIG=	3
TIME=1100	EU=	14	SIG=	0

Figure 7(b). The RUNO Display

NOTE: Information entered by the decision maker is underlined.

entering RUNS or RUNO when the SELECT DISPLAY cue is displayed. In either case, the tabular display generated by ADA presents the expected utility and its standard deviation for each time period of interest (Figures 6b and 7b). The corresponding graphical presentations are shown in Plates 1 and 2.

The graphical form of presentation of the expected utilities and probable ranges for each of the decision alternatives enables the decision maker to quickly compare the alternatives and then select the one he considers most appropriate. We use the term "appropriate" here because although, in the long run, the alternative that has the maximum expected utility is theoretically the "best," it may be the case that a decision maker will not select this alternative. His own attitudes towards risk-taking or his knowledge about aspects of the situation that may not have been incorporated in the models, may cause him to select an alternative with, e.g., a lower expected utility, but also a smaller probable range. Such a choice is not necessarily wrong; in fact, depending on the circumstances, it might be a more appropriate decision than selecting the alternative with the highest expected utility. What is important is that the form of presentation used in the aid permits the decision maker to evaluate his alternatives and their probable consequences with respect to a standardized value scale that clearly tells him how much he can expect to gain or lose by selecting each alternative.

There are three shortcomings associated with the "Utility vs. Alternative" presentations shown in Plates 1 and 2. First, the decision maker has no way of determining where the utilities are coming from -- how much comes from target destruction and how much from own force losses -- because these figures have been buried in the overall utility calculation. Secondly, the utilities that are displayed are meaningless units in that the decision maker cannot readily relate them to the quantities "percent target destruction" and "own force losses" that were combined to arrive at the number. Decision makers may prefer to base their decisions on numbers that they can understand, rather than constructs. And third, many decision makers want to know what accounts for an outcome, how sensitive the outcomes are to errors in estimation of the inputs, and what can be done to improve the outcomes. These three types of analyses and data are supplied to the decision maker in the sensitivity analyses and loss nomograph discussed in Sections 4.8 through 4.9.

4.7 INPUT DISPLAYS

This section describes the displays of input quantities available to the decision maker and his subordinate officers. The expected values of the five conditioning elements are displayed in both a tabular and a graphical format. While there are basic similarities in each of the formats, each display is slightly different, depending on the characteristics of the specific variables. Variables with differing characteristics (discrete/continuous, Bayesian updated/non-updated, etc.) have been used to demonstrate both the flexibility of the display methodology and the ability of the algorithms to handle such variations.

4.7.1 The OFR Display

The air strike mission as described in the scenario specifies a desired mix of A-6, A-7, and F-14 aircraft to be used to carry out the mission. The OFR display presents to the decision maker the readiness officer's estimates of how the probable number of aircraft available at each of the possible strike times compares with this desired complement. The display shown in Figure 8 indicates the time of the report

```
     SELECT DISPLAY (OFR,EGD,EAD,WAT,WAC,STATE,OUTCOME,LEGD,LEAD,
     PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-OFR

                           OWN FORCE READINESS (OFR)
Line
  1  TIME OF REPORT 0600                       NEXT REPORT AT 1200

                   READY AIRCRAFT BY TYPE

     TIME                       A-6        A-7      F-14

  2  0600                      6+- 1    12+- 6    10+- 1
  3  0700                      7+- 1    14+- 4    12+- 2
  4  0800                      8+- 1    16+- 2    14+- 2
  5  0900                      9+- 1    18+- 2    16+- 2
  6  1000                     10+- 1    20+- 2    16+- 2
  7  1100                     11+- 1    22+- 2    16+- 2

  8  AVAILABLE              12        24        18
  9  DESIRED                12        18        13

     DO YOU WISH TO ENTER A NEW REPORT? NO
     DO YOU WISH TO CHANGE A LINE IN THE CURRENT REPORT? NO
```

Figure 8. The OFR Display

NOTE: Information entered by the decision maker (or a subordinate officer) is underlined.

and the time at which the next report is expected (line 1). Then, for each succeeding one-hour interval, the display indicates the expected numbers of A-6, A-7, and F-14 aircraft that will be available (lines 2 through 7). Finally, lines 8 and 9 indicate the desired strike complement and the total number of each type of aircraft available in the task force.

The corresponding graphical display (Plate 11) presents the data on the expected availability of each type of aircraft relative to the number of aircraft of each type desired in the strike complement. The allowable strike times are indicated along the x-axis. The available aircraft are shown by colored vertical bars, each aircraft in a different color. The horizontal line at zero on the y-axis indicates the desired strike complement. Those aircraft distributions extending above the line indicate times at which the number of aircraft of that type may exceed the number desired for the mission.

Those distributions extending below the line indicate times at which the number of available aircraft may fall below the desired strike complement. The horizontal band through each distribution indicates the readiness officer's best estimate of the number expected to be available. This number is interpreted by the decision algorithm to be the mean of a normal distribution whose σ values are shown by the ends of the bars.

4.7.2 The EAD Display

The air strike mission scenario assumes that Orange will keep 25 percent of its available planes in the air at all times and that Blue's reconnaissance flights will report back every four hours on the number of enemy aircraft observed. The number observed therefore serves as an indicator of the number of planes that Orange has available. The decision algorithm uses this number in a Bayesian updating process to update a prior estimate of the enemy aircraft distribution to provide a posterior estimate. (The likelihood ratios used to perform the update are displayed on the LEAD display -- Figure 9b.) The posterior estimate is considered to obtain for the four hours following receipt of the report, after which it is assumed that either a new report will have been received or the enemy will revert to his standard tactics. Therefore, for launch times greater than four hours after the most recent report, the prior distribution is used.

The EAD display (Figure 9a) summarizes these estimates of the enemy air defenses:

- Line 1 indicates the time of the report and the time at which the next report is expected.
- Line 2 indicates the number of aircraft reported by the reconnaissance mission.
- Lines 3 through 6 display the prior and posterior probabilities that the number of available aircraft are within specified values.
- Line 7 indicates the useful lifetime of the report.
- Lines 8 and 9 indicate the mean number of enemy aircraft expected to be available for the four hours after the report and the number expected to be available for times greater than four hours after the report.

In addition, they indicate the expected numbers of aircraft at the 25 percent and 75 percent cumulative probability points.

BEST AVAILABLE COPY

```
SELECT DISPLAY (OFR,EGD,EAD,VAT,VAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-EAD

Line                     ENEMY AIR DEFENSES (EAD)

 1   TIME OF REPORT 0600                    NEXT REPORT AT 1000
 2   ENEMY AIRCRAFT SPOTTED=  7

                             PROBABILITIES
     EAD       PRIOR TO REPORT              POST REPORT

 3    0-23           0.00                        0.00
 4   24-43           0.58                        0.84
 5   44-63           0.40                        0.15
 6    =>64           0.02                        0.00

 7   USEFUL LIFETIME OF THIS REPORT IS  4 HOURS

     EXPECTED EAD              Q25%      AV      Q75%
 8     NEXT  4 HOURS            31       33       35
 9     AFTER 4 HOURS            40       50       60

     DO YOU WISH TO ENTER A NEW REPORT? NO
```

Figure 9(a). The EAD Display

```
SELECT DISPLAY (OFR,EGD,EAD,VAT,VAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-LEAD

        LIKELIHOOD RATIOS FOR ENEMY AIR DEFENSES  (LEAD)

PRIOR DISTRIBUTION=NORMAL, MEAN= 50  SIGMA= 10

INDICATOR-- NUMBER OF ENEMY AIRCRAFT SPOTTED
```

	LIKELIHOOD RATIOS				POSTERIOR DISTRIBUTIONS			
INDICATOR	0-23	24-43	44-63	=>64	0-23	24-43	44-63	=>64
<=5	0.90	0.05	0.04	0.03	0.00	0.64	0.35	0.01
6-10	0.07	0.60	0.16	0.07	0.00	0.84	0.15	0.00
11-15	0.03	0.30	0.70	0.15	0.00	0.38	0.61	0.01
=>16	0.00	0.05	0.10	0.75	0.00	0.35	0.48	0.18
				PRIOR	0.00	0.58	0.40	0.02

Figure 9(b). The LEAD Display

NOTE: Information entered by the decision maker (or a subordinate officer) is underlined.

The graphic display (Plate 12) accompanying this tabular display simply shows these final values -- the expected number of enemy aircraft and the 25 percent and 75 percent cumulative values for each of the feasible launch times.

4.7.3 The EGD Display

The air strike mission scenario categorizes the enemy ground defenses expected into four discrete states: NONE, LOW, MEDIUM, and HIGH. The state of the enemy's actual defenses are indicated by the intensity of defenses encountered by the last strike. The intensity is also categorized into four states: NONE, LOW, MEDIUM, and HIGH. A set of likelihood ratios (displayed on the LEGD display -- Figure 10b) relate the prior estimates for the enemy ground defenses to the posterior estimates that would obtain after a Bayesian update based upon the strike debrief estimates of the level of enemy ground defenses encountered. The EGD tabular display (Figure 10a) indicates that time at which the last report was entered, the time the next report is expected (line 1), the estimate of enemy ground defenses based on the strike debrief (line 2), and the prior and posterior probabilities for each of the possible states of the enemy ground defenses. Since it is assumed that the enemy cannot resupply his ground defenses, the posterior probabilities pertain until the next report is received.

The corresponding graphical display (Plate 13) shows the cumulative probabilities of each of the states. This display enables the decision maker to estimate rapidly the probability of, e.g., the enemy's defenses being no worse than LOW.

BEST AVAILABLE COPY

SELECT DISPLAY (OFR, EGD, EAD, WAT, WAC, STATE, OUTCOME, LEGD, LEAD,
PST, SENS, RUNS, RUNO, LOSS, STOP, OR HELP)-EGD

ENEMY GROUND DEFENSES (EGD)

TIME OF REPORT 0600 NEXT REPORT AT 1000
LATEST INTELLIGENCE REPORTED MED DEFENSES ENCOUNTERED

PROBABILITIES

EGD	PRIOR TO REPORT	POST REPORT
NONE	0.05	0.00
LOW	0.10	0.08
MEDIUM	0.25	0.27
HIGH	0.60	0.65

USEFUL LIFETIME OF THIS REPORT IS INDEFINITE

DO YOU WISH TO ENTER A NEW REPORT? NO

Figure 10(a). The EGD Display

SELECT DISPLAY (OFR, EGD, EAD, WAT, WAC, STATE, OUTCOME, LEGD, LEAD,
PST, SENS, RUNS, RUNO, LOSS, STOP, OR HELP)-LEGD

LIKELIHOOD RATIOS FOR ENEMY GROUND DEFENSES (LEGD)

INDICATOR -- ENEMY GROUND DEFENSES SIGHTED

	LIKELIHOOD RATIOS				POSTERIOR DISTRIBUTIONS			
INDICATOR	NONE	LOW	MEDIUM	HIGH	NONE	LOW	MEDIUM	HIGH
NONE	1.00	0.20	0.10	0.00	0.53	0.21	0.26	0.00
LOW	0.00	0.40	0.20	0.10	0.00	0.27	0.33	0.40
MEDIUM	0.00	0.30	0.40	0.40	0.00	0.08	0.27	0.65
HIGH	0.00	0.10	0.30	0.50	0.00	0.03	0.19	0.78
				PRIOR	0.05	0.10	0.25	0.60

Figure 10(b). The LEGD Display

NOTE: Information entered by the decision maker (or a subordinate officer) is underlined.

4.7.4 The WAT Display

The WAT display (Figure 11) provides the decision maker with the weather officer's estimates of the probability of weather suitable for the air strike existing at each of the possible arrive-at-target times. The weather officer's estimates, in that they are probabilities, are expressed as single numbers.*

The associated display (Plate 14) simply plots these values.

4.7.5 The WAC Display

Favorable landing conditions depend on factors such as sea state, visibility, etc. Rather than modeling all possible factors, the aid assumes that a landing index consisting of a continuous parameter on a scale of 0 to 1 could be constructed from these factors to indicate the probability of suitable conditions. In addition, it is assumed that, because of the vagaries of weather and the estimation process, one could assign a range of probable error to this estimate. These numbers -- the landing weather index and its probable error -- are displayed on the WAC tabular display (Figure 12) and the corresponding graphical display (Plate 15).

4.8 SENSITIVITY ANALYSES

In addition to the expected utilities and their associated uncertainties, the decision maker is likely to be

---

* Conceivably the officer could be asked to express them as probabilities and probable ranges around those values, but the problem that would result from compounding a probability distribution with another probability distribution would be severe.

```
SELECT DISPLAY (OFR,EGD,EAD,WAT,WAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-WAT

                    WEATHER AT TARGET (WAT)

TIME OF REPORT 0600                      NEXT REPORT AT 1000

TARGET VISIBILITY INDEX (SCALE 0-1)=PROBABILITY OF GOOD VISIBILITY
NOTE: WAT IS  GOOD IF INDEX IS GREATER THAN .30

TIME       INDEX

0600        0.88
0700        0.88
0800        0.88
0900        0.88
1000        0.88
1100        0.88
1200        0.90

DO YOU WISH TO ENTER A NEW REPORT? NO
DO YOU WISH TO CHANGE A LINE IN THE CURRENT REPORT? NO
```

Figure 11. The WAT Display

NOTE: Information entered by the decision maker (or a subordinate officer) is underlined.

```
SELECT DISPLAY (OPN,EGD,EAD,WAT,WAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-WAC

                    WEATHER AT CARRIER (WAC)

TIME OF REPORT 0600                    NEXT REPORT AT 1200

LANDING WEATHER INDEX (SCALE 0-1)=PROBABILITY OF FAVORABLE CONDITIONS
NOTE: WAC IS GOOD IF INDEX IS GREATER THAN .40

TIME      INDEX

0600    0.90+-.10
0700    0.90+-.10
0800    0.90+-.10
0900    0.90+-.10
1000    0.90+-.10
1100    0.90+-.10
1200    0.95+-.05
1300    0.95+-.05

DO YOU WISH TO ENTER A NEW REPORT? NO
DO YOU WISH TO CHANGE A LINE IN THE CURRENT REPORT? NO
```

Figure 12. The WAC Display

NOTE: Information entered by the decision maker (or a subordinate officer) is underlined.

interested in the sensitivity of the results of the decision aid to variations in the input quantities. The sensitivity analyses available in the decision aid give him the capability to examine the effect of such variations.

There are seven sensitivity analyses available: all but one function in the same way. Three of the analyses examine the sensitivity of the results to own force readiness by varying the available numbers of A-6, A-7, and F-14 aircraft. Three of the remaining analyses examine sensitivity to enemy air defenses, weather at the target and weather at the carrier. Each analysis runs the decision algorithm for all possible values of the parameter under study. The final analysis, the enemy ground defense sensitivity analysis, differs from the others in that it requires the decision maker to enter a hypothesized EGD distribution. All the analyses assume that the values of all conditioning elements other than the one under study are to be held constant at the values that they have at the launch times being evaluated.

The sensitivity analyses are invoked by typing SENS in response to the SELECT DISPLAY cue. The decision aid responds with the message:

```
SELECT EITHER A6, A7, F14, EAD, EGD, WAT, OR
WAC AS THE INDEPENDENT CONDITIONING ELEMENT
```

If the decision maker selects anything except EGD, the aid will automatically exercise whichever algorithm (either the STATE or OUTCOME model) was run last for all possible values of the independent conditioning element. Examples of the resulting tabular displays are shown in Figures 13a through 13g. The corresponding graphics are shown in Plates 5 through 10. Across the top of the

SELECT DISPLAY (OFR, EGD, EAD, WAT, WAC, STATE, OUTCOME, LEGD, LEAD, PST, SENS, RUNS, RUNO, LOSS, STOP, OR HELP)-SENS

SELECT EITHER A6, A7, F14, EAD, EGD, WAT, OR WAC AS THE INDEPENDENT CONDITIONING ELEMENT-A6

	0600	0700	0800	0900	1000	1100
1	19+- 3	31+- 3	68+- 3	81+- 3	68+- 3	32+- 1
2	20+- 2	32+- 2	68+- 3	81+- 3	68+- 3	32+- 1
3	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
4	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
5	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
6	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
7	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
8	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
9	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
10	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
11	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1
12	20+- 1	32+- 1	68+- 3	81+- 3	68+- 3	32+- 1

Figure 13(a). The A-6 Sensitivity Analysis

SELECT DISPLAY (OFR, EGD, EAD, WAT, WAC, STATE, OUTCOME, LEGD, LEAD, PST, SENS, RUNS, RUNO, LOSS, STOP, OR HELP)-SENS

SELECT EITHER A6, A7, F14, EAD, EGD, WAT, OR WAC AS THE INDEPENDENT CONDITIONING ELEMENT-A7

	0600	0700	0800	0900	1000	1100
1	20+- 0	24+- 0	41+- 2	49+- 2	42+- 2	19+- 0
2	19+- 0	23+- 0	41+- 2	50+- 2	42+- 2	18+- 0
3	19+- 0	22+- 0	41+- 2	51+- 2	43+- 2	18+- 0
4	18+- 0	22+- 0	41+- 2	51+- 2	44+- 2	18+- 0
5	17+- 0	21+- 0	42+- 2	52+- 2	44+- 2	17+- 0
6	17+- 0	20+- 0	42+- 2	53+- 2	44+- 2	17+- 0
7	16+- 0	20+- 0	43+- 2	54+- 2	45+- 2	16+- 0
8	15+- 0	19+- 0	43+- 2	54+- 2	45+- 2	16+- 0
9	14+- 0	19+- 0	44+- 2	55+- 2	45+- 2	15+- 0
10	13+- 0	19+- 0	44+- 2	55+- 2	45+- 2	15+- 0
11	12+- 0	19+- 0	45+- 2	56+- 2	46+- 2	14+- 0
12	11+- 0	18+- 0	45+- 2	56+- 2	46+- 2	14+- 0
13	11+- 0	18+- 0	45+- 2	57+- 2	46+- 2	13+- 0
14	11+- 0	18+- 0	46+- 2	57+- 2	46+- 2	13+- 0
15	10+- 0	17+- 0	46+- 2	58+- 2	47+- 2	13+- 0
16	10+- 0	17+- 0	46+- 2	58+- 2	48+- 2	13+- 0
17	9+- 0	16+- 0	46+- 2	59+- 2	49+- 2	14+- 0
18	8+- 0	16+- 0	47+- 2	60+- 2	50+- 2	13+- 0
19	8+- 0	15+- 0	47+- 2	61+- 2	50+- 2	13+- 0
20	7+- 0	15+- 0	47+- 2	62+- 2	51+- 2	13+- 0
21	6+- 0	14+- 0	48+- 2	63+- 2	52+- 2	14+- 0
22	5+- 0	14+- 0	49+- 2	64+- 2	53+- 2	14+- 0
23	5+- 0	13+- 0	49+- 2	65+- 2	54+- 2	14+- 0
24	4+- 0	13+- 0	50+- 2	66+- 2	54+- 2	14+- 0

Figure 13(b). The A-7 Sensitivity Analysis

NOTE: Information entered by the decision maker is underlined.

SELECT DISPLAY (OFR, EGD, EAD, WAT, WAC, STATE, OUTCOME, LEGD, LEAD, PST, SENS, RUNS, RUNO, LOSS, STOP, OR HELP)-SENS

SELECT EITHER A6, A7, F14, EAD, EGD, WAT, OR WAC AS THE INDEPENDENT CONDITIONING ELEMENT-F14

	0600	0700	0800	0900	1000	1100
1	19+- 0	22+- 0	41+- 2	51+- 2	44+- 2	16+- 0
2	18+- 0	22+- 0	41+- 2	51+- 2	44+- 2	16+- 0
3	17+- 0	21+- 0	42+- 2	52+- 2	45+- 2	15+- 0
4	17+- 0	20+- 0	42+- 2	53+- 2	45+- 2	15+- 0
5	16+- 0	20+- 0	43+- 2	54+- 2	45+- 2	14+- 0
6	15+- 0	19+- 0	43+- 2	54+- 2	45+- 2	14+- 0
7	14+- 0	19+- 0	44+- 2	55+- 2	46+- 2	13+- 0
8	13+- 0	19+- 0	44+- 2	55+- 2	46+- 2	13+- 0
9	12+- 0	19+- 0	45+- 2	56+- 2	46+- 2	13+- 0
10	11+- 0	18+- 0	45+- 2	56+- 2	46+- 2	13+- 0
11	11+- 0	18+- 0	45+- 2	57+- 2	47+- 2	14+- 0
12	11+- 0	18+- 0	46+- 2	57+- 2	48+- 2	13+- 0
13	10+- 0	17+- 0	46+- 2	58+- 2	49+- 2	13+- 0
14	10+- 0	17+- 0	46+- 2	58+- 2	50+- 2	13+- 0
15	9+- 0	16+- 0	46+- 2	59+- 2	50+- 2	14+- 0
16	8+- 0	16+- 0	47+- 2	60+- 2	51+- 2	14+- 0
17	8+- 0	15+- 0	47+- 2	61+- 2	52+- 2	14+- 0
18	7+- 0	15+- 1	47+- 2	62+- 2	53+- 2	14+- 0

Figure 13(c). The F-14 Sensitivity Analysis

SELECT DISPLAY (OFR, EGD, EAD, WAT, WAC, STATE, OUTCOME, LEGD, LEAD, PST, SENS, RUNS, RUNO, LOSS, STOP, OR HELP)-SENS

SELECT EITHER A6, A7, F14, EAD, EGD, WAT, OR WAC AS THE INDEPENDENT CONDITIONING ELEMENT-EAD

	0600	0700	0800	0900	1000	1100
1	15+- 0	19+- 1	45+- 2	56+- 3	46+- 2	13+- 0
2	13+- 0	19+- 1	46+- 2	58+- 3	49+- 2	14+- 0
3	12+- 0	18+- 1	46+- 2	59+- 3	50+- 2	14+- 0
4	12+- 0	18+- 1	46+- 2	60+- 3	51+- 3	14+- 0
5	11+- 0	17+- 1	46+- 3	60+- 3	51+- 3	14+- 0
6	11+- 0	17+- 1	45+- 3	60+- 3	51+- 3	14+- 0
7	10+- 0	16+- 1	44+- 3	59+- 3	51+- 3	13+- 0
8	10+- 0	15+- 1	42+- 3	58+- 3	49+- 3	13+- 0
9	9+- 0	13+- 1	41+- 3	56+- 3	48+- 3	13+- 0

Figure 13(d). The EAD Sensitivity Analysis

NOTE: Information entered by the decision maker is underlined.

BEST AVAILABLE COPY

SELECT DISPLAY (OFR,EGD,EAD,WAT,WAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-SENS

SELECT EITHER A6,A7,F14,EAD,EGD,WAT, OR
WAC AS THE INDEPENDENT CONDITIONING ELEMENT-EED
SELECT EITHER A6,A7,F14,EAD,EGD,WAT, OR
WAC AS THE INDEPENDENT CONDITIONING ELEMENT-EGD
ENTER FOUR VALUES REPRESENTING THE NONE, LOW, MEDIUM,
AND HIGH HYPOTHESIZED PROBABILITIES FOR LGD DISTRIBUTION-.1 .3 .4 .2

0600	0700	0800	0900	1000	1100
21+- 2	34+- 3	72+- 5	34+- 6	72+- 5	34+- 3

Figure 13(e). The EGD Sensitivity Analysis

SELECT DISPLAY (OFR,EGD,EAD,WAT,WAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-SENS

SELECT EITHER A6,A7,F14,EAD,EGD,WAT, OR
WAC AS THE INDEPENDENT CONDITIONING ELEMENT-WAT

	0600	0700	0800	0900	1000	1100
1	11+- 0	12+- 0	21+- 1	25+- 1	21+- 1	5+- 0
2	11+- 0	13+- 0	24+- 1	29+- 1	25+- 1	6+- 0
3	11+- 0	14+- 0	27+- 1	34+- 2	29+- 2	7+- 0
4	11+- 0	14+- 0	31+- 2	38+- 2	32+- 2	8+- 0
5	11+- 0	15+- 0	34+- 2	43+- 2	36+- 2	9+- 0
6	11+- 0	16+- 0	37+- 2	47+- 3	40+- 2	10+- 0
7	11+- 0	17+- 0	40+- 2	52+- 3	44+- 2	12+- 0
8	11+- 0	17+- 1	44+- 2	56+- 3	48+- 3	13+- 0
9	11+- 0	18+- 1	47+- 3	61+- 3	52+- 3	14+- 0
10	11+- 0	19+- 1	50+- 3	65+- 4	56+- 3	15+- 0

Figure 13(f). The WAT Sensitivity Analysis

SELECT DISPLAY (OFR,EGD,EAD,WAT,WAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-SENS

SELECT EITHER A6,A7,F14,EAD,EGD,WAT, OR
WAC AS THE INDEPENDENT CONDITIONING ELEMENT-WAC

	0600	0700	0800	0900	1000	1100
1	10+- 0	16+- 1	43+- 3	59+- 3	50+- 3	13+- 0
2	10+- 0	16+- 1	44+- 3	59+- 3	50+- 3	13+- 0
3	11+- 0	16+- 1	44+- 3	59+- 3	50+- 3	13+- 0
4	11+- 0	16+- 1	44+- 3	59+- 3	50+- 3	13+- 0
5	11+- 0	17+- 1	45+- 3	59+- 3	50+- 3	13+- 0
6	11+- 0	17+- 1	45+- 3	60+- 3	51+- 3	13+- 0
7	11+- 0	17+- 1	45+- 3	60+- 3	51+- 3	13+- 0
8	11+- 0	17+- 1	46+- 3	60+- 3	51+- 3	13+- 0
9	11+- 0	18+- 1	46+- 3	60+- 3	51+- 3	14+- 0
10	12+- 0	18+- 1	46+- 3	60+- 3	51+- 3	14+- 0

Figure 13(g). The WAC Sensitivity Analysis

NOTE: Information entered by the decision maker is underlined.

tabular displays all the allowable strike times are listed. Each row corresponds to a different value for the conditioning element under consideration. For the A-6, A-7, and F-14 analyses, these are the numbers of the respective aircraft actually launched; for EAD, each line is an assumed number of available enemy aircraft (in increments of 10); for WAC and WAT, each line is a successively higher value of the weather index (in increments of 0.1). Entries under the column headings are the expected utilities and their standard deviation.

If the decision maker selects the EGD sensitivity analysis, the aid asks the decision maker to enter a hypothesized distribution of values for the four EGD states. It then outputs a table similar to those output by the other sensitivity analyses, based upon the hypothesized distribution.

4.9 THE LOSS NOMOGRAPH

When the outcome calculator is used as the underlying decision algorithm, information is available from the aid on the actual expected number of own aircraft lost, segment by segment, and the corresponding expected enemy losses. The former information is available to the decision maker in the LOSS nomograph; the latter has not been implemented at the present time.

The LOSS nomograph (Plate 3) is a four-quadrant nomograph, the axes of which represent different mission segments. The number of aircraft launched is represented along the x axis; the number enroute, along the +y axis; the number that reach the target, on the +x axis; the number on the return leg, on the -y axis; and the number that land safely, on the -x axis. The decision algorithm plots the between-segment losses and displays them by a line drawn in each quadrant. The nomograph is used by hypothesizing a number of aircraft launched and drawing a line from the corresponding point along the -x axis parallel to the y axis until it intersects the line in that quadrant, at which time a line is drawn parallel to the x axis until it intersects the y axis. The process is repeated around the nomograph until the -x axis is again reached. The resulting distance between the "launched" and "landed" values on the -x axis permits a quick estimation of the number of Blue aircraft lost.

The decision aid performs this process for the decision maker automatically. When the decision maker requests the LOSS nomograph, the aid responds with the instruction:

ENTER DESIRED CALCULATION TIME

When the decision maker has entered a time, the aid draws the axes and the reflection lines. It then asks the decision maker to

ENTER NUMBER OF AIRCRAFT LAUNCHED

The lines corresponding to the desired number of aircraft are then drawn for the decision maker (Plate 4). Up to six values can be displayed, after which the aid automatically asks the decision maker to select a new display. The number of aircraft expected to land is printed on the tabular display (Figure 14).

4.10 SAMPLE DECISION PROBLEM

As an example of the evaluation process faced by the decision maker using ADA, consider the following problem.

```
SELECT DISPLAY (OFR,EGD,EAD,VAT,VAC,STATE,OUTCOME,LEGD,LEAD,
PST,SENS,RUNS,RUNO,LOSS,STOP, OR HELP)-LOSS

ENTER DESIRED CALCULATION TIME-0700
ENTER NUMBER OF AIRCRAFT LAUNCHED-5
EXPECTED NUMBER OF AIRCRAFT LANDED-     4
ENTER NUMBER OF AIRCRAFT LAUNCHED-10
EXPECTED NUMBER OF AIRCRAFT LANDED-     9
ENTER NUMBER OF AIRCRAFT LAUNCHED-15
EXPECTED NUMBER OF AIRCRAFT LANDED-    13
ENTER NUMBER OF AIRCRAFT LAUNCHED-20
EXPECTED NUMBER OF AIRCRAFT LANDED-    17
ENTER NUMBER OF AIRCRAFT LAUNCHED-25
EXPECTED NUMBER OF AIRCRAFT LANDED-    20
ENTER NUMBER OF AIRCRAFT LAUNCHED-30
EXPECTED NUMBER OF AIRCRAFT LANDED-    23
```

Figure 14. The LOSS Display

NOTE: Information entered by the decision maker is underlined.

The decision maker (the task force commander) has just been informed by his senior operations officer that the assault force which had debarked earlier in the day arrived on land and was progressing toward their objective. In order for the ground assault force to reach their objective by 1400 hours the following day, they would cross the main bridge early in the morning. The intelligence officer reported that an enemy mechanized division appeared to be aware of the assault force objective and was progressing toward the same bridge with an ETA of 1100 hours. The operations officer properly concluded that an air strike to destroy the bridge after friendly forces had crossed, but prior to the enemy mechanized division's crossing was desirable and brought the problem of ordering an air strike to the task force commander's attention.

The task force commander was aware that enemy forces maintained a continuous air intercept force around the bridge area. A successful bombing run would require a complement of 18 air superiority fighters and 12 or more fighter bombers. Because of the uncertainty of crossing time both for friendly and hostile forces, the task force commander has a great preference to conduct the air strike at 0900; a lesser but significant preference for conducting it at 0800 or 1000; and feels that conducting the strike at 0700 or 1100 is of marginal positive value. Due to the limitations of the crossing times, there are no other practical times worthy of consideration.

The task force commander calls for execution of ADA with time preference factors set to the following values for the period 0600 through 1100 hours -- 0, 0.2, 0.8, 1.0, 0.8, 0.2. He begins execution of the aid and asks his intelligence officers to provide their most current inputs on available own forces, enemy airborne fighter capability and weather, both at the target and landing areas. After examining the value assignments, the commander expresses satisfaction with present values and weights and commences execution of ADA.

ADA presents its principal output to the commander. The expected utilities and their range of variation predicted by the aid are virtually identical for the strike times 0800, 0900 and 1000. However, upon examining the possible variation of the results at 1000, the commander estimates this as a less desirable option. He is thus faced with the choice of selecting 0800 or 0900.

In order to make this selection, the commander calls for a display of the sensitivity of the results to knowledge of the enemy's airborne fighter force. The commander knows that this input is based on aging intelligence data which he considers highly suspect. The sensor system used to obtain this data has recently given erratic responses. The commander observes that the utilities predicted by ADA correspond to a point in the sensitivity analysis for 0800 where a variation of only 20 percent in the intelligence estimate would significantly alter expected results. However, a similar impact is not observed at 0900. This leads the commander to request display of the enemy air defense data input to ADA. Upon seeing this display, the commander observes that the intelligence officer has entered a constant expected value with an increasing variation with time. However, the variation assigned for 0800 hours is deemed overly optimistic given the recent reliability of the sensor system. The commander therefore changes the input assumption to allow for a larger possible variation and re-executes the aid. The primary output display now clearly predicts that the greatest expected achievement and narrowest range of variation will occur at 0900.

The commander now wishes to examine whether any increase in his planned strike force will give him a further guarantee of achieving his objective. He therefore calls for the loss nomograph. The loss nomograph shows him that of the losses he can expect to suffer in executing the air strike, the major component occurs inbound toward the target rather than over the target area. The task force commander therefore concludes that by increasing the number of fighter bombers, he can saturate the inbound airborne defenses and allow a larger number of bombers to reach the bridge area unimpeded by further enemy defenses. Accordingly, the task force commander decides to launch his air strike such that the bridge will be destroyed at 0900 hours and to increase his planned force mix to use all available fighter bombers.

This discussion is a hypothetical example of how the decision aid could be used in support of a tactical decision problem. It is quite similar to the prototype implementation of ADA, but is enough removed to emphasize the tactical bases and methods of use of many of the features that have been incorporated in the aid.

V. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In developing the nomograph decision aid described in this report five major goals were accomplished.

- Development of a decision aid that permits the generalization of the parameters in the decision algorithm, e.g., unlimited numbers of conditioning elements, use of discrete and continuous, Bayesian and non-Bayesian updated parameters, etc.
- Incorporation of uncertainty in inputs in such a way that it is clearly represented in the outputs.
- Inclusion of a capability for handling problems in which the states of the conditioning elements are time-dependent.
- Development of display techniques that are readily understandable and interpretable by the target population of decision makers.

- Development of a methodology that can be adapted to different decision making algorithms, e.g., both state models and outcome calculators, with inputs and outputs that can be readily related to real-world quantities.

During the development of the decision aid, we had the opportunity to observe the behavior of several different decision makers as they became acquainted with the aid. These experiences led to the following conclusions which are probably useful considerations with respect to any decision aid being developed:

- Presentation of the potential variability of an outcome gives a decision maker the opportunity to take risks from a more informed perspective.

- The ability to examine the sensitivity of an outcome to changes in inputs enables the decision maker to consider alternative ways to accomplish his goals by redirecting his resources; it also enables him to develop a better feel for the possible perturbations in outcomes that could be expected due to changes in the input conditioning elements.

- The ability to describe the outcomes in concrete terms, e.g., "own aircraft lost" and "percent target destruction," add to the acceptability of the aid.

- It is very difficult for a decision maker to establish and use a consistent set of rules governing the association of utilities with states; assignments of utilities to outcomes are much more readily and consistently achievable (and are more clearly interpreted as a common unit for multi-attribute combination as would be equivalent aircraft or equivalent dollars for example).

5.2 RECOMMENDATIONS

There are two major courses of action to pursue -- experimental evaluation and development/refinement. Since further development/refinement should logically take advantage of lessons learned in experimental evaluation, Analytics recommends that an experimental evaluation program be undertaken to determine:

- How specific design variations in graphic presentation (such as use of color, complexity of displays, output of physical attributes versus or in conjunction with utilities) impact performance.
- Whether flexibility as embodied in the aid is an asset to decision makers.
- How the state model compares with the outcome model.
- How the nomograph display technique compares with other approaches such as those used by DDI (Reference 1) and/or NPRDC (Reference 2).

Further, during such evaluation preliminary information on cost/benefit should be accumulated to aid ONR in an overall evaluation of alternatives for automated decision aiding.

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APPENDIX A. THE SCENARIO

A.1 SOURCE MATERIAL

The scenario employed in developing the specific problem implemented in the Analytics decision aid was derived from Stanford Research Institute Memorandum NWRC-RM-83, ONRODA Warfare Scenario (Reference 2). The portion of the scenario that concentrates on air strikes on the ONRODA airport begins on page 55 of the SRI publication. The air strikes are addressed as Phase I of operations in OPORDER CTF-1, No. 1-7X, and its annexes (especially Annex E). The scenario is briefly summarized below.

A.2 THE SETTING

CTF-1 is situated 400 nmi west of ONRODA Island as shown in Figure 1. CTF-1 consists of two CVs each with twelve A-6, twenty-four A-7, and eighteen F-14 aircraft; there are additional support aircraft. Both CVs have off-loaded RA-5C aircraft at Mid-Ocean Island to assist in scheduled reconnaissance operations.

Daylight extends from 0600 to 1800 hours daily. Weather in the area is generally clear with winds variable from 12 to 15 knots NW. There are occasional frontal passes with associated light rain and 20- to 25-knot SW winds. Fronts generally pass in 12 hours or less. During frontal passes, there are broken clouds above 4000 to 5000 feet. On approximately 10 percent of all mornings, there is ground fog.

The ONRODA terrain is quite flat. The airport is located in rolling hills no higher than 250 feet above sea level.

Intelligence estimates indicate an enemy fighter capability of 120 planes located on the island. There are also 37 SAM and AA batteries. The Orange air force conducts routine strikes on Gray cities from the ONRODA base of operations.

A regular schedule of RA-5C flights has been established to give updated estimates of Orange air activity and weather at ONRODA every 4 hours.

A.3 CONCEPT OF OPERATIONS

Blue air forces will be launched in Alpha strike complements of six A-6, eighteen A-7, and eight F-14 aircraft by each CV including all supporting air platforms. Due to political considerations, all flights are restricted to operate north of latitude NS. The oporder calls for ground level approach from outside radar detection range as well as avoidance of Red picket ships outside the strike perimeter.

The strike objectives are destruction of aircraft and ground defenses. Secondary objectives will be added in later days of the strike.

The oporder calls for 2 Alpha strikes per carrier per day during daylight. Aircraft ordnance will consist primarily of LGBs and visual acquisition weapons. Since strike mission time is 2½ hours, a minimum strike cycle time of 5 hours is recommended. The maximum number of aircraft consistent with the desired complement must be launched.

On the first day of the campaign, each CV launches 2 Alpha strikes at predetermined times to achieve surprise. On subsequent days, only 1 CV will launch strikes while the other performs the air defense mission. The CVs will alternate functions.

Pilot debrief will be available no less frequently than every 18 hours on AA counterfire experienced in the prior raid. By direction, the readiness officer will provide updates at least at 0600, 1200, and 1800 hours including the period through the next report.

Due to concurrent blockade operations, it is presumed the enemy cannot resupply lost aircraft or defenses.

APPENDIX B. STATE MODEL ALGORITHM

B.1 INTRODUCTION

This appendix presents a single thread description of the state model algorithm used in ADA, which is based upon a model suggested by DDI (Reference 1) and extended by Analytics to include both larger numbers of conditioning elements and continuous measures of the state of the world. This model includes the following features:

- Unlimited number of alternatives.
- Unlimited number of conditioning elements.
- Continuous conditioning elements as well as discrete many-state elements.
- Time-dependent states of the world.
- Time-extensive alternatives.
- Unlimited number of criteria.

- Time preference for action.
- Bayesian probability updating.

Because of constraints imposed by the test implementation, specific limits were set on those parameters with potentially unlimited numbers. The technique, however, does not have any of the limitations implied by these selections.

The reader is referred to the DDI report cited in Reference 1 for the development of the methodology used here. That reference also explains the application of multi-attribute utility assessments and Bayesian updating as incorporated here.

The scenario is described in Appendix A.

B.2 CRITERIA

Elemental utilities will be assigned for two criteria (C):

- Target destruction (C_{TD}).
- Loss of own force resources (C_L).

Weights W_{TD} and W_L, subject to the constraint $W_{TD} + W_L = 1$, will be used to combine the utilities associated with each criterion into a composite expected utility. Default values for these weights will be 3/4 and 1/4, respectively.

B.3 MISSION PROFILE

The mission consists of five segments whose times relative to the time of launch, L, are listed in Table B-1.

TABLE B-1. MISSION SEGMENTS

SEGMENT	NAME	TIME
I	Launch	L to L + 30
II	Enroute	L + 30 to L + 70
III	Target	L + 70 to L + 90
IV	Return	L + 90 to L + 120
V	Landing	L + 120 to L + 150

B.4 CONDITIONING ELEMENTS

The conditioning elements used in the algorithm are shown in Table B-2.

B.4.1 Readiness

B.4.1.1 OFR

It is presumed that one of the CVs in CTF-1 will provide the support aircraft needed for the strike (one E-2, one EA-6, and three KA-6).

For each time interval (one hour) in the planning range (six hours), the readiness officer will be requested to input the expected value and probable error* of aircraft available by type in response to questions of the form:

> At 0600 hours, what will the expected number of A-6s available be? ________
> with probable error ± ________.

The readiness officers' responses are used to generate a table of the form shown in Figure B-1.†

These values are considered to be the mean (μ) and standard deviation (σ) of a discrete distribution (whose envelope is the normal distribution) truncated over the ranges

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* Probable error here is equated with sigma (σ) rather than with the formal definition of 0.6745 σ.

† The values shown in this and in all other tables are the default values used in the decision aid.

TABLE B-2. CONDITIONING ELEMENTS USED IN DECISION ANALYTIC ALGORITHM

SEGMENT	NAME	DESCRIPTION	RANGE	DISTRIBUTION	BAYESIAN
I	Fighter Own Force Readiness (OFR_F)	Number of F-14	0-18	Normal (μ, σ) Discrete	No
	Bomber Own Force Readiness (OFR_B)	Number of A-7 Plus A-6	0-36	Normal (μ, σ) Discrete	No
II	Enemy Force Readiness — Enroute (ERF_{II})	1/16 of available fighter aircraft on ONRODA	0-5	Normal (μ, σ) Discrete	Yes
III	Enemy Force Readiness at Target (EFR_{III})	3/16 of available fighter aircraft on ONRODA	0-15	Normal (μ, σ)	Yes
	Enemy Ground Defenses (EGD)	Ground AA	—	Four States None Low Moderate High	Yes
	Weather at Target (WAT)	Target visibility index	0-1	Probabilistic	No
IV	Enemy Force Readiness Return (EFR_{IV})	0.194 of available fighter aircraft	0-16	Normal (μ, σ) Discrete	Yes
V	Weather at Carrier (WAC)	Landing weather index	0-1	Normal (μ, σ) Continuous	No

A/C \ TIME	A-6	A-7	F-14
0600	6 ± 1	12 ± 6	10 ± 1
0700	7 ± 1	14 ± 4	12 ± 2
0800	8 ± 1	16 ± 2	14 ± 2
0900	9 ± 1	18 ± 2	16 ± 2
1000	10 ± 1	20 ± 2	16 ± 2
1100	11 ± 1	22 ± 2	16 ± 2

Figure B-1. OFR Table

A/C \ TIME	OFR_F	OFR_B
0600	10 ± 1	$18 \pm \sqrt{37}$
0700	12 ± 2	$21 \pm \sqrt{17}$
0800	14 ± 2	$24 \pm \sqrt{5}$
0900	16 ± 2	$27 \pm \sqrt{5}$
1000	16 ± 2	$30 \pm \sqrt{5}$
1100	16 ± 2	$33 \pm \sqrt{5}$

Figure B-2. Combined OFR Table

0 to 12 (A-6), 0 to 24 (A-7), and 0 to 18 (F-14).* The fighter own force readiness is simply the number of F-14s:

$$OFR_F = OFR_{F-14}$$

The A-6 and A-7 are combined to form a bomber own force readiness estimate:

$$OFR_B = OFR_{A-6} + OFR_{A-7}$$

Thus, from Figure B-1 and the fact that if A and B are independent anJ

$$C = A + B$$

then

$$\sigma_C = \sqrt{\sigma^2_A + \sigma^2_B}$$

and

$$\mu_C = \mu_A + \mu_B$$

a combined OFR table of the form shown in Figure B-2 can be formed.

* Truncation is performed over the range of available aircraft on the CV.

B.4.1.2 Relationship Between EAD, EFR_{II}, EFR_{III}, and EFR_{IV}

Based on the scenario, it is assumed that only aircraft will be encountered enroute. After S-day, the enemy has between 0 and 80 fighters. Given a μ and σ, and assuming a normal distribution, a prior P for n = 0, 1, ..., 79, 80 can be generated. The default distribution used in the decision aid has a μ of 50 and a σ of 10.

Intelligence on enemy aircraft comes from RA-5C reconnaissance. They report every 4 hours on target conditions, including fighters airborne for intercept. Since Orange can expect attack at any time of day, it is <u>assumed</u> that he will keep 1/4 of his available fighters airborne. It is also <u>assumed</u> that the fighters are distributed such that 1/4 of those airborne (1/16 of those available) will be encountered enroute, thus

$$EFR_{II} = \frac{1}{16} \text{ EAD}$$

If the states of the relevant indicator for EAD (up aircraft seen by RA-5C) are $\leq$ 5, 6 to 10, 11 to 15, and $\geq$ 16, the general appearance of the EAD Bayesian updating process would appear as in Table B-3.

It is assumed that the intelligence data has a useful lifetime of only 4 hours. Therefore, when a decision is to be made, for all launch times $\leq$ 170 minutes after the time at which the reported indicator was obtained, the posterior probabilities obtained from applying the likelihood ratios to the priors are used. For all times > 170 minutes, the prior probabilities are used. (The 170-minute breakpoint derives from the 4-hour useful lifetime minus the 70 minutes required for the completion of Segment II after the start of the mission.)