AN APPLICATION OF MULTI-ATTRIBUTE UTILITY THEORY: DESIGN-TO-COST EVALUATION OF THE U.S. NAVY'S ELECTRONIC WARFARE SYSTEM

DECISIONS AND DESIGNS INCORPORATED

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Introduction. This report reflects the development, validation, and utilization of a multi-attribute utility (MAU) model for use by the Naval Electronic Systems Command (NAVELEX) in comparing and evaluating six Electronic Warfare (EW) suite design proposals submitted by contractors under new design-to-cost policies enunciated by the Department of Defense (DoD) in its directive 5000.1 (Acquisition of Major Defense Systems) and, subsequently, in its directive 5000.28 (Design to Cost).

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Background and Approach. In light of Secretary of the Navy Instruction (SECNAVINST) 5000.1, which implemented DoD Instruction 5000.1, NAVELEX engaged the services of a contractor (Decisions and Designs, Incorporated) to assist in the development of a Request for Proposal (RFP) and a means of evaluating the design proposals which would be submitted in response to the RFP for an EW system, a group of sophisticated and complex suites for detecting and responding to different threats to different Naval surface vessels in different situations. As a result, a MAU model was developed and validated for use by NAVELEX.

The approach used in the development of the MAU model was to create a hierarchical structure by means of which higher-level elements were successively decomposed into sub-elements in order to relate the degree to which measured performance levels of technical system characteristics enhanced the worth of the EW suite design proposals.

After completing the hierarchical structure of the model, Navy experts quantified the relationships among the elements at the same levels, assessed the effectiveness of varying performance levels of controllable parameters and assigned weights to each component. The last steps in developing the model consisted of validating or modifying the resulting model in the light of sensitivity analyses and calibration based on data from existing EW suites.

Findings and Implications. Implementation of DoD Directive 5000.1 in the design and evaluation stage of the Navy's EW System marked the first time that the design-to-cost procurement policies had been implemented from the very initiation of a program to procure a major military system. It also marked the first time that a MAU model, a device with broad decision analytic applications to problems of evaluation, had been applied to the design and evaluation of a major military system. In this case, several iterations of the model reduced the number of contractors from six to the two who are now undertaking engineering development of prototype systems. The Navy is modifying the model used for initial selection in order to evaluate the two prototype systems and, on the basis of this evaluation, to select the better one.

Although the development and utilization of the MAU model was successful in the case of the Navy's EW System, it is apparent that additional research is needed to (1) ensure the systematic selection of scenarios that are representative of the population of possible scenarios and that discriminate among the alternatives being evaluated; and (2) ascertain the effects of approximating complex relationships by using relatively simple combination rules.

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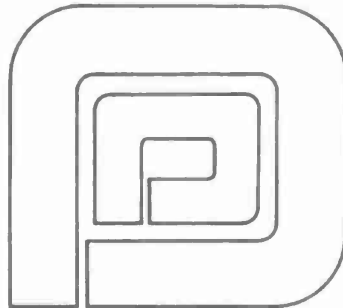# AN APPLICATION OF MULTI-ATTRIBUTE UTILITY THEORY: DESIGN-TO-COST EVALUATION OF THE U.S. NAVY'S ELECTRONIC WARFARE SYSTEM

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October, 1975

SUMMARY

Introduction. This report describes how Department of Defense (DoD) and Secretary of the Navy (SECNAV) design-to-cost policies led to the development and use of a multi-attribute utility (MAU) model for evaluating suite design proposals for the Navy's Electronic Warfare (EW) System. It also explains how that model or evaluating mechanism functions.

Background and Approach. Faced with increasing costs and tightening budgets in the procurement of major military systems, DoD promulgated a new procurement policy in 1971 linking designed performance and its attendant benefits to cost ceilings. This policy, which is enunciated in DoD Directive 5000.1, stated that:

> discrete cost elements (e.g., unit production costs, operating and support cost) shall be translated into 'design to' requirements.[1]

The intent of this policy statement was to emphasize the need to balance (by means of an interactive design process) system performance, costs, and schedules with the quantities required to achieve the most effective military capability with available DoD resources.

The design-to-cost concept introduced by the 1971 DoD Directive has recently been superceded by DoD Directive 5000.28, which further states that:

> The Design to Cost concept establishes cost as a design parameter during a system's design and development phase and provides a cost discipline to be used throughout the acquisition and operation of a system.[2]

Meanwhile, in light of Secretary of the Navy Instruction (SECNAVINST) 5000.1, which implemented DoD Instruction 5000.1, the Naval Electronic Systems Command (NAVELEX) engaged the services of a contractor[3] to assist in evaluating the suite design proposals which would be submitted in

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[1] Acquisition of Major Defense Systems, DoD Directive 5000.0, July 13, 1971.

[2] Design to Cost, DoD Directive 5000.28, May 23, 1975.

[3] Decisions and Designs, Incorporated (DDI).

response to the Request for Proposal (RFP) for the Navy's
EW System, a group of sophisticated and complex suites for
detecting and responding to different threats to different
naval surface vessels in different situations.

Results. Implementation of the foregoing policies in
the design and evaluation stages of the Navy's EW System
marked the first time that design-to-cost procurement
policies had been implemented from the very initiation of a
program to procure a major military system. It also marked
the first time that a MAU model, a device with broad decision-
analytic applications to problems of evaluation, had been
applied to the design and evaluation of a major military
system. In this case, the model was used as an evaluating
mechanism to select two contractors from among six, who were
then to initiate the engineering development of prototype EW
suites.

Research Implications for MAU Model Development. This
application pointed to two important methodological issues
in need of further in-depth research. One is the design and
use of scenarios for the evaluation of suites to be deployed
in an uncertain future. The other is the sensitivity of MAU
models to the effects of approximating the complex relation-
ships that exist among factors in the model.

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ACKNOWLEDGMENT

ABBREVIATIONS

DoD	Department of Defense
EW	Electronic Warfare
MAU	Multi-Attribute Utility
NAVELEX	Naval Electronic Systems Command
RFP	Request for Proposal
SECNAV	Secretary of the Navy
SECNAVINST	Secretary of the Navy Instruction
TSU	Technical Systems Utility

AN APPLICATION OF MULTI-ATTRIBUTE UTILITY THEORY: DESIGN-TO-COST EVALUATION OF THE U.S. NAVY'S ELECTRONIC WARFARE SYSTEM

1.0   INTRODUCTION

Faced with increasing costs and tightening budgets in the procurement of major military systems, the Department of Defense (DoD) promulgated a new procurement policy in 1971 linking designed performance and its attendant benefits to cost ceilings. This policy, which was enunciated in DoD Directive 5000.1 and subsequently implemented by means of instructions published by each of the Military Services, stated that:

> discrete cost elements (e.g., unit production costs, operating and support cost) shall be translated into 'design to' requirements. System development shall be continuously evaluated against these requirements with the same rigor as that applied to technical requirements. Practical tradeoffs shall be made between system capability, cost, and schedule. Traceability of estimates and costing factors, including those for economic escalation, shall be maintained.[1]

The intent of this policy statement was to emphasize the need to balance (by means of an interactive design process) military costs and management with the quantities required to achieve the most effective military capability with available DoD resources.

The design-to-cost concept introduced by DoD Directive 5000.1 has recently been superceded by DoD Directive 5000.28, which further states that:

> The Design to Cost concept establishes cost as a design parameter during a system's design and development phase and provides a cost discipline to be used throughout the acquisition and operation of a system.[2]

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[1] Acquisition of Major Defense Systems, DoD Directive 5000.1, July 13, 1971.

[2] Design to Cost, DoD Directive 5000.28, May 23, 1975

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Meanwhile, in light of Secretary of the Navy Instruction (SECNAVINST) 5000.1, which implemented DoD Instruction 5000.1, the Naval Electronic Systems Command (NAVELEX) engaged the services of a contractor[3] to assist in evaluating the suite design proposals which would be submitted in response to the Request for Proposal (RFP) for the Electronic Warfare (EW) System, a group of sophisticated and complex semi-automated, computerized suites for detecting and responding to different threats to different naval surface vessels in different situations.

1.1 Purposes of the Report

The purposes of this report are:

1. To describe how the effective DoD and Secretary of the Navy (SECNAV) design-to-cost policies affect the evaluation phase in the procurement policy;

2. To describe and compare approaches to evaluation and to explain the selection of the multi-attribute utility (MAU) approach;

3. To relate the circumstances in which the Navy employed the MAU approach in evaluating EW suite design proposals;

4. To explain the development and application of the MAU model for evaluating those proposals; and

5. To outline those areas in which further research in MAU models and their application is required.

1.2 Background and Scope

The research conducted by the contractor in developing the MAU model for evaluating EW suite design proposals has a certain historical and technical interest. Although design-to-cost policies have been in effect since 1971, their early implementation was limited to systems already beyond the design and development stage and ensured only that the systems would be produced within previously budgeted limits. The design and evaluation stage of the Navy's EW System, however, marked the first time that design-to-cost procurement policies had been implemented from the very initiation of a program to procure a major military system. It also marked the first time that a MAU model, a device with broad

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[3]Decisions and Designs, Incorporated (DDI).

decision-analytic applications to problems of evaluation, had been employed in the procurement of a major military system. Since the EW System is not yet in production, much less in operation, experience with this and other systems procured under design-to-cost policies must be acquired before a final verdict on their ultimate value and that of the models may be made. This report makes no effort, therefore, to address this issue.

Instead, it attempts only to set forth the implications of these policies for design and to show how a MAU model was employed to assist in evaluating suite design proposals submitted under provisions of these policies and served as one means of selecting two from among six design proposals for further engineering development of prototypes for testing. Specifically, although a MAU model was employed throughout the entire evaluation, it was developed and applied extensively only in the evaluation of technical systems utility (TSU). Other elements of military worth or of cost and management were evaluated differently.

2.0   DESIGN-TO-COST PROCUREMENT POLICIES AND THEIR IMPLICATIONS FOR TECHNICAL SYSTEMS DESIGN

Changes in procurement policies obviously involve new procurement practices and require new responses in system design. Design-to-performance and design-to-cost procurement policies both relate performance and cost, but each does so differently, by placing different emphasis upon the one or the other. Since their impact upon system design is also different, an understanding of the differences between the two kinds of procurement policies as they affect system design encompasses the reasons for the change and suggests means of adapting to it.

Under a design-to-performance procurement policy, performance requirements in the RFP are stated as absolute descriptions of needs. Any system failing to meet the stipulated requirements is defined as essentially worthless. If, for example, the requirement that a military system respond within ten minutes to a distant threat were taken literally, a system responding within ten-and-a-half minutes would be regarded as worthless. However, in most cases, such a system would not be worthless, only worth less than a system actually satisfying the requirement. Taken literally, such a requirement implies a price-is-no-object attitude toward design because the technology necessary to satisfy the requirement may be extremely expensive. Although seldom reflected in practice, such an attitude is implicit in performance requirements and can lead to over-designed systems. Since over-design is as much an economic as an engineering concept, a design-to-performance procurement policy may over-emphasize performance and lead to cost overruns, reduced acquisitions, or compensatory sacrifices in operational performance elsewhere in the system.

Under a design-to-cost procurement policy, these problems may be reduced or eliminated. Rather than stating absolute performance requirements, the policy stipulates a production cost ceiling for each unit of the system and allows the levels of performance to vary within certain limits. These variable levels of performance are suitably valued across that range. Accordingly, since the design of a system requires the maximum value of performance within a budgetary constraint, over-design is less likely, military value is maximized, and the risks of cost overruns, insufficient acquisitions, and compensatory sacrifices in operational performance are minimized in most cases. There is some controversy whether or not more modest levels of

performance dictated by cost-per-unit ceilings will be
sufficient to meet mission requirements in certain special
cases. This, however, is not an issue addressed in this
report.

For this contractor, the most immediate implications
involve his responsibilities for a new system. Previously,
when a Military Service defined the technical requirements
of a system, the contractor's primary responsibility,
theoretically, was to propose a system design meeting those
requirements. He also attempted to determine a means of
producing the proposed system within minimum production
standards of quality at a cost lower than that of a com-
petitor. Presently, since a Military Service simply out-
lines the mission requirements of a system in rather general
terms and states the production cost-per-unit ceiling and
since all contractors have the same production ceilings and
standards to meet, their primary responsibility is to propose
a system design offering more and efficient technical ad-
vantages, not lower cost, than does a system design developed
by a competitor.

In practice, the design-to-cost procurement policy is
governed by three dominant considerations: one, the prob-
ability of meeting production and installation schedules;
two, the acceptability of development and acquisition costs;
and, three, military worth.

First, after issuing an RFP and receiving proposals in
reply, the Military Service must estimate the likelihood
that each contractor can meet the production and instal-
lation schedules if his proposal were accepted. This
estimate is based upon assessments of, among other con-
siderations, the contractor's past performance in fulfilling
Government contracts and his capabilities to produce the
proposed system along with his other, possibly unrelated,
production commitments.

Second, the Military Service must judge the expense
required to develop a working prototype for testing. Since
the burden of designing a system under design-to-cost pro-
curement policies falls largely upon each contractor, the
Military Service has paid selected contractors to develop
their proposals.

Third, (and of major concern in this case study), the
Military Service must evaluate the military worth of a
contractor's design proposal and compare that proposal with
other, often quite different, proposals. For implicit in
design-to-cost procurement policies is a tacit reliance upon
the ingenuity of each contractor to achieve maximum value
for a stipulated cost. The flexibility permitted by the
absence of specific technical requirements allows each

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contractor to develop a proposal which appears to him to
meet best the requirements of a given system. Since flexi-
bility allows diversity--each contractor develops a design
that reflects his particular corporate interests, his under-
standing of the mission, and his technical and manufacturing
capabilities--some method of evaluating system design proposals
that may be quite different from each other is required.
The general requirements for such an evaluating mechanism
are described in Section 3.0.

3.0 GENERAL APPROACHES TO TECHNICAL SYSTEMS EVALUATION

3.1 Criteria for Evaluating Mechanisms

The logic of evaluation and the nature of competitive bidding require that any program for evaluating design proposals be carefully constructed to meet four general criteria; namely, it must:

1.   Discriminate effectively among the alternative design proposals. Any program of evaluation must not only differentiate among proposed designs, but also rank them in order of their worth.

2.   Be reliable. The program must reproduce for any evaluator consistently similar results from similar information and options.

3.   Be intelligible. The program must have an explicit logic that facilitates understanding of the relationships between the data and the results of the evaluation.

4.   Be equitable. The program must have no inherent bias. Each design proposal must have the same · chance a priori to be selected as does any other proposal.

These criteria are fairly general and do not preclude the use of a number of different procedures or approaches, like simulation runs, global assessments, or MAU models. In fact, it is common practice for two or more of these procedures or approaches to be employed simultaneously on different aspects of an evaluation problem. Any program for evaluation, however constituted but meeting these criteria, has but one operational purpose: to relate available data relevant to the evaluation of a proposed system design to its total worth to the Military Service. Since the scope of this report is limited to the use of a MAU model in evaluating technical systems utility (TSU) of the EW suite design proposals, the purpose of this particular model is to relate measures of performance levels of the controllable parameters of a design proposal to the military worth of the proposed system. Examples of such parameters are detection range, number of targets prior to saturation, and effective radiated power. For the sake of brevity, "performance levels of the controllable parameters" will be called, simply, "technical characteristics."

The first two of these criteria, discrimination and reliability, are satisfied or not by the nature of the model--in this case, the MAU model--for evaluating design

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proposals. A means of ensuring that the third criterion, intelligibility, is fulfilled is to structure the evaluating mechanism so that the paths from the data to the results of the evaluation are explicit in the model.

To address the fourth criterion, equity, an evaluating mechanism for relating the data derived from diverse design proposals to the results of the evaluation must be comprehensive and flexible. Comprehensiveness ensures that all possible considerations known to be relevant prior to evaluating a design proposal are encompassed by the evaluating mechanism. Flexibility allows modification of the evaluating mechanism in the event of unforeseen relevant factors and thus ensures that arbitrary stipulations do not bias the evaluating mechanism against distinctive design proposals allowed by the latitude of design-to-cost RPF's. An evaluating mechanism meeting these four criteria ensures equity because it enables the Military Service to justify its selection or allows contractors to challenge it on a rational and constructive basis.

3.2   Possible Methodologies for Technical Systems Evaluation

The two questions addressed by a methodology for evaluating TSU of design proposals which meets the four criteria are: What is the actual performance of a system built according to its design proposal likely to be, and what is that level of actual performance worth? The first question requires a prediction as an answer, the second an evaluation. To predict performance of proposed systems, it would be ideal to have a clairvoyant capable of looking into the future in which the systems were built and of observing their technical effectiveness. Since no such clairvoyant exists, the problem becomes one of making the best-informed and best-reasoned predictions possible. To evaluate the predicted performance of such systems, it would be ideal to have a permanent and absolute standard of value. In lieu of one, the problem becomes one of making the best judgments possible.

The possible methodologies for system evaluation all involve one way o another both questions. It should be noticed that questions requiring a prediction should be answered separately from questions requiring an evaluation. Answers to questions requiring a prediction concern the effectiveness of the proposed system; answers to questions requiring an evaluation concern the utility of the proposed system. These distinctions between prediction and evaluation, and between effectiveness and utility will be observed throughout the rest of this paper as the details of possible methodologies are discussed. However, the problem to which such methodologies address themselves will be regarded as one of evaluation in a broader sense.

3.2.1 Approaches to predictions - There are essentially
two kinds of approaches to predictions: 1) personal assess-
ments ranging from guesses or hunches to expert opinion; and
2) predictive models. The line between the two is not so
sharp that models may not be biased in one way or another
and is further blurred by vagueness about the point at which
a proposal becomes too complex for a simple personal assess-
ment. Since most evaluation problems in the procurement of
military systems are very complex, however, predictive
models, because they pool knowledge and sophistication of
many experts, are preferred sources of predictions. Of
these, simulation models are commonly the most effective
means of predicting the effectiveness of proposed systems.
The impressiveness of simulation runs in predicting per-
formances, however, is no substitute for evaluating them.
Since prediction is quite different from evaluation, no
amount of performance data can yield a judgment of even so
simple a kind as "more is better" without involving a pre-
scriptive, not a descriptive, assertion. The point needs to
be emphasized because simulation runs, while often desirable
in any evaluation of system design proposals, are not by
themselves a possible methodology for system evaluation in
the broad sense of the term; rather, they are a means of
making predictions of performance characteristics.

3.2.2 Approaches to evaluations - There are
essentially two kinds of approaches to evaluations: 1)
global and 2) decomposed. The line between the two is not
always a sharp one because most global judgments result from
a few judgments of lesser scope. The difference between
them, though theoretically one of degree, is sharp enough,
however, to separate those approaches that are general and
implicit and those that are specific and explicit.

A global approach to evaluation consists of
global judgments which are ratings of an entire system (or
an entire sub-system) on one or more scales and are often
accompanied by written explanations. Because the scope of
global judgments is very large, there is usually a broad
intuitive leap from the information at hand to the judgment
in mind. Nevertheless, in evaluating systems or sub-systems
that are not complex, a global approach may be entirely
adequate and appropriate.

The difficulties of the global approach arise
most noticeably in cases involving the evaluation of complex
proposals. These include the inability to use all the
information available, the instability of evaluating stan-
dards, and a variety of biases. As a general rule, the more
heterogeneous and complex the information, the lower the

quality of the global judgment. Aids for reducing (or eliminating) the impact of these difficulties have been suggested but have not as yet proven themselves effective.[1]

A global approach to evaluation of complex design proposals, then, is not presently bound to satisfy at least three of the four criteria for an evaluating mechanism. Although it can discriminate among design proposals, it cannot ensure its reliability or intelligibility. Accordingly, there can be no assurance of its equity. These difficulties ultimately result from the broad intuitive leap from information to judgment.

The decomposed approach, on the contrary, is a means of systematically combining information and specific judgments to produce an evaulation of a design proposal. One such approach is known as a multi-attribute utility approach; its central principle is to address an evaluation problem by decomposing all the elements relevant to it into the smallest possible sub-elements and then to combine them, first into increasingly aggregated measures of effectiveness based upon predicted performance characteristics and then into increasingly aggregated estimates of utilities.

Since one of the purposes of this report is to explain the development and application of the MAU model for evaluating EW suite design proposals, especially their TSU, the explanation in Section 5.0 will show the ways in which the model satisfied the four criteria of evaluating mechanisms.

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[1] See, for example, Paul Slovic and Sarah Lichtenstein, "Comparison of Bayesian and Regression Approaches to the Study of Information Processing in Judgment," Organizational Behavior and Human Performance, 6.6 (November, 1971), 649-744.

4.0   IMPLEMENTING THE DESIGN-TO-COST PROCUREMENT POLICIES
        FOR THE NAVY'S ELECTRONIC WARFARE SYSTEM

4.1   Developing the Request for Proposal

Design-to-cost procurement policies, since they require
that design be integrated with management and cost in the
procurement process, imply the need for developing an RFP
with regard to the nature of the responsive design proposals.
The process begins with Navy experts addressing two general
kinds of questions: one, what kind of performance is re-
quired to accomplish what kinds of missions against what
kinds of threats in what kinds of environments; and two,
what is such performance worth and what factors affecting
operational performance can enhance or compensate for it?
The RFP which addressed these kinds of questions avoided
answering them with system requirements. Instead, it called
for the submission of design proposals for five interrelated
suites comprising the EW System--each suite with its own
cost-per-unit ceiling and each for a different class of
ships--and outlined the missions and scenarios for their
deployment. The RFP also indicated those considerations of
particular importance to the Navy, modularity and growth.
In providing funds to contractors for preparing their EW
suite design proposals, the Navy reduced expense while main-
taining competition by initially selecting six from among those
responding as most capable of designing and producing an EW
system.

4.2   The Evaluation Problem

Since the design-to-cost procurement policy permits,
even encourages, diversity in design proposals, and since
the RFP for an EW suite was general enough to ensure such
diversity, the Navy faced the problem of evaluating six
feasible, but potentially quite different, design proposals
and reducing this number to two. The two finalists were
then to undertake engineering development of prototypes for
testing and to submit more specific proposals for meeting
management and cost objectives from production through
operational deployment.

The general evaluation problem was, of course, to
evaluate the contractors' proposals in their entirety, that
is, their military worth, cost, and management. Although
the decomposed approach could have been used for cost (life-
cycle cost and risk with estimated cost) and management
(organization, plans and schedules, review cycles, change
mechanisms, and the like), it was not. Nor were sub-elements
of each system comprising military worth (acceptability of

operational performance) similarly decomposed. In fact, of eight such sub-elements, only TSU was decomposed into a hierarchically-structured model. The modeling effort described henceforward in this report concerns the determination only of TSU; that is, the Navy employed a fully developed MAU model in evaluating the benefit derived only from technical performance of design proposals. To address this specific evaluation problem, Navy experts, assisted by analysts of the supporting contractor[1], developed a MAU model, or evaluating mechanism, that would satisfy the criteria for evaluation.

4.3 The Methodology Selected

To evaluate TSU of the EW suite design proposals, the Navy preferred a model combining a decomposed approach supported by simulation runs to a global approach supported by them. These two approaches are represented graphically in Figure 4-1.
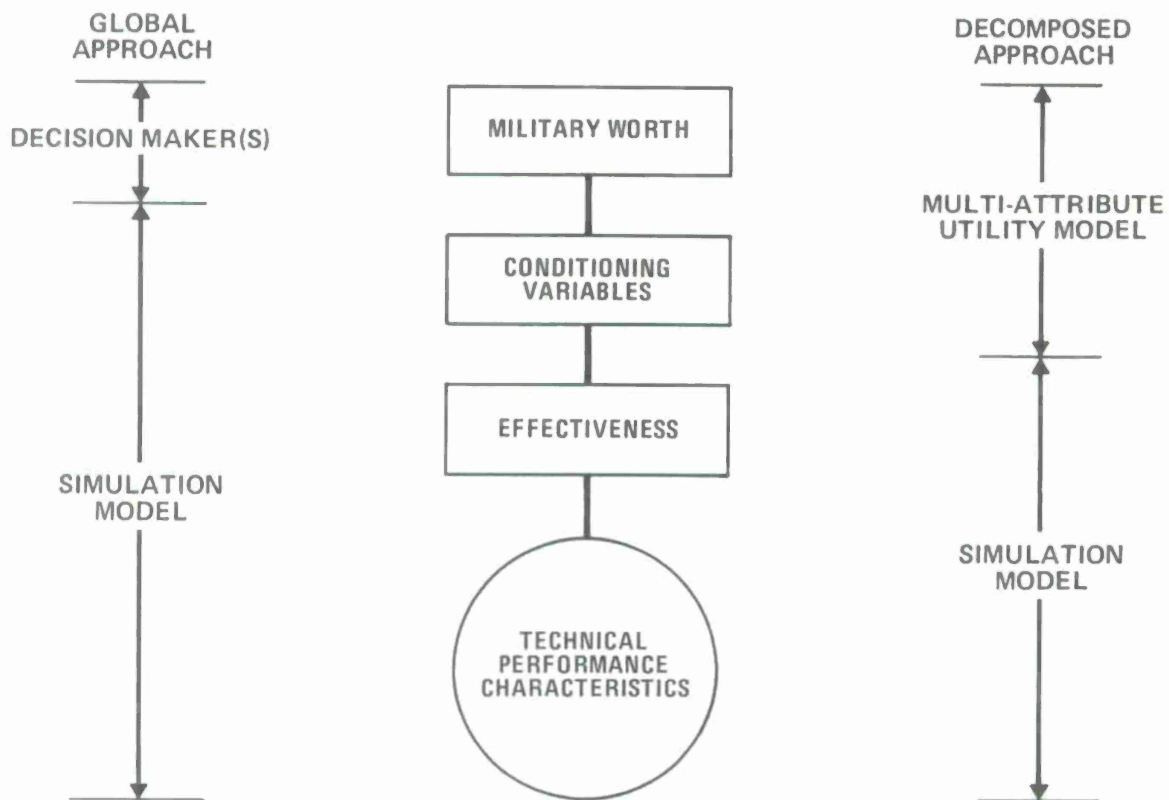

Figure 4-1

TWO POSSIBLE METHODOLOGIES FOR COMPLEX EVALUATIONS

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[1]Decisions and Designs, Incorporated (DDI).

One of the essential differences between them is that the
global approach more extensively employs simulation runs
than does the decomposed approach. The use of simulation
runs in the global approach extends up through certain
contextual aspects of performance, whereas in the decomposed
approach it extends no further than the strictly technical
aspects of performance. Another difference, of course, is
that the global approach attempts to evaluate military worth
by means of global judgments, and the decomposed approach,
in this case, by means of a formal MAU model.

The Navy preferred the latter approach for basically
two reasons. It found that the level of effort necessary to
use simulation runs at higher levels would result in a cost
exceeding funds allotted for evaluation. And it anticipated
that the decomposed--henceforth, MAU--approach would be more
intelligible and its requests more justifiable than the
global approach.[2]

In developing the model for TSU Navy experts, on the
basis of analytical studies and their operational experience,
assessed the probabilities, weights, and utility curves
called for by the model. In particular, the structure and
nature of the MAU model translated the data reflecting
different levels of performances of different kinds into a
unified figure representing the total technical systems
utility of each EW suite proposed. In doing so, the MAU
model attempted to evaluate in detail the TSU of each of the
six suite design proposals without prejudice toward any of
them for using new or different technologies.

In applying this model, the Navy appraised the figures
of performance stated or implied in each EW suite design pro-
posal, for the Navy reserved to itself and exercised the right to
assess whether or not the figures were reasonable. If they
were considered to be reasonable, they were incorporated
directly into the evaluating mechanism; if not, they were
amended by the Navy on the basis of its analysis of the
proposed design and then incorporated into the evaluating
mechanism. From among the original six contractors sub-
mitting design proposals, the evaluating mechanism served as
one basis for selecting two to proceed with engineering
development of prototypes for testing. The ranking of all

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[2]The difference between static and dynamic models was not
 perceived to affect the appropriateness of using such a
 model for a dynamic process. Although MAU models are usually
 of a static nature, they can be used to make reasonable
 approximations of dynamic processes under special circumstances.
 These occur in the case of EW suites since their weapon
 delivery times are almost instantaneous.

six suite design proposals according to TSU was, in the final decision, slightly affected by other considerations bearing upon military worth and by consideration of management and cost in the final evaluation.

In short, the MAU model, or evaluating mechanism, performed in accordance with expectations. It discriminated among the proposals submitted and selected two finalists. And it did so fairly since the mechanism showed no bias for either innovative or conservative proposals. In fact, the proposals which were selected for engineering development and testing were quite different from each other.

5.0 DEVELOPMENT OF THE MULTI-ATTRIBUTE
UTILITY MODEL FOR DETERMINING
TECHNICAL SYSTEMS UTILITY

The central problem in any effort to evaluate military system design proposals for the purpose of selecting a contractor to build the system is to relate its predicted technical performance to military worth. The evaluating approach is the means of relating predicted performance to military worth. Under design-to-cost procurement policies, the evaluating mechanism must be capable of discriminating the relative military worths of different, sophisticated, and complex design proposals reliably, intelligibly, and fairly, without penalizing innovative proposals submitted under those policies. In the case of the Navy's EW System, the evaluating mechanism developed was a MAU model which translated predicted levels of performance of controllable parameters, or performance characteristics, into a unified estimate of TSU for each of the EW suite design proposals.

The essential fact about decomposed models, especially MAU models, is that they are explicitly structured to manage information so that one or more experts may contribute to the final evaluation in a logical manner. The structural principle of the MAU model used in this case was hierarchical decomposition; that is, each element of the particular evaluation problem was analyzed into its sub-elements, each of which in turn analyzed into its respective sub-elements until the most minute sub-elements of a controllable parameter of performance demonstrably affecting performance were reached. Conversely, predicted levels of performance of the lowest-level sub-elements in the model may be aggregated until a unique figure representing TSU is determined. Accordingly, expert opinions may be selectively involved for the appropriate component or sub-element.

In the discussion which follows, the structure of the MAU model developed as the evaluating mechanism for EW suite design proposals is described; that part of the model used for evaluating TSU is then explained. In this second part of the discussion, terminology will be defined precisely and the rationale for this part of the model will be offered.

5.1 Description of the Model for Evaluating Design Proposals

The hierarchical structure of the MAU Model consisted of nine levels, six of which are illustrated in Figure 5-1, the remaining three of which are illustrated in Figure 5-2.

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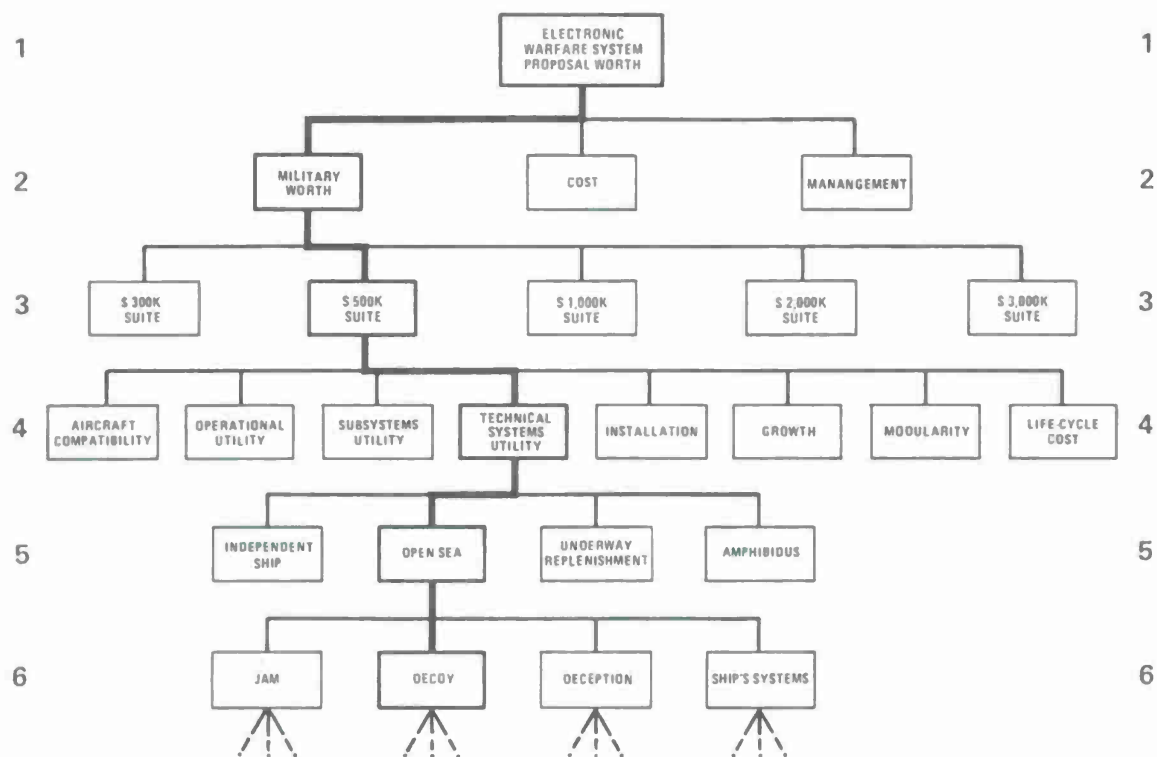
Figure 5-1

**THE STRUCTURE OF THE MULTI-ATTRIBUTE UTILITY
MODEL FOR ELECTRONIC WARFARE SYSTEM PROPOSALS**

The <u>first level</u> of the hierarchical structure corresponds
to the single figure representing the total worth of each EW
Suite design proposal.

The <u>second level</u> represents three major elements:
military worth, cost, and management, the first of major
concern in this article.

The <u>third level</u> represents the conditioning variables
ship platforms. The five values--$300,000; $500,000;
$1,000,000; $2,000,000; and $3,000,000--represent the cost-
per-unit ceiling of the five EW suites constituting the entire
EW System, each cost configuration associated exclusively
with a single class of ship platforms. For example, the
$300,000 suite was intended for destroyer escorts, the
$500,000 cost configuration for destroyers, the $2,000,000
for cruisers. These conditioning variables are necessary for

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determining the importance of technical characteristics and aggregates thereof. The evaluating mechanism uses these variables to help distinguish the importance of protecting one kind of ship rather than another.[1]

The fourth level represents eight functional or deployment aspect of a system.[2]

The fifth level represents four conditioning variables, each delineating a different scenario describing missions and threats to the completion of those missions; the four scenarios are independent ship, open sea, underway replenishment, and amphibious. Although a scenario has no value in itself, the model indicates the probability that the situations described will occur and the relative importance of threats to the missions.

The sixth level represents four kinds of responses to a threat.
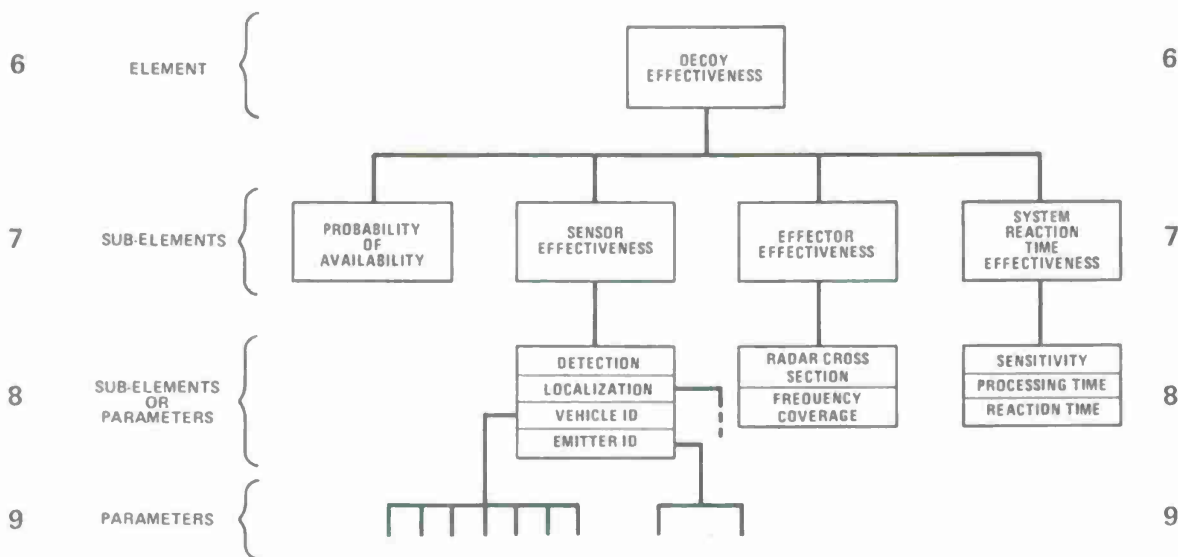
Figure 5-2

THE SUB-STRUCTURE OF THE MULTI-ATTRIBUTE
UTILITY MODEL FOR THE DECOY IN THE OPEN SEA SCENARIO

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[1] As it turned out, the evaluation revealed that the Navy maximized military worth by developing an EW system consisting of three, rather than five configurations. It specified one $1,400,000-per-unit suite instead of the three suites with cost-per-unit ceilings of $1,000,000; $2,000,000; and $3,000,000.

[2] During evaluation, aircraft compatibility was dropped from consideration.

The seventh, eighth, and ninth levels are illustrated in Figure 5-2.

The seventh level represents the operational aspects of these responses.

The eighth and ninth levels represent the parameters of performance associated with a particular aspect of a response in a particular situation.

Note that the heavy line in Figure 5-1 represents but one possible thread through this hierarchy from a response to a threat to proposal worth. A similar heavy line might have been drawn in Figure 5-2 from, say, frequency coverage up to effector effectiveness and up to decoy effectiveness. Since there is a large number of possible threads, this hierarchical structure organizes in a manageable way the great quantity of data needed to determine the worth of alternative, complex EW system proposals.

5.2 Aspects of the Model

5.2.1 Importance of structuring - Developing a MAU model is, of course, a complex and demanding task. The many considerations addressed in developing the model are finally organized hierarchically; more general elements are successively decomposed until a structure is developed that aggregates measures of performance characteristics up through TSU of each design proposal or that justifies any higher-level figure of utility or effectiveness by reference to lower-level figures. For these reasons, correct structuring of the problem is the most important step in the process. Moreover, correct structuring helps to reduce possible errors in judgment and to ensure that variations in the design proposals are reflected in different figures of TSU.

5.2.2 Definitions of "utility" and "effectiveness" - The words "utility" and "effectiveness" are used in this report in senses consistent with, though not necessarily so specific as, their usage in related disciplines. To some extent, the words are interchangeable; the summary measures at any particular level in the hierarchy for TSU could logically be called utility measures or effectiveness measures, for both terms indicate measures which translate technical characteristics or aggregates thereof onto a scale of benefit, or utility. Ordinary usage, however, distinguishes the two terms. "Utility" is the more general term since it is applicable to all subjective evaluations of worth at all levels from highest to lowest in a MAU model. Conversely, "effectiveness" is restricted in its usage to levels in the model up to but not beyond that involving the performance of the

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mission. As a result, conventional usage makes it possible to speak of the benefit, or utility, of being in one situation to being in another but not to speak of the effectiveness of being in one situation or another. Accordingly, the word "utility" is not inevitably constrained to usage associated with the higher levels in the hierarchy as "effectiveness" is constrained to usage associated with lower levels in the hierarchy. There should be no suggestion, however, that utility is better or more significant than effectiveness; one is mainly concerned with evaluation (in the narrow sense), the other with prediction, and each has its important part in evaluation (in the broad sense). The distinction, admittedly slight (see Figure 4-1 for the area in which simulation runs may or may not be used), is that between determinations essentially involving military trade-offs and those involving technical system capabilities.

5.2.3 <u>Scaling utility and effectiveness</u> - Since a MAU model involves many different kinds of elements and many different units of measurement, it is important to have a common unit of measurement that makes all measures commensurable to facilitate aggregation up through the model. Such a unit is utility or effectiveness, and the convention is to scale either one from zero to 100. Accordingly, various performance characteristics may be measured as a percentage--of what, we shall consider later. Once translated into percentages, they become amenable to aggregation at higher levels in the MAU model. Moreover, since the model is hierarchical, the manner in which a change in performance characteristics affects aggregated utility or effectiveness at successively higher levels can readily be traced throughout the model and conveniently adapted for use on an interactive graphics computer.

5.3 Steps in Developing the Model

The MAU model is developed in five basic steps: 1) decomposing the evaluation problem into its structured elements, 2) defining element relationships, 3) establishing element boundaries, 4) developing effectiveness curves, and 5) determining element weights. Although these steps must be listed and discussed sequentially, they should be understood to be taken iteratively in practice, especially the last three.

5.3.1 <u>Decomposing the evaluation problem</u> - The first step is to decompose the evaluation problem into its structured elements. The principle of hierarchical decomposition identifies the elements as it structures them, as any analytic process relates parts to wholes. Errors can, of course, be corrected, but their ratification requires a readjustment in all subsequent steps involving structuring related elements.

There are two general kinds of elements that emerge in developing a MAU model of TSU: one, the controllable parameters of performance and, two, the factors mediating between these parameters and the aggregate TSU of the EW suite. The controllable parameters of performance require no further explanation; they are the technical characteristics of the systems. The factors mediating between the parameters and the aggregate TSU do; the inclusion and nature of some factors in the MAU model is not always self-evident.

All mediating factors define the context in which the utility or effectiveness of each sub-factor is assessed. One kind of mediating factor is an aggregate of utility or effectiveness which summarizes measures of utility or effectiveness of performance characteristics. For example, one can speak of the effectiveness of a decoy as well as of the effectiveness of its sensor. The other kind of mediating factor is called a conditioning variable, a contextual construct for modeling purposes. For example, although one can speak of the effectiveness of a decoy, one cannot speak of the effectiveness of an open sea scenario. The difference is that between those factors which pertain to the system itself and those which pertain to constraints upon its cost or to the situations in which it is employed.

Conditioning variables constitute an explicit recognition of the fact that the utility or effectiveness of the same measure of performance may change with a change in the context of that performance. A conditioning variable is a set of conditions that provides a context in which measures of performance are predicted to occur and are evaluated as a percentage of maximum utility or effectiveness. In the present MAU model of TSU, there is only one level of conditioning variables. It represents selected military environments in which an EW suite may be operationally deployed. These environments in which all the events describing the contexts of an EW suite operationally deployed are called scenarios. Since the MAU model was used to determine TSU of each of five suites defined by their cost configuration (cost-per-unit ceiling) and employed four scenarios designating four different situations, the model yields 20 different measures of TSU for each EW system proposal. For example, at the same level of technical performance, the effectiveness of the decoy in the $3,000,000 suite in the open sea scenario might be far greater than that in the $500,000 configuration in the amphibious scenario.

The use of scenarios in evaluation, especially in MAU modeling, is necessary as an economical means of

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predicting and evaluating performance. It is also necessary as a means of reducing to a manageable number the infinite number of details required to describe an infinite number of possible futures. Scenarios serve, then, as classifying abstractions, that is, sets of generalized features which characterize a class of possible futures.

For purposes of modeling, even this greatly reduced number of generalized descriptions is neither economical nor manageable. Accordingly, a selection of scenarios must be made to ensure that the sampling is representative of what the future may be like on the one hand and that the selection discriminates among the design proposals on the other. Conversely, scenarios which are not representative cannot help evaluate proposed designs in the situations for which they are intended, and those which do not discriminate among the proposals do not address themselves to one of the principal criteria for evaluation. The procedures for selecting an economical and manageable number of scenarios that are at once representative and discriminating raise difficult methodological questions.[3] Nevertheless, they have been sufficiently developed and refined by experience to enable the selection of scenarios that can serve as a basis for dependable evaluation.[4]

5.3.2 Quantifying the model - The remaining four steps--defining the element relationships, establishing element boundaries, developing effectiveness curves, and determining element weights--involve a highly iterative process. It goes on continuously and leads to refinements of initial quantifications until the model is satisfactory to those who must use it. Since the model must generate figures indicative of the relative TSU of design proposals, the relationships among the elements as well as their measures of utility and effectiveness must be expressed mathematically.

One of the most important steps in developing the MAU model involves a determination of the rules, or formulae, for representing element relationships within the model. The elements subordinate to the same immediate mediating factor combine to determine its worth (a term used

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[3] The subject is discussed theoretically in Michael F. O'Connor and Ward Edwards, "The Use of Scenarios in the Evaluation of Complex Alternatives" (forthcoming).

[4] In this case, the Navy reduced an original selection of eight scenarios to four and tested the results obtained from the MAU model by comparing them with the results of a much-reduced number of simulation runs.

to encompass either utility or effectiveness). The worth of the decoy in the open sea scenario (see Figure 5-2) is determined by the aggregated worths of probability of availability, sensor effectiveness, effector effectiveness, and system reaction time. The rule, or formula, for representing the relationship among them must validly capture the manner in which they affect the performance of the decoy in the open sea scenario. In short, the combination rules define the principles of aggregating the worths of elements throughout the MAU model; they capture the value independence of the worths of the elements or the nature of their value dependency.

Often the manner in which the elements combine is extremely complex, the result of a dynamic sequential process. Nonetheless, the essence of the process can sometimes be captured by fairly simple combination rules. Such is the case if the worth of the element to which sub-elements contribute increases with the increasing worth attached to different levels of performance of the sub-elements.

Generally, the manner in which sub-elements, say, A, B, C, and D, combine to determine the worth of an element, say, X, can be captured by one of three types of combination rules.

1) The additive rule. If changes in the worth of element X as a function of changes in the level of performance of sub-element B do not depend on the level of sub-element C, and vice versa, and if the same is true for the relationship between sub-elements C and D and also B and D, then we say that B, C, and D contribute to element X independently of each other, and we use an additive combination rule to capture this value-independent relationship. That is, the worth of the system with respect to element X is the sum of the worths of sub-elements B, C, and D. For example, improved performance of vehicle identification may enhance the effectiveness of the sensor without regard to the performance of emitter identification. The rule for expressing mathematically the manner in which the effectiveness of each of these two types of performance contributes to the effectiveness of the sensor is additive. Additive rules are also known as compensatory rules, for decreases in the worth of one sub-element can be compensated for by increases in the worth of other sub-elements related to it in an additive manner.

2) The multiplicative rule. Another type of relation between an element say, X, and associated sub-elements, say, A, B, C, and D, occurs when a certain type of dependency exists. Suppose element X is the sensor effectiveness of the decoy in the open sea scenario and sub-

elements A, B, C and D are, respectively, detection effec-
tiveness, localization effectiveness, vehicle identification
effectiveness, and emitter identification effectiveness (as
shown in Figure 5-3).   Sub-elements B, C, and D contribute

1.	2.	3.	4.	5.
WEIGHT	SUB-ELEMENTS OR PARAMETERS	WEIGHT	PARAMETERS	EFFECTIVENESS CURVES
X	DETECT			YES
+3%	LOCALIZE	+90%	DF ACCURACY	YES
		+10%	ELEV. (YES–NO)	YES*
+6%	VEHICLE ID	+40%	FREQUENCY	YES
		+17%	PRI	
		+3%	PULSE WIDTH	
		+7%	SCAN RATE	
		+20%	CORRELATION	
		+5%	PCM	
		+8%	UNIQUE CHAR.	
+21%	EMITTER ID	+53%	H/I BAND	YES
		+47%	J BAND	
+70%	ADDITIVE CONSTANT			NO

* See |Page 27| for a
discussion of maximum,
minimum effectiveness
curves.

Figure 5-3

**THE EFFECTIVENESS OF THE SENSOR
OF THE DECOY IN THE OPEN SEA SCENARIO**

independently to the effectiveness of the sensor, and the
relation among the three is captured by an additive rule, as
we have seen. If the sensor cannot detect the threat,
however, the sensor does not perform. That is, if detection
effectiveness goes to zero, sensor effectiveness goes to
zero. As a consequence, the performance and related effec-
tiveness of the other sub-elements of the sensor are irrel-
evant. A multiplicative rule captures this kind of value-
dependent relationship. Effectiveness of detection ability
is multiplied by the sum of the effectiveness associated
with localization, vehicle ID, and emitter ID to yield

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sensor effectiveness (appropriate re-scaling constants are explained later). Note that if the effectiveness associated with detection ability drops to 50 percent, the maximum effectiveness that the sensor can have is 50 percent of what it would have been if detection ability were at the level of 100-percent effectiveness, and this 50-percent effectiveness occurs only if the remaining sensor sub-elements are at levels of maximum sub-element effectiveness. In this manner, the multiplicative combination rule can be used to describe non-compensatory processes in which degradation by one element cannot be compensated for by an increased performance of another.

3) Other combination rules. This discussion of additive and multiplicative rules is not meant to suggest that other, more complicated relationships do not exist. For example, another type of combination rule captures what is known as the "either-or" relationship, in which an element achieves its maximum effectiveness when any one sub-element attains maximum effectiveness but achieves its minimal effectiveness only when all sub-elements attain minimal effectiveness.[5] Such sophisticated rules played a negligible role in this MAU model. The question of when dependencies are important enough to merit in-depth analysis is one that is presently receiving a great deal of attention.

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[5] The reason for the multiplicative relationship here is best explained by considering the different kinds of dependencies that can occur. Consider system X, the effectiveness of which is a function of two performance characteristics, A and B. Denote the effectiveness of X as X_E, the effectiveness of A and B as A_E and B_E, respectively. Maximum effectiveness of X, A, and B will be assigned the arbitrary value of 100 and minimum effectiveness of X, A, and B the arbitrary value of 0.0.

When A and B can contribute independently to the effectiveness of X, that is, are value independent, each is given a weight proportional to its relative contribution. Suppose, for example, each can contribute equally to effectiveness. Then each will be assigned a weight of .5. If both A and B are at their maximum effectiveness, X will have an effectiveness of 100. If either A or B is at its minimal effectiveness with the other element at its maximum effectiveness, X will have an effectiveness that is 50 percent of its maximum. Only if both A and B are at minimum effectiveness is the effectiveness of X at 0.0. This relationship is captured by the additive combination of $A_E + B_E$ to determine X_E; that is, $X_E = .5A_E + .5B_E$.

Once the combination rules are established--
remember: they continue to be amended as necessary as the
next two steps are taken--it is necessary to establish
element boundaries on ranges of levels of performance of
controllable parameters. The purpose of such boundaries is
twofold: first, they limit the range of performance to be
measured to plausible dimensions; and second, they permit
the importance of that performance to be gauged realistically.
Too often the importance attached to a specific kind of
performance is inflated because it is considered universally,
without regard to the range of technically and economically
feasible levels of performance likely to be suggested by
design proposals. This is one point at which the impact
of a design-to-cost procurement policy is felt. Thus,
whereas an expert may wish the sensor of an EW suite

(5 cont.) Now suppose that if either A or B is at its
minimum effectiveness, the effectiveness of X is (0.0).
Further, degradation of either element degrades overall
effectiveness proportionally. If A_E is 50, the maximum
effectiveness X can have is .5, and then only when B_E is
at its maximum effectiveness. If A_E is 0.0, X has an
effectiveness of 0 no matter what B_E is. This dependency
is captured by making the effectiveness of X a function of
the product of factors A and B; that is, $X_E = A_E \times B_E$.

Thus far, the only way that X can have maximum effec-
tiveness is if A and B are both at maximum effectiveness.
If an additive relationship exists, the only way for X_E to
be at 0.0 is for both A_E and B_E to be 0.0. If a multi-
plicative relationship exists, X_E is 0.0 if either A_E or
B_E is 0.0. Now suppose that X can be at its maximum effec-
tiveness of 100 if either A or B is at maximum effectiveness.
A multiplicative combination of the following sort can
capture such a relationship:

$$X_E = [100 - \frac{(100-A)(100-B)}{100}]$$

Note that if either A_E or B_E has a value of 100, X_E has a
value of 100, no matter what the value of the other element.
X_E is 0.0 only if both A_E and B_E are 0.0. If both A_E
and B_E are 50, X_E is 75 percent of its maximum effectiveness.

This "either-or" multiplicative rule is a specific
instance of the more general formulation of the multiplica-
tive utility function discussed by R. L. Keeney, "Multi-
plicative Utility Functions," Operations Research, 22
(1974), 22-34. The mathematically inclined reader should
consult this article for a more detailed discussion.

to have a large capacity to detect discrete targets and avoid saturation, he may set a range of targets prior to saturation from zero to 25 and make other judgments with respect to that range, like those for effectiveness curves and weights. However, if design proposals drawn up in light of cost-per-unit ceiling have capacities from four to ten targets prior to saturation, it is unlikely that the expert will find much difference among the proposals in this respect or attach the proper degree of importance to it. Accordingly, experts must set boundaries based on their best estimates of what range is technically and economically feasible.

Completing the quantification of the model involves two more iterative steps: developing effectiveness curves and determining element weights. It is necessary first to translate measures of performance of controllable parameters into levels of effectiveness expressed as percentages, then to assess the importance of the bounded ranges of performance. The translation is achieved by having the appropriate experts assess the levels of effectiveness (on a scale of 0 to 100) for varying levels of performance within previously defined boundaries. The result is an effectiveness curve, a graphic representation of the relationship between levels of performance with respect to a mediating factor and effectiveness. An example of an effectiveness curve is shown in Figure 5-4. The signifi-
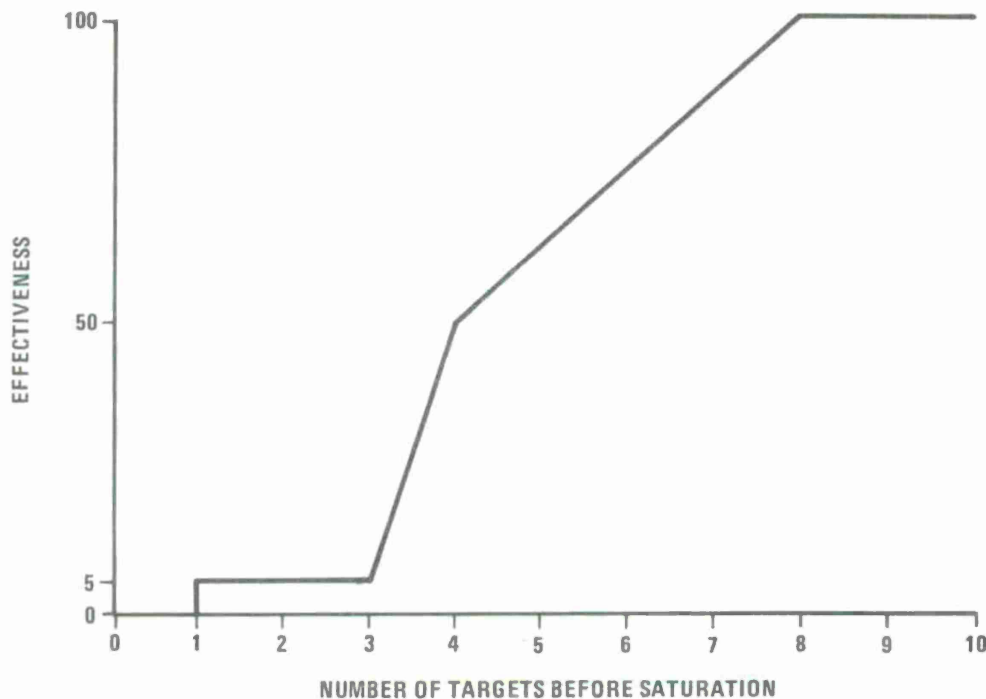

Figure 5-4

EFFECTIVENESS CURVE FOR DETECTION
BY THE SENSOR OF THE DECOY IN THE OPEN SEA SCENARIO

cance of an effectiveness curve is that performance is immediately related to and cannot be considered apart from worth. The curve itself means that performance is seen as a continuum over a range of levels of performance; a particular level of performance is but one possibility within the range of plausible levels of performance, not a point immutable. Similarly, effectiveness varies with the range of levels of performance; many levels of performance within the previously specified boundaries have some, though less than optimum, effectiveness with respect to the mediating factor. Effectiveness, then, is an intra-parametric measure of worth throughout the plausible range of levels of performance.

The use of effectiveness curves has two benefits. First, an effectiveness curve avoids categorizing a particular level of performance as either acceptable or unacceptable, as the stipulation of system requirements demands. Specific requirements can, in fact, be represented by effectiveness curves in which effectiveness is a minimum when the requirement is not satisfied, at a maximum when it is. A specific requirement, in other words, stipulates a very special kind of effectiveness curve. The absence of such requirements permits a more general use of effectiveness curves, which are thus more flexible, sophisticated, and experiential. The second benefit from the use of effectiveness curves is that the particular shape of an effectiveness curve reveals those ranges of performance in which a slight change in performance may result in a significant change in effectiveness, for better or worse, or those ranges in which a significant change in performance may result in little or no change in effectiveness. The effect of changing levels of performance in terms of TSU can be readily displayed, and the shape of an effectiveness curve may often be diagnostic of that range in which a trade-off between performance and cost is desirable.

The final step in this highly iterative process in developing a MAU model is to determine the relative importance to be assigned to sub-elements of the same component. As part of the quantification of the model, relative importance is expressed as a decimal between 0.0 and 1.0. The figure indicating importance is called a weight, and the determination of relative importance is called weighting.

The purpose of weighting is to recognize the different contributions that sub-element effectiveness makes to element effectiveness. Otherwise, the assumption is that the effectiveness of each sub-element contributes equally to the effectiveness of the element--which assumption is usually false.

The problem in weighting, then, is a methodological one. Since weights impinge upon the figures for effectiveness and the formula for aggregating them, the difficulty is twofold: how to assess weights and how to incorporate them into existing but as yet incomplete combination rules for aggregating measures of effectiveness.

Assessing weights depends upon the relative influence a change in the effectiveness of a sub-element has upon the effectiveness of an element, an influence that may be affected by the relationship among the sub-elements. That is, weights assigned to sub-elements are a function of their effect upon the element as the effectiveness of each changes from minimum to maximum. As the effectiveness of B, C, and D each changes from 0.0 to 100, the effectiveness of X changes in response.

If the combination rule for B, C, and D is additive, the changes in X are produced by changes in B, C, and D from their minimum to their maximum effectiveness, the ratio of these changes enables the determination of weights renormalized to sum to one. For example, changes in the effectiveness of B, C, D from 0.0 to 100 result in changes of the effectiveness of X of 20, 5, and 5, respectively, the ratio can be renormalized to sum to one, with weights of .666, .167, and .167, respectively.

If the combination rule for elements is multiplicative, say, A x (B+C+D), weights are developed differently. Since B, C, and D are combined additively and together are combined with A multiplicatively, weights cannot be used additively for all four elements though they can be and are for B, C, and D. The problem is to establish some quantified measure of relative importance for elements components combined multiplicatively. The solution is to use what may be called rescaling constants that reflect the degree to which the effectiveness of an element may be degraded by its sub-elements. If the effectiveness of A, B, C, and D are at a maximum, reducing the effectiveness of A to its minimum reduces the effectiveness of X. Although the more general case does not require that when the effectiveness of A is zero, the effectiveness of X is zero, this special case is very common.

For example, the maximum effectiveness of the sensor depends upon the maximum effectiveness of detection, localization, and vehicle identification and emitter identification. If the effectiveness of detection alone drops to a minimum, or zero, the effectiveness of the sensor likewise drops to a minimum, or zero; a sensor which cannot detect

targets is not performing and, obviously, has no effectiveness. Accordingly, no rescaling constant is associated with A; the maximum effectiveness of X is limited to the maximum effectiveness of A. On the other hand, if the effectiveness of A remains at a maximum and the effectiveness of B, C, and D are reduced to zero, the effectiveness of X is reduced to only .7. Accordingly, no rescaling constant is added to A; if it goes to zero, X goes to zero; a rescaling constant of .7--it may also be called a degradation constant--is added to the sum (B+C+D). If B+C+D are each zero, the effectiveness of X will be the product of the effectiveness of A times the degradation factor. Since the relative importance of the effectiveness of B, C, and D may differ, their relative importance is established according to the procedure outlined above for an additive combination rule. However, their weights are normalized to .3, not 1.0, because of the degradation constant of .7. The completed combination rule in this example (see Figure 5-4) is:

$$E_X(\text{sensor}) = (E_{A(\text{detect})} + 0.0)(.03E_{B(\text{localize})} +$$

$$.06E_{C(\text{vehicle ID})} + .21E_{D(\text{emitter ID})} + .7).$$

When other combination rules, reflecting the nature of the relationships among sub-elements, become more complex, eliciting the weights becomes more complex. These refinements are not discussed in this report.

Weights assigned to conditioning variables are dependent upon the nature of those variables. In the case of the MAU model for EW suite proposals, each scenario is assigned two sets of weights, one for the relative probabilities of occurrence of the scenario, the other for the relative importance of accomplishing the mission in the scenario. The weights for each variable are multiplied, and the products are then normalized to 1.0. The conditional utilities assessed for each scenario are multiplied by the corresponding normalized weights, and the products are combined according to the rule, here, additively. This general procedure provides for the correct weighting of conditional utilities and the aggregation of these utilities throughout the MAU hierarchy.

5.4 Validating the Model

Once the MAU model is developed, two types of validation analyses are conducted. The first, internal validation, consists of examining the effects of variations in weights

and effectiveness curves for purposes of identifying critical aspects of the model. It is typical that such evaluation models are effective despite small errors in utility functions or weights. These sensitivity analyses ensured that the same was true for this particular model. It is also typical that such models are extremely sensitive to changes in combination rules or associated structural changes resulting from different interrelationships among model factors. It is the structure of the model that either does or does not capture the true nature of the problem. Internal sensitivity analyses cannot, however, guarantee this type of validity.

The second type of validation, external validation, provides evidence of the validity of the model structure, for known systems are used to calibrate the model. The model should assign to these known systems, whose record of performance has been well documented, values that are consistent with the generally accepted assessments of the systems based upon that record. If it does so, it helps to ensure that the model behaves as it should. If not, structural changes are required.[6]

The implementation of such models on interactive computers also allows "what-if" type analyses that can accommodate proposed design changes. Similarly, the model can actually be used to search for those feasible configurations that have maximum utility.[7]

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[6] In the actual external validation of the EW model, it was found that not enough credit had been given the sensor for its ability to detect false alarms. The model was altered to account for this fact.

[7] The EW MAU model was implemented on computers at the Naval Research Laboratories, Washington, D.C. and was used both for numerous "what-if" type analyses in the procurement stage as well as for other design problems on related projects.

6.0   EVALUATION OF THE MULTI-ATTRIBUTE UTILITY APPROACH

6.1   The Multi-Attribute Utility Approach and the Criteria
      for Evaluation

      Correctly implemented, the MAU approach meets the four
general criteria set forth for evaluations. The approach
used in this case is designed to discriminate among pro-
posals in terms of TSU. The approach is reliable, yielding
reproduceable results from the same data; differences that
arise among different sets of evaluators can be resolved by
means of discussions about model structure, combination
rules, boundaries of ranges of levels of performance levels
of controllable parameters of performance, effectiveness
functions, or weights. A major strength of the approach is
its intelligibility. The logic by which data are translated
into measures of utility or effectiveness is explicit and
subject to challenge and modification. The procedure is
equitable, since the model is not biased against any kind
of design proposals. The approach also satisfies the other
specific criteria set forth. It leads to models which
develop unambiguous, quantified measures of utility. The
approach itself is comparatively inexpensive and is con-
ducive to inexpensive "what-if" and sensitivity analyses.

6.2   Ultimate Benefit of the Multi-Attribute Utility Approach

      Of the benefits derived from using the MAU approach,
the immediate, practical one was that it served its purpose
in helping the U.S. Navy select two from among six con-
tractors to proceed with engineering development of proto-
types for testing in a systematic and methodologically sound
manner. More general benefits from using the MAU approach
can be summarized by stating that it effectively meets all
requirements earlier set forth as either mandatory or desirable
for the evaluation of complex systems. In this, it is more
satisfactory than the global approach or an exclusive re-
liance upon simulations runs. Moreover, the MAU approach
has the desirable property that the complexity of its modeling
can be tailored to the need for complexity in analyzing the
problem. The emphasis has been on the controllable para-
meters of performance as opposed to all parameters of per-
formance. Certain aspects of a problem usually are nearly
constant for all options. Accordingly, these aspects
require little in the way of evaluative effort, and those
that do require effort can have it allocated optimally from
a cost effectiveness point of view.

      Perhaps the major benefit to be derived from the MAU
approach, however, is that the approach effectively organizes

large amounts of information into results that can be used effectively by evaluation board members. It is not uncommon that results of many large evaluations have been ignored because they could not be summarized in the concise fashion that is necessary for high-level decision makers. This failure often results from a lack of intelligibility owing to a high degree of (perhaps unnecessary) complexity.

A model has truly done its job if it can be discarded when the evaluation effort is finished and the evaluators can summarize the results of the model or explain the final decision in a clear, yet well-documented, manner.[1] MAU models succeed in just this way. At the same time, they are flexible enough to allow decision makers and evaluators to introduce last minute questions and conduct "what-if" type analyses. Because of these strengths, the MAU approach is enjoying increasing popularity as an evaluation technique. Shepard has said that "the optimum choice (out of a given set of alternatives) is the one that leads to the highest subjective evaluation of its ensuing consequences."[2] Such a definition would seem to ignore cost, but the point is nevertheless relevant. The choice of an evaluation approach for large complex systems is an exceedingly important one, and the MAU approach has many apparent benefits, but the ultimate relative value of the approach will be determined as the results of its more widespread use are observed. Until such time, evaluation must proceed, as it has in this report, according to reasonable criteria and desiderata for evaluative approaches.

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[1] As a result of this stage of the evaluation, the Navy was able to explain its approach, to debrief the contractors, and, in particular, to detail the strengths and weaknesses of their design proposals.

[2] R.N. Shepard, "On Subjectively Optimum Selections Among Multi-Attribute Alternatives," in Human Judgments and Optimality, edited by M.W. Shelly and G.L. Bryan (New York: Wiley and Sons, 1964); reprinted in Decision Making: Selected Readings, edited by Ward Edwards and Amos Tversky, Penguin Books (Harmondsworth: Penguin Books, 1967), pp. 258-59.

7.0   CONCLUSIONS

7.1   Implications

Although the development and use of the MAU model was deemed sufficient in the case of the Navy's EW System, it is apparent that additional research is needed to develop prescriptive principles for specifying the procedures for selecting scenarios to be included in the model and for selecting appropriate combination rules, that is, the formulae capturing the relationships among the elements of the model.

Since the choice of scenarios has not yet been systematized, further research is required to ensure that the selected scenarios are both representative of the population of possible scenarios and that they discriminate among the alternatives being evaluated. These prerequisites for scenarios suggest that a stratified sampling procedure would be useful in the process of defining or selecting the scenarios. Stratification would first specify scenarios that discriminate maximally among the alternatives being evaluated and then assign relative probabilities and weights to the scenarios so that they may be weighted in accordance with their probability of occurrence and their relative importance.

Second, most designers of MAU models have tended to use additive rather than multiplicative combination rules. This tendency likely represents a propensity to start with the simplest possible combination rules and to move to more complex rules only as a last resort. However, multiplicative rules are more appropriate in cases in which the effectiveness of an element goes to zero if the effectiveness of any sub-element goes to zero, as in this MAU model of TSU of EW suite design proposals. Other more complex combination rules may be more appropriate for capturing more complex relationships. Research is required to identify when more complex rules to capture combinations of elements are necessary or when simpler approximations are sufficient.

7.2 Afterword

The Navy's use of this evaluating mechanism, or MAU model, reflected the first implementation of DoD's design-to-cost procurement policies from the inception of a program to develop a sophisticated and complex military system. The MAU model served to select two proposals from among six for engineering development and testing of prototypes. Perhaps even more important, the use of the MAU model affected the kind of EW suite designs which the Navy selected. Certain initial considerations, like five suites, with one especially

adapted for airborne use, were eliminated as of negligible military value. The use of the MAU model has not stopped at this stage in the program. Modifications in the original model have led to a revised version that will be used to evaluate the two prototypes when they are tested and to select the better one.

Nor is it likely that the use of MAU models will be confined to the evaluation and selection of design proposals and prototypes. It should be clear that a MAU model can be used not only for these purposes, but also for aiding in the design of a system and in diagnosing areas in which tech-nological development is worthwhile. It is therefore, likely that MAU models will be employed by contractors to assist in the design of other sophisticated and complex systems.

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