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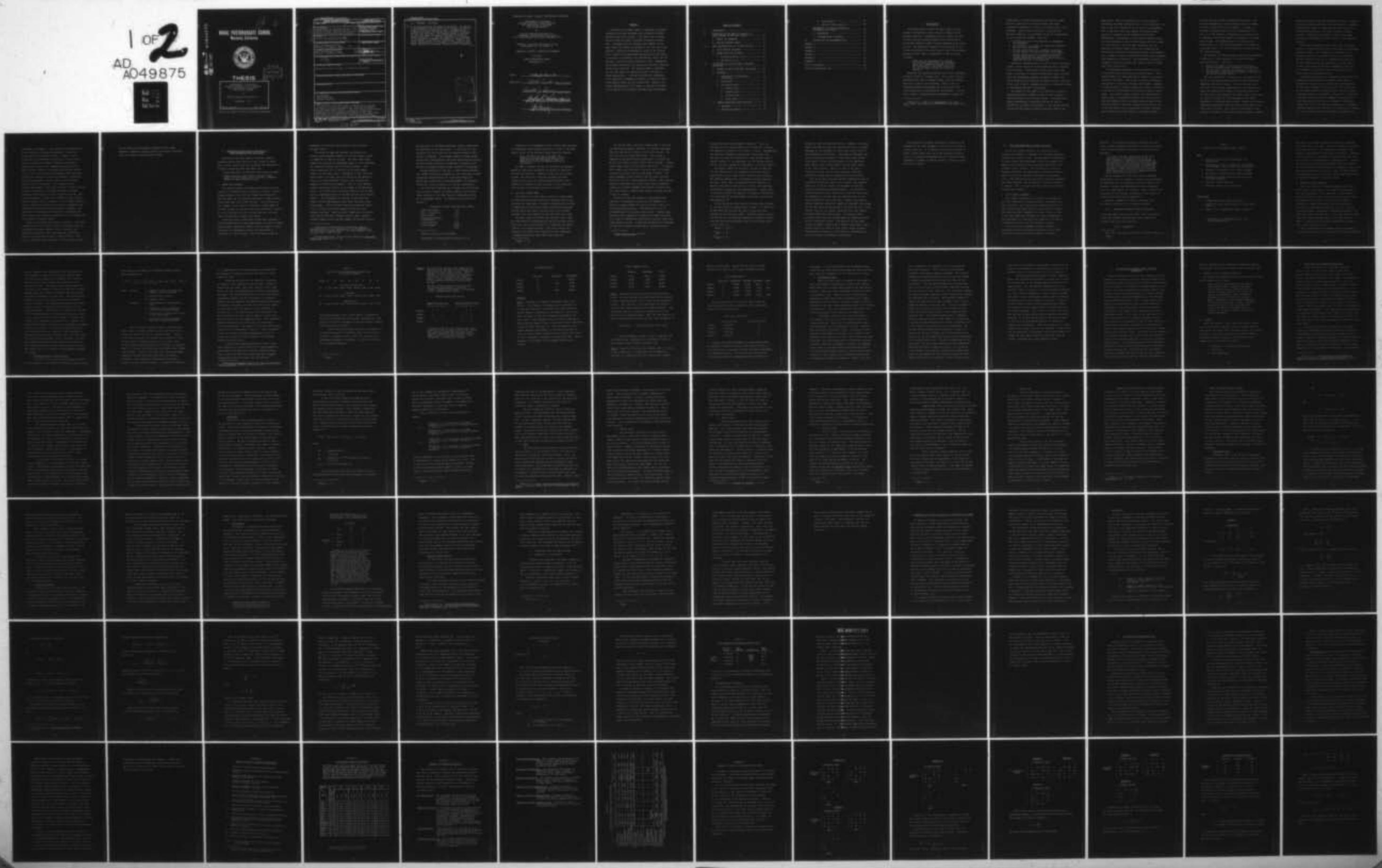

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THESIS

A METHODOLOGY TO EVALUATE MILITARY SYSTEMS IN NAVAL INVENTORY FOR INSTALLATION ON EXISTING COAST GUARD CUTTERS

by

William Jennings Wilkinson III

September 1977

Thesis Advisor: P.M. Carrick

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cont. on assigned peacetime missions of the vessel. To arrive at an estimate of an alternative's worth over all missions a multi-attribute technique is used. Assumptions and problems associated with using multi-attribute selection criteria are discussed. The proposed model is developed for the case where the additive function criterion is deemed appropriate. A constant-sum method is developed to use subjective judgement of experts to arrive at ratio scale benefit values for the alternatives. However, the actual implementation of the model is contingent on NOSC's factor analysis of attributes currently under development.

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A Methodology to Evaluate Military Systems in Naval Inventory for Installation on Existing Coast Guard Cutters

by

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ABSTRACT

A modified cost-benefit model is developed to evaluate alternative military equipments for installation aboard existing Coast Guard vessels. Life-cycle costs of alternative systems are used to estimate alternative systems cost. Identified are the relevant cost elements to the Coast Guard that should be included in the life-cycle cost equation. Benefits are measured in terms of the alternative's impact on assigned peacetime missions of the vessel. To arrive at an estimate of an alternative's worth over all missions a multi-attribute technique is used. Assumptions and problems associated with using multi-attribute selection criteria are discussed. The proposed model is developed for the case where the additive function criterion is deemed appropriate. A constant-sum method is developed to use subjective judgement of experts to arrive at ratio scale benefit values for the alternatives. However, the actual implementation of the model is contingent on NOSC's factor analysis of attributes currently under development.

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I. INTRODUCTION

Increasing emphasis within the Coast Guard is being placed on evaluating military systems in terms of their peacetime benefits. Evaluating military systems in terms of their expected peacetime benefits has evolved due to the greater number of combat systems installed on new class vessels. The importance attached to this concept in the systems selection for the Coast Guard's new 270 foot medium endurance cutter (MEC) is exemplified in the following statement.

> Right from the beginning, the dialogue with the Navy demonstrated the importance which they viewed the program (270 MEC) and the benefits which would accrue from our use of combat systems for peacetime mission.[1]

Measuring the expected peacetime cost of the alternative military systems is a complex task. The system's physical characteristics such as weight, volume, and power requirements are in reality cost elements. Shore as well as shipboard manpower requirements and system acquisition costs should also be classified as cost elements. For new class cutters, selecting military equipments includes the

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[1] Moore, R.G., "MEC-270", The Bulletin, U.S. Coast Guard Alumni Association, Vol. 39, No. 2, March/April 1977, p. 22.

requirement of trading off peacetime missions for added military capability as limited personnel and budget constraints influence the actual size and missions of new platforms. Due to these constraints, increasing the military capability of a platform can only be accomplished by four alternative methods. These are:

1. Increase the size of the platform to accommodate all equipments.
2. Hold platform size fixed, but reduce the peacetime missions to be performed.
3. Utilize unused space on a platform for military systems and also increase personnel requirements.
4. Utilize unused space on a platform for military systems whose benefits eliminate the need for certain peacetime equipments, but still allow all peacetime missions to be performed.

Successful implementation of any of the four alternatives requires careful analysis of the actual benefits a military system provides. Naval Ocean Systems Center (NOSC) San Diego, California, is currently developing a multi-attribute selection methodology primarily designed to address the fourth alternative of providing increased military capability on new class cutters. Appendix A presents a tentative outline of the methodology NOSC is developing.

The purpose of this paper is to extend the concept of evaluating military systems in terms of their expected peacetime benefits for existing cutters. A modified cost-benefit methodology is developed that may be used in conjunction with NOSC's methodology to help verify that the system with the greatest expected peacetime benefits has been chosen. When the application of the cost-benefit methodology and NOSC technique result in the selection of the same system, the credibility of the study is strengthened. This is possible since the proposed cost-benefit model requires a different set of assumptions than NOSC's methodology. Unfortunately, even complete agreement among the two methodologies does not fully ensure the best system has been selected. Both the NOSC methodology and the proposed cost-benefit model require the assumption that the wholistic problem of system selection may be decomposed into a number of smaller dimensional problems which separately lend themselves to analysis. The requirements necessary to decompose a wholistic problem into smaller parts are admittedly quite restrictive.

The methodology proposed in this discussion is not a cost-benefit model from classical economic theory. Cost-benefit models are techniques used by analysts to evaluate non-market decisions. Most often cost-benefit techniques are applied to decisions affecting public goods. Examples of public analysis include studying the impact of building a new dam or the desirability of building a Federal courthouse. Cost-benefit models determine the desirability of public goods by measuring the dollar cost of the project and then comparing this to a dollar-value estimate of the benefit received. Thus, the building of the dam may cost 10 million dollars but the increased irrigation provided may increase agriculture output by 20 million dollars in the area and also provide recreational facilities. The proposed methodology in this discussion does not attempt to place a dollar value on the benefits. Instead, it provides a technique where costs are estimated by life-cycle costs and benefits are measured in a restricted way by comparing the expected impact of alternatives on peacetime missions. The intended use of the proposed cost-benefit model is to aid the decision-maker in arriving at a rational choice. It is not intended to replace the need for a decision-maker.

The proposed cost-benefit model requires two assumptions in addition to those necessary to use multi-attribute selection criteria. These are:

1. Missions assigned to existing cutters currently prohibit the additional assignment of new missions.
2. The alternative systems list prepared by the Navy include only systems which are capable of fulfilling the stated military mission.

The first assumption is necessary as only benefits that accrue to existing peacetime missions are considered when comparing alternative systems. If one of the selection criterion is to evaluate alternatives by considering their impact on increasing the number of peacetime missions an existing cutter could perform, this model should not be used. In reality, however, the second assumption does appear reasonable for existing class cutters. Current and projected operational commitments indicate that existing cutters are being fully utilized. Thus, even if an alternative could increase the number of peacetime missions performed, current resource limitations and time constraints prohibit assigning additional peacetime missions to existing cutters. Appendix B presents the number of additional platforms required to operate existing cutters with their presently assigned missions. Shortages of platforms in every class cutter indicate that the addition of new missions is not currently feasible.

The second assumption is more restrictive and in many cases may severely limit the use of this model in evaluating military systems. This assumption is necessary as no benefits accrue for the system's ability to perform the military mission. Since it is reasonable to assume that the Navy would place on the alternative list only those systems which could perform their intended military use, this assumption is plausible when evaluating systems by their impact on peacetime missions.

After having discussed the assumptions required prior to implementing the proposed cost-benefit study, further assumptions required of the specific model are discussed as they arise throughout the discussion. The actual need for the Coast Guard to evaluate military systems by their peacetime benefits is discussed in Chapter Two. Identified in Chapter Three are the cost elements relevant for the Coast Guard and a life-cycle cost formula is developed to estimate the cost of the various alternatives. An example problem on applying the life-cycle cost equation is presented for the case where Coast Guard manpower requirements are equivalent to the Navy's. Also discussed in Chapter Three is the importance of properly measuring externalities associated with alternative systems. Finally, a brief discussion on the problem of evaluating a system cost per year for systems with unequal lifetimes is presented. Chapter Four discusses the assumptions necessary to use multi-attribute theory in estimating the expected benefit ratios of the systems. Specific requirements and limitations of using the selection criteria of dominance, minimax and maximin, lexicography, utility theory, and the additive function form are presented. Also included are the different measurement scales each selection criteria utilizes. Chapter Five proposes a constant-sum model to estimate peacetime benefit ratios for each alternative system. This technique produces a ratio scale estimate of each system's expected benefit which is required in a cost-benefit analysis. Finally, Chapter Six discusses the specific assumptions and limitations required to use the constant-sum method. Also presented in the conclusions are specific recommendations where further study should be conducted prior to implementing the proposed cost-benefit model.

Finally, one further point merits discussion. The actual implementation of the proposed model is contingent upon the completion of a factor analysis study to identify the independent attributes that, when combined, collectively describe the peacetime missions a cutter performs. This study is currently being conducted by NOSC and their results will be the list of attributes required for this model. Appendix C presents a partial glossary of possible attributes that are currently being analyzed at NOSC.

II. BACKGROUND OF THE NEED TO EVALUATE U.S. NAVAL SYSTEMS BY THE COAST GUARD

The need for the Coast Guard to carefully examine available United States Naval military systems is great. The two major factors that are increasing the importance of carefully evaluating Naval equipments are:

* Increasing costs of electronic surveillance equipment

* Trend within the Coast Guard to install larger numbers of more sophisticated electronic equipment aboard its newly designed vessels.

A. BUDGET AND PERSONNEL

This chapter presents the budget limitations the Coast Guard has in developing major electronics systems. Specific program elements within the Navy budget are presented to show the high cost of developing electronic systems in areas which effect many Coast Guard missions. Also discussed in this chapter is the trend of installing a larger number of military systems on the newer Coast Guard platforms. Finally, a brief discussion as to why the Navy furnishes the Coast Guard with military systems is presented.

Increasing costs of electronic surveillance equipment is a major factor that the Coast Guard should not ignore. Budget and personnel constraints severely limit the amount of funds available for independent research and development or production of sensor systems. These limitations apply to equipments for existing class vessels as well as newly designed cutters.

The amount of funds and personnel associated with research and development efforts in the Coast Guard is small in comparison to that of the Navy. The total Coast Guard request for research and development funds in 1976, excluding the transition quarter, was 20.7 million dollars. This figure represents only 1.9 percent of the total budget request for the Coast Guard. In addition to this relatively small request for funds, only five tenths of one percent of total Coast Guard personnel (military and civilian) were engaged in the RDT and E program.[2] The U.S. Navy, however, spends a much larger portion of its budget in the RDT and E sector. In 1976 the total obligation authority for the Navy under the appropriations title of RDT and E was 3.314 billion dollars. This represents 11.5 percent of the total Navy budget, and was approximately three times the entire Coast Guard budget. Since 1973 this trend for allocating roughly 11 to 12 percent of the Navy budget for RDT and E has remained constant.[3] While no direct comparison of the Coast Guard and Navy RDT and E budgets should be made, certain program elements within the Navy budget can be used to depict

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[2] Department of Transportation and Related Agencies Appropriations for 1976, Hearings before a Subcommittee of the Committee on Appropriations, H.R., 94th Congress, First Session, Part 1, 1976, p. 82.

[3] United States Navy, Chief of Naval Operations, Historical Budget Data, March 1977, p. 60.

the high cost of developing electronic sensor systems which are applicable to the Coast Guard. In 1976 the U.S. Navy requested 53.8 million dollars for program element 62702E, tactical technology. This program element includes target acquisition, identification, and ocean monitoring and control. The Navy further requested an additional fourteen million dollars for program element 62708E, advanced C^3 technology.[4]

Systems developed by the Navy in these program elements will become increasingly important as the Coast Guard assumes increasing responsibilities of ocean surveillance and monitoring in the fields of law enforcement, environmental protection, fisheries patrols and military preparedness.

The 1976 Coast Guard RDT and E request has been divided into its major elements to further exemplify the limited funds available to the Coast Guard for developing systems on an independent basis. All figures are in millions of dollars.[5]

Allocation of Coast Guard RDT and E Funds

Search and Rescue	2.14
Aids to Navigation	1.50
Marine Safety	3.36
Marine Environmental Protection	9.01
Ocean Operations	0.15
Program Support	4.50
	20.66

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[4] Hearings on Military Procurement.

[5] Department of Transportation, Hearings, p. 82.

Coupled with the phenomenon of the limited funds available for developing sophisticated electronics systems is the Coast Guard's policy on how RDT and E funds should be expended.

> As in the past, our aim is to apply the benefits of science and technology to Coast Guard missions and operations in order to reduce costs as well as improve services to the public.[6]

In order to improve services to the public the greatest amount of funds must undoubtedly be devoted to peacetime missions and operation. However, in the case of existing cutters, the selection of military systems from Naval inventory which have the largest peacetime benefits and perform the required military missions is also compatible with the goal of improving services to the public.

B. MILITARY SYSTEMS TREND

The trend of the Coast Guard to install a large number of sophisticated systems aboard newly designed cutters also increases the importance of properly evaluating Navy systems. A comparison of the installed major electronic and weapons systems aboard the newest existing cutters with planned equipments for the proposed 270 foot MEC shows this trend.

The Coast Guard's 378 foot high endurance cutter (HEC) has been chosen as representative class of existing cutters. This class vessel was selected as it represents the newest cutter in its respective class. This class cutter also represents the vessel which would be the most compatible in augmenting military multi-unit naval exercises.

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[6] _Ibid._, p. 82.

The 378 foot HEC's were first commissioned in 1967 and the following equipments represent the standard equipments presently aboard most vessels in this class vessels. The 378's utilize an on board ASW system. This system is composed of the SQA-38 sonar system which is coupled with MK 301 fire control system to direct MK-32 torpedos. Surface search radars consist of the SPS-29 and SPS-51. To complete the systems suite installed is the MK-56 gun fire control system which directs the five-inch mount on board.[7] The above equipment systems indicate that the major military mission of the 378 is anti-submarine warfare. While military coastal surveillance and surface search can be adequately carried out, present armament and electronic systems limit this class vessel's effectiveness against incoming aircraft or missile threats.

The new 270 foot MEC, because of improvements and additions of equipments systems, has the capability to perform a greater number of military missions, while at a much reduced manning level. ASW capabilities will be performed under the ship-helo team concept. Current plans provide for the capability of deploying a LAMPS helicopter to be used in conjunction witha passive tactical towed array sonar onboard the MEC. In addition the MEC will be provided the MK-92 fire control system used in conjunction with a

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[7] Janes Fighting Ships 1976-77.

revised version of the OTO-Melara 76mm guns.[8] Also, an electronics system module (ESM) will be installed to provide the capability of anti-missile defense. Finally, complementing the installed equipments, space-weight reservations have been made to allow the installation of the Phalanx close in weapons systems, or its equivalent, and the Harpoon missile, both of which are planned for availability in the mid 1980's.[9]

The greater numbers of electronic systems on board the 270 foot MEC have not only expanded the military mission capabilities of this class vessel, but also have increased the potential capabilities of performing various peacetime missions. Major tasks of peacetime missions expected to benefit from these systems are air, surface, and underwater surveillance, navigation, and communications. Indeed, there is currently an R&D study underway to establish the modifications required for the ESM package to provide a law enforcement capability.[10]

The discussion has been limited to establishing the need of the Coast Guard to evaluate Naval systems. It should also be mentioned that the Navy has much to gain from joint cooperation with the Coast Guard. The major benefit derived for the Navy is the additional immediately available surface platforms and trained personnel that the Coast Guard could

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[8] Moore, p. 22-24.

[9] *Ibid.*, p. 22.

[10] *Ibid.*, p. 22.

provide in times of actual hostilities. However, the actual benefit derived from the Coast Guard vessels will be largely dependent on the equipment on board these vessels prior to the beginnings of hostilities. Refitting of equipments and the re-training of personnel on board Coast Guard vessels could greatly reduce the effectiveness of the additional Coast Guard vessels during the most critical early period of any short conflict. Thus it is also in the Navy's interest to ensure that the Coast Guard has sufficient quantities of high quality equipment aboard its vessels.

Thus, given that increased military capabilities will be required of future and current class cutters, the question remains as to how one selects the equipment system that provides the greatest peacetime benefits. One problem of system selection for hte Coast Guard is that the best piece of equipment for the Navy does not guarantee that it will also be optimal for the Coast Guard. Indeed, there may be several competing systems all capable of adequately performing the military missions agreed upon by the Navy and Coast Guard. However, each may have unique characteristics that benefit different peacetime mission areas. The extent of this problem becomes even more evident when the competing systems are of a dissimilar nature. Such would be the case when trying to compare systems such as sonars, towed arrays, and electro optics, in terms of their overall impact on peacetime missions, assuming all are capable of performing the military mission of underwater surveillance.

The proposed cost-benefit methodology presented in the remainder of the paper attempts to deal with the problem of systems selection. As it becomes increasingly difficult to choose systems based solely on stated operating characteristics, the proposed methodology based on using subjective judgements of experts to measure benefits, becomes a useful tool for the analyst.

III. COST CONSIDERATIONS OF SYSTEM SELECTION

In any cost-benefit analysis, the identification of relevant cost elements is important in developing meaningful estimates of a system's cost. The high degree of uncertainty in total research and development and also procurement cost elements for proposed systems often make total-dollar cost estimates highly variable. This variability of the cost estimate often masks the importance of conducting detailed analysis of the cost elements associated with operating costs. When considering the selection of existing equipments from Naval inventory, the uncertainty of all cost elements is reduced. Thus it becomes even more important to identify relevant cost elements.

A. JOINT SERVICE AGREEMENT

This chapter identifies the relevant cost elements to the Coast Guard when considering military equipments from Naval inventory. The joint-service agreement between the Navy and the Coast Guard allows the Coast Guard to acquire and operate military equipments at a much lower cost than if the Coast Guard had developed the system independently. Also developed is a life-cycle cost equation to be used in estimating the dollar cost of alternative systems.

The joint-service agreement provides a detailed description of the cost elements applicable to the Coast Guard when selecting military equipments from Naval inventory. The underlying concept of allowing the Coast Guard to select equipments from Naval inventories is stated in the following general provisions of the joint-service agreement.

> To ensure the ready integration of the Coast Guard units into the Navy in time of war or other emergency as approved by the President of the United States, the Chief of Naval Operations shall provide to the Coast Guard all requirements for Navy-owned military readiness equipment and associated support material that the Navy deems necessary to enable the Coast Guard or specific Coast Guard units to carry out assigned missions while operating with the Navy...[11]

Further examination of the joint-service agreement demonstrated that cost elements of research and development and production are not relevant to the Coast Guard's cost estimate. Research and development and also production costs are borne entirely by the Navy. Table I presents the allocation of cost elements applicable to each service as stated in the joint-service agreement.[12]

Using the information of Table I indicates that the typical life-cycle cost estimating function

$$\text{Cost} = f(\text{Research Development, Production, Operation})$$

is not applicable for the Coast Guard. The Coast Guard's stated cost elements indicate that a more appropriate relevant life-cycle cost equation is

$$\text{Cost} = f(\text{Operation}) \ .$$

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[11] Nav. Mat. Instruction 4400.18 of 20 October 1969, p. 3.

[12] Ibid.

TABLE I

ALLOCATION OF COST ELEMENTS AMONG SERVICES

Navy

1. Initial issue of all basic equipment for installation
2. Related repair parts, assemblies, field changes, test equipment, special tools, and accessories
3. Scheduled replacement of Navy owned equipment
4. Replacement of defective Navy owned equipment
5. Maintenance support material and services for installed equipment
6. Logistics support functions
7. Technical and tactical publications

Coast Guard

1. Transportation and installation costs
2. Spares and repair parts peculiar to Coast Guard vessels
3. Annual cost of maintenance support material*

* Indicates on a reimbursable basis to an agreed maximum limit.

Even many cost elements generally considered as operating costs are borne by the Navy. Items two through six assigned to the Navy in Table I are operating cost elements that should be removed from a Coast Guard cost analysis. Reducing life-cycle costs to a function of only operating costs does not eliminate all uncertainties in estimating cost. However, for the problem of selecting equipments from Navy inventory, the systems personnel requirements and equipment reliabilities have been established by the Navy. Thus, the major element of uncertainty in the cost estimate arises from transforming the known requirements into dollar values.

B. UNSPECIFIED COST ELEMENTS

While the stated cost elements assigned to the Coast Guard should be considered, cost elements not mentioned in the joint-agreement are also important. These elements of cost are borne by the Coast Guard and represent a large percentage of the system's life-cycle cost estimate. Omitted cost elements which must also be considered in arriving at a meaningful estimate of a system's cost are operating manpower requirements, maintenance personnel, and their associated training costs. These cost elements, along with those identified applicable to the Coast Guard in Table I, should be utilized when computing the estimate of each system's life-cycle cost.

Having defined the cost elements that are included in the cost-benefit analysis of alternative systems, the elements are now separated into recurring and non-recurring costs. This procedure is required as life-cycle costing takes into account the actual flow of expenses over a system's lifetime by applying a present value analysis to the expected cash flow. The present value concept applied to cash flows is an attempt to reflect the fact that a dollar expended today has a higher alternative opportunity value than a dollar expended at a later date. Non-recurring cost elements are those costs that occur only once during a system's lifetime. Only transportation and initial installation costs are considered non-recurring costs in the proposed analysis. Installation costs should also include costs for modifications to existing cutters required solely for the addition of the proposed systems. All other cost elements are classified as recurring costs. However, the proposed cost-benefit model omits the maintenance and support material cost element. Elimination was deemed reasonable as the actual cost of this category is more dependent on management and accounting techniques within the Coast Guard than on the actual equipment chosen. Therefore, omitting this element assumes that proper management policies are being followed and that the Coast Guard properly documents and requests the correct amount of reimbursement necessary for support.

1. Estimating Dollar Life-Cycle Costs

As a result of the joint-service agreement and the stated assumptions, the equation to determine relevant dollar life-cycle cost estimates for alternative weapons systems may be expressed as:

$$\text{Cost} = \sum_{\ell=1}^{j} [I_{\ell} + \sum_{k=1}^{n} \frac{1}{(1+i)^{k}} (O_{\ell k} + S_{\ell k} + M_{\ell k})] \quad . \text{[EQ. 1]}$$

where indices: j = number of vessels for which the system is being considered

n = time horizon in years

i = discount factor

variables: I = installation and transportation costs

O = life-cycles cost of operating personnel including training

S = yearly costs of spare parts unique to the Coast Guard

M = life-cycle cost of maintenance personnel including training.

Due to the small number of vessels comprising each ship's class, the analyst often may have sufficient time to examine the problem of cost on a detailed level. However, if the analyst can only use average cost estimates for each of the variables, equation one may still be used. Care should be taken when calculating cost estimates on a detailed level for a single vessel and using this vessel as an average cost estimate. Vessels of the same class often have unique equipments on board and great disparities of attached personnel. Thus, average cost estimates derived from a single ship can be very misleading. To avoid this situation, it is suggested that when using average cost values they be obtained by averaging costs over all vessels in their respective class.

Obtaining estimates for the variables in equation one requires close cooperation with the Navy. Values for installation and yearly spare parts unique to Coast Guard vessels can only be determined after interface requirements are known. The actual determination of Coast Guard manpower requirements presents the most challenge to the analyst. However, once the manpower requirements have been determined, the analyst next applies the life-cycle dollar cost output from the Navy billet cost model to obtain estimates of personnel cost. This method requires the assumption that Naval enlisted billet costs can be equated to Coast Guard enlisted billet costs for comparable rates. This assumption should be omitted if life-cycle costs for Coast Guard billets are available. An excerpt of Navy life-cycle billet costs for 1972 is presented in Table II. This is presented to show the billet cost models disaggregation level of output and is used in the later example of determining relevant life-cycle costs.

Actual dollar figures presented in Table II have been calculated to reflect total cost to the government of establishing a military billet within a proposed system. Thus, billet costs take into account base pay, training, transportation, and retirement costs of personnel.[13]

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[13] Navy Military Manpower Billet Cost Data for Life-Cycle Planning Purposes, NAVPERS 15163, April 1972.

TABLE II

ANNUAL ENLISTED MANPOWER BILLET COSTS FOR LIFE-CYCLE PLANNING[14]

Rating	E2	E3	E4	E5	E6	E7	E8	E9
Electronic Technician								
ET	11,140	12,506	13,025	16,240	21,667	24,868	27,651	32,499
Radarman								
RD	10,443	10,628	12,046	13,413	19,188	22,440	25,038	27,239
Quartermaster								
QM	10,109	10,332	11,397	12,665	16,448	19,396	22,797	27,782

Calculating manpower costs in this method is appropriate for the system selection problem under consideration. The addition of military equipments on existing cutters requires that new billets be created.

After having established the major cost elements of the proposed equation to determine dollar life-cycle cost estimates, an example of how to apply the proposed cost estimating technique is presented. All data is fictional for illustrative purposes.

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[14] *Ibid.*

Example: The Coast Guard and Navy have agreed on air-search mission (military) to be performed by the 250 foot Coast Guard vessels. There are currently 4 active cutters in this class. The Navy has also furnished the Coast Guard with a list of 4 alternative air-search radars in their inventory which are capable of satisfactorily performing the military mission.

The Navy further furnishes the Coast Guard with systems requirements of the four systems. Manpower requirements are presented in the following matrix format.

Manpower Requirement Matrix

	Operators Required (RD's)					Electronic Technician (ET's)				
	E-3	E-4	E-5	E-6	E-7	E-3	E-4	E-5	E-6	E-7
System 1		1	2		1			2	1	
System 2		2		1			1	1	2	
System 3		3		1			2		1	
System 4			2		1		1	1	2	

In addition, the Navy also provides the Coast Guard with years of useful life of each system, and a meeting between Navy and Coast Guard engineers yielded the cost estimate for spare parts unique to Coast Guard vessels. This information is presented as follows:

Information Matrix

	Years Life	Spare Parts	Installation
System 1	8	0	130,000
System 2	12	5,000	50,000
System 3	10	0	75,000
System 4	8	4,000	100,000

Solution:

Step 1: Transform the manpower requirement matrix into dollars. This example, in keeping with the assumption of 100 percent utilization of present Coast Guard resources, assumes manpower requirements as presented by the Navy are proxy variables of Coast Guard manpower requirements for each system. Thus, manpower costs per year are computed by multiplying the number of men in each rate by their respective life-cycle costs from Table II. For the purpose of this example manpower requirements are considered constant for the life of the system. Equation one will allow these costs to vary if manpower is expected to change over time. Dollar manpower cost estimates for the example problem are as follows:

Yearly Manpower Costs

	Operating	Maintenance	Total
System 1	61,312	54,147	115,459
System 2	43,280	72,599	115,879
System 3	55,326	47,717	103,043
System 4	59,709	72,599	132,308

Step 2: Determine the time horizon for each alternative system. The Navy provides the Coast Guard with an expected system's remaining useful life for each of the alternative systems. This, however, is not necessarily the years of life the Coast Guard should use for planning purposes. The Coast Guard must also consider the expected life of the vessel prior to decommissioning. Thus, the time frame to be used for determining life-cycle cost for each alternative is:

Time Horizon = Min(Systems life, vessel life).

This presentation assumes a vessel's expected life of fifteen years. Therefore, the time frame for each of the systems is their original estimated life.

Step 3: Apply the life-cycle cost equation [EQ. 1] to each of the alternatives. To ensure all cost elements are included it is suggested that the following cost element matrix be constructed. Inputs are the results of steps one and two as well as the original information matrix.

Cost Element Matrix

	Time Horizon	Installation	Operators	Maintenance	Spares
System 1	8	130,000	61,312	54,147	0
System 2	12	50,000	43,280	72,599	5000
System 3	10	75,000	55,326	47,717	0
System 4	8	100,000	59,709	72,599	4000

Applying equation one to the above data yields the following life-cycle costs relating to each system being installed on all four vessels.

Life Cycle Cost Matrix

	Life Cycle Cost	Systems Life Time
System 1	2,983,433	8
System 2	3,494,194	12
System 3	2,832,385	10
System 4	3,308,267	8

Finally, one further assumption in the proposed method to determine relevant life-cycle costs should be noted. A zero dollar cost is assigned to weight and space requirements of alternative systems. In the system selection problem for existing cutters, no meaningful dollar estimates are obtainable. If existing platforms can accommodate these systems and no other systems are planned for future installation, then the assumption of a zero dollar cost is valid.

2. Externality Costs

While no dollar value is assigned to the weight or space requirements of alternative systems, these requirements should not be deleted when preparing the cost-benefit analysis. Space and weight requirements should be treated as externality costs. These are costs associated with alternative systems that cannot be expressed in a common denominator such as dollars. For many problems of choice, externality costs may be the determining factor for selecting an alternative. Thus, the importance of the analyst identifying externality costs cannot be over-emphasized.

No attempt is made to list here all externality cost elements relevant to the Coast Guard's problem of systems selection. These must be identified each time a new alternative list is formulated by the Navy. However, some of the major externality costs, in addition to space and weight requirements, that appear to be common to most analyses of this nature are listed. These include the costs associated with restricted access to foreign ports because of certain electronic equipments or weapons; the changing public image of the Coast Guard from a peacetime service to a more military-oriented service; and the overarming of a vessel to such a degree that no adequate weapons would be available in peacetime situations. Finally, one other item is handled as an externality cost in the proposed cost-benefit analysis. This is the cost of selecting equipments with unequal expected lifetimes. The proposed methodology to determine life-cycle costs does not attempt to compute an average life-cycle cost per year for each alternative. Thus, the decision-maker must consider both total life-cycle costs and the system's expected lifetimes when arriving at a final selection. Two alternative methods for handling unequal expected systems lifetimes were examined and considered less desirable. Both methods attempted to combine time and life-cycle cost estimates into a single-dimension estimate of cost per year. The first alternative method took the total life-cycle cost estimate for each system and divided these values by their expected useful operating life. This method produced what is sometimes called an average cost per system. While it is appealing to present the decision-maker with directly comparable costs in this fashion, the results can be misinterpreted. The rational decision-maker would be expected to choose the system with the least average cost if their benefits were equal as it can be assumed that the goal of the organization is to minimize total costs. The major disadvantage of this procedure is the cost values obtained from the computation above are not really average cost values. The inclusion of the present value concept in equation one implies that equal dollar expenditures over time are assigned different values in the total cost estimate. Since dividing a total life-cycle cost estimate by the system's lifetime does not yield a valid average cost, minimizing this value does not guarantee that the true average cost is also minimized.

The second alternative method to obtain comparable yearly cost estimates for alternative systems was to adjust all time horizons to the maximum expected lifetime of any single system. This included the expected life of the platform. Thus, if system's A and B had expected lifetimes of 5 and 10 years, respectively, then it would be assumed that after 5 years an additional system A must be procured to complete the 10 year lifetime of system B. A decision of this nature is really a multi-stage decision, however. The outcome of a multi-stage decision is rarely realized in military problems. This is due to the face that available military systems and the decision-maker are constantly changing. It is more probable that at the end of system A's initial life time another analysis of alternative systems will be conducted. After this analysis it is quite probable that system A will not be purchased. Because yearly cost estimates may be misleading to the decision-maker, no attempt has been made to quantify life-cycle costs and systems' lifetimes into single numerical values.

IV. AN OVERVIEW OF EXISTING MULTI-ATTRIBUTE TECHNIQUES

Having established the cost of the alternative systems, whether by the proposed life-cycle costing technique or by other methods such as devising cost estimating relationships, the next problem is to establish the actual benefits of the systems. The exact measurement of peacetime benefits each system provides to existing cutters is a complex problem. Existing cutters have the responsibilities of performing several peacetime missions. Thus, a single vessel may be expected to perform missions such as search-and-rescue, enforcement of laws and treaties, marine environmental protection, or any number of the designated Coast Guard peacetime missions. If the goal of the Coast Guard is to select the system with the greatest peacetime benefits, the systems must be evaluated in terms of their benefits to each mission. Once this information has been obtained, however, the question remains as to how the decision-maker should select the best system. Since many missions comprise the peacetime responsibility of the cutter, one method of arriving at a rational selection is to use multi-attribute decision theory. This chapter discusses the requirements necessary to utilize multi-attribute decision techniques as a decision-making aid. Discussed are the requirements necessary to perform any form of multi-attribute analysis. This discussion further examines specific requirements of the more frequently used techniques of Dominance, Maximin, Lexicography, Utility Theory and the Additive function form.

A. CONCEPT OF MULTI-ATTRIBUTE ANALYSIS

The underlying concept of multi-attribute decision theory may be summarized as follows:

> Given a list of alternative systems and the organizational goals, decompose the goals into a complete list of attributes and then attempt to measure each system's impact on each of the attributes. Next, establish a procedure that will reflect the decision-maker's preference of the relative importance of each of the attributes. Finally, obtain a decision-making rule that will select the system that obtains the highest value, or utility, to the decision-maker based on his stated preferences.

B. PROBLEMS

While the concepts of multi-attribute decision theory have strong intuitive appeal, there are several inherent problems of utilizing a multi-attribute analysis for systems selection. First to be discussed are problems common to all multi-attribute techniques. These problems may be summarized in the following categories.

* Constraints on information processing
* Uncertainty
* Data requirements

1. Constraints on Information Processing

One of the reasons for using multi-attribute decision theory is the limited amount of data that a decision-maker can process and make a choice consistent with his subjective evaluation of the data. The underlying concept of multi-attribute decision theory is that the analyst should strive to reduce number of relevant variables of the problem, referred to as the dimensionality of the problem, to a smaller dimensional problem the decision-maker can comfortably handle. Ideally, the decision-maker would like to base his decision of choice considering all attributes simultaneously. However, as the number of attributes increase, the decision-maker loses the ability to subjectively choose among alternatives. This phenomenon on the limitation of information processing has been studied for several years. The result of studies indicates that people can utilize no more than five to ten chunks of conceptual information at any given time.[15]

Multi-attribute decision techniques rely on the underlying assumption that wholistic problems of choice can be decomposed into the several smaller problems, each of which is simpler for the decision-maker to evaluate than the aggregate problem. One of the necessary assumptions, therefore, is the goal of the decision process can be described completely by a finite number of attributes. This assumption

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[15] Fischer, G.W., Four Methods for Assessing Multi-Attribute Utilities: An Experimental Validation, Technical Report, University of Michigan, September 1972, p. 3-4.

seems plausible in studies involving systems selection since quite often an equipment can be characterized by either physical parameters such as weight, power requirements, etc., or by subjective values of broadly defined attributes that comprise the goal. Violations of the assumption of obtaining a complete list of attributes most often occur when attempting to define the attributes of a psychological goal, such as measuring intelligence, where no agreed upon list of atrributes has been established.

The second assumption brought about by the decomposition principal necessary for most multi-attribute techniques is that attribute values are independent. Independence implies that the judges preference for m attributes are not influenced by the state of the remaining n-m attributes in the n dimensional problem. Independence requirements are the basis of most models used to describe multi-attribute decision making. Another implication of independence is the requirement that no cross-product worth or other complementaries exists among any attributes.

The exception to techniques requiring the independence assumption is a method known as effectiveness index theory. Effectiveness index models allow for the functional form of the value of system over all attributes to be any general form. Cross-product terms or any functional form involving one or more attributes may be utilized to approximate a judge's worth of a system. To use the effectiveness index model requires the analyst to be able to construct the functional form that approximates the decision-maker's subjective judgment. To accomplish this task the analyst has two options. He may ask the decision-maker to specify the functional form that he used in arriving at the decision or he may attempt to arrive at a functional form of the decision-makers judgment process given only the judge's values of the attributes. If the analyst cannot arrive at the decision-maker's functional form, he has few options but to accept the requirement of independence among attributes.

Existing multi-attribute decision techniques allow the analyst to select whatever dimensionality of the problem he wishes to consider when making his recommendations to the decision-maker. However, the assumptions required for techniques using full dimensionality in the decision criteria are so restrictive that full dimensionality is of limited use in most situations. Unfortunately, the reduction of the original full dimension problem to a single attribute or numerical value does not simplify the problem of choice. Indeed, further assumptions are also required to base a decision on a single numeric value. These assumptions are discussed in the presentation of existing multi-attribute decision techniques that require a single numeric value. The major disadvantage of utilizing a single numeric representation of an alternative's worth is not the acceptance of the required assumptions. Generally, these assumptions are necessary for the decision-maker to use an analysis and arrive at a rational choice. The problem is that often the assumptions required are deemed valid by the analyst and not the decision-maker. These assumptions are then unknown to the decision-maker when he makes a rational choice from the prepared analysis. An analyst should strive to present the analysis to the decision-maker in the maximum dimensional form that the decision-maker can utilize his expertise to arrive at rational choice.

2. Uncertainty

Uncertainty in decision-making process refers to the uncertainty of the outcome of selecting any alternative system. Most actual problems have some degree of uncertainty associated with them. Existing techniques, however, often begin by assuming that the outcome is certain. This requirement of certainty on the outcome space is necessary for several reasons. The major technique utilized to reach a choice among alternative candidates that formally considers uncertainty is the expected utility principal. However, for the analyst to apply utility theory to actual problems of choice requires severe assumptions. The expected utility principle requires not only the existence of a utility function, but also that the decision-maker is able to specify a probability distribution over the possible consequences of each action. This requirement is difficult to fulfill in actual decision-making problems since often the decision-maker cannot establish all the possible outcomes of a decision. If all outcomes of each course of action are known to the analyst, he next must assign a probability to the outcomes occurring. Finally, a rule to combine the utilities across all attributes must be devised.

If one is willing to make the assumption that a decision-maker can specify probability distributions over each of the possible outcomes, other problems arise in using the expected utility principle. One problem is determining what functional form the analyst should use when combining the various probabilities and utility values over all possible outcomes to arrive at a single utility value for each alternative. Expected utility principle requires that the expected utility of an action be an additive functional form represented by:[16]

$$EU(A_i) = P_{1i}\ U(x_1) + P_{2i}\ U(x_2) + \ldots\ P_{ni}\ U(x_n)$$

where

EU = Expected utility

A_i = i^{th} action

P_{ni} = Probability of n^{th} outcome with respec to i^{th} action

$U(x_i)$ = Utility of outcome (X_i)

For the functional form $EU(A_i)$ to additive, it has been demonstrated that an additional assumption is necessary.

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[16] Ibid., p. 10.

This is the assumption of marginality among gambles.[17] The marginality requirement implies that if two finite gambles are marginally equivalent then the decision-maker must be indifferent between the gambles. Two gambles are marginally equivalent if they give rise to identical marginal probability distributions.

Thus, if one had a choice of the following two gambles

G_1 = Probability .5 of receiving a 100 percent increase in mission 1 and a 75 percent increase in mission 2.

Probability .5 of receiving a 10 percent increase in mission 3 and a 20 percent increase in mission 4.

G_2 = Probability .5 of receiving a 100 percent increase in mission 1 and a 20 percent increase in mission 4.

Probability .5 of receiving a 75 percent increase in mission 2 and a 10 percent increase in mission 3.

Then for marginality to be present the decision-maker must be indifferent as to which of the gambles he selects. This is due to G_1 and G_2 being marginally equivalent. However, if the decision-maker prefers gamble G_2 since it assures him of a high value outcome, then the additive form for

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[17] *Ibid.*, p. 11-15.

combining utilities is not appropriate. Other functional forms have been devised for the case in which the expected utility is not valid due to the violation of the marginality requirement. For further discussion in this area the interested reader is referred to [Fischer].

The last assumption of utility theory in decision making context is the requirement that the decision-maker selects his decision based on maximizing his expected benefits. In many situations, however, the decision-maker may be risk-averse and selects the decision which does not maximize his expected gains but minimizes his expected losses. Other forms of decision criteria have been observed and in one laboratory experiment, with subjects trained in obtaining probabilities, 41 out of 64 subjects made decisions by some other technique than maximizing expected utility.[18]

3. Data

The last problem that influences all multi-attribute decision analysis is the problem of data. The analyst is faced with two problems in dealing with data. First, the analyst must decide the type of data to collect and then he must transform the original data into comparable values across attributes. The actual multi-attribute decision rule he selects will determine the extent that the data must be manipulated. Certain decision criteria require only that the data be comparable within each attribute. However, these

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[18] Beach, B.H., Direct and Indirect Methods for Measuring Utility, Technical Report, University of Washington, July 4, 1972.

decision criteria are sufficently restrictive as to be rarely useful. Other criteria require complete comparisons of values across attributes. In these situations physical characteristics must be transformed into values that lend themselves to comparison. Finally, other decision criteria require that values across attributes be additive. Thus, ratio-scale values are required. The following discussion is intended to help the analyst in arriving at the proper scale necessary to use the various multi-attribute selection criteria. Also presented are the properties each measurement scale possesses.

a. Nominal Scale

This technique represents the lowest form of measurement scales. This type of scale is produced when a judge is asked to place items in similar groupings based on any desired property. The final groupings have no order of worth, however. Nominal scales have the undesirable feature that statistical techniques depending on a distance between points concept, such as the mean, median, or standard deviation cannot be utilized. Nominal scales require only that each item in the same group be assigned the same number and that no two groups receive the same number. As such, any one-to-one transformation on the original data is permitted and will preserve the groupings. For multi-attribute analysis data obtained on a nominal scale is of limited value. This is due to the fact that there is no method to combine values across attributes. For single attribute problems, nominal scaling techniques do have some advantageous properties. Statistics based on frequencies, modes, and coefficients of continuity can be calculated from nominally scaled data.[19] More importantly, however, is the fact that this type of scaling requires the least amount of work for the judges scaling the alternatives. The judge is not required to give a numerical value of an alternative's worth but only to place items in groupings.

b. Ordinal Scale

Unlike the nominal scale, data obtained on an ordinal scale implies a difference of worth exists among groupings. Most often ordinal scale data are obtained by having judges rank order alternatives via some parameter or property. Ordinal scaling allows the analyst to differentiate among equality, greater than, or less than among alternatives. As such, any monotone increasing transformation is allowable on the original data as it preserves order within the alternatives. Ordinal scaling is a popular method for obtaining information from judges as it requires the judges to simply rank order alternatives. Obtaining original data does not require the judges to assign any numerical value to the difference in worths among alternatives. Further, popularity of ordinal scales is increased by the fact that many procedures exist of a non-parametric nature allowing for the differences among alternatives to be obtained without assuming a normal distribution on judges

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[19] Guilford, J.P., Psychometric Methods, p. 8-19.

responses. The major disadvantage of ordinal scales is that no absolute value of the difference in worth among alternatives is possible. Also no procedure exists to combine ordinal data across attributes. Thus, while methods are available to compute the overall rank order of alternatives based on several judges' responses within a single attribute, there is no way to determine how much better the "best" alternative is from the second best or even the worst. From a cost-benefit approach this procedure is of limited use since the amount of difference in equipment's worth is necessary to perform a tradeoff analysis between alternatives.

c. Interval Scales

The third level on which data may be obtained is the interval scale. Interval scales are commonly referred to as equal-unit scales and have important properties over both the nominal and ordinal scales. The major property of interval scaling is that numerically equal distances stand for equal distances in some aspects of the alternatives being scaled.[20] As a result of this property, two items that have numbers 10 and 20 assigned to them are as far apart as two items having the numbers 50 and 60. The property of equal distance arises from the fact that interval scales have an arbitrary origin and arbitrary units which are constant over the scale. Since the origin and units on an interval scale are arbitrary, any linear

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[20] Ibid., p. 14.

transformation may be applied of the form $x' = a + bx$, where x denotes original value, a is a constant, and b is a scalar greater than zero. However, since the origin is arbitrary, little meaning may be attached to addition across attributes of numbers obtained on an interval scale.

✓ Common forms of data obtained on an interval scale are temperature measurement, altitude, and calendar time. While direct addition of numbers on interval scales is not permitted, actual distances measured between two values do have the additive property. This allows for almost all statistical procedures to be performed on interval scale values within an attribute. These include calculating the analysis of variance, means, and the standard deviation. The one statistical procedure not allowed is the computation of the coefficient of variation, which is based on the ratio of the standard deviation to the mean of the distribution. This ratio is not meaningful since it depends on where the arbitrary zero point is located.[21]

While interval scaling procedures have far more use to the analyst than either nominal or ordinal scales it must be noted that the requirements on the judges have been greatly increased. No longer is it sufficient for the judge to group or rank alternatives. The judge is required to actually assign a numerical value to the alternatives in a consistent way.

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[21] Ibid., p. 15.

d. Ratio Scale

The last measurement technique available to the analyst is the ratio scale. Ratio scales occur in data where there is a fixed or natural origin. Examples of ratio scales are length, cost and time with a fixed 0 point. Since ratio scales have an absolute zero point, it is possible to equate meaningful ratios on the number scale. This implies that not only all previously mentioned statistics may be calculated on ratio scale values, but also the coefficient of variation may be computed. Values computed from ratio scale data may be compared for equality, inequality, equality of raios of intervals and equality of ratios themselves. The original data may be transformed by the use of any equation in the form $x' = bx$, where b is a scalar greater than zero.

While ratio scales are the most powerful in terms of the number of statistics that may be calculated, this scaling method requires the analyst to use ratio scales on subjective judgments. To obtain ratio scales the judge must perform the task of expressing alternatives worth in terms of ratios. As the number of alternatives requiring scaling increases it is quite common to observe inconsistencies in values the judges assign to alternatives. Since both addition and multiplication may be performed on ratio scales, however, the ratio scale is very popular in analysis where a natural zero origin exists and the number of alternatives to be examined is small.

Summarizing the discussion on scaling methods available to the analyst, as one progresses from nominal to ratio scales the amount of data manipulation permissible increases and the scales become more robust in the number of statistics that may be calculated. Tempering the analyst on the proper scale to utilize, however, is stated requirements of each scale as well as the increasing requirements on the judges' response level. Equally important as selecting the proper scaling method is the assurance that the limitations of the chosen scaling method are followed. Often many limitations are violated in the attempt to obtain more information from data than the scaling methods allow. An example is attempting to obtain interval scale data from rank orderings by judges. Arbitrary values are often assigned for various ranked positions, i.e., 10 for the item ranked first, 9 for second, down to 0 for the lowest ranked alternative. Finally, an average value is computed based on the number of points acquired. The deficiency of this procedure is that the results often depend on the arbitrary numerical values assigned to the rank-ordered list.[22] Therefore, when addition of values across attributes is required the analyst must realize the values must be obtained on a ratio scale level.

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[22] Moon, J.W., "A Problem on Rankings by Committees", Econometrica, Vol. 44, 1976.

C. COMMON TECHNIQUES UNDER CERTAINTY

After having discussed the problems of uncertainty, information processing capability, and data gathering that affect all multi-attribute decision techniques, the remainder of this chapter will be devoted to examining riskless decision criteria. Even riskless multi-attribute techniques require many assumptions that are difficult to verify in actual problems. Since they require fewer assumptions than methods incorporating risk, analysts frequently use one or even several riskless techniques to arrive at their recommendations. Appendix D presents the multi-attribute decision making techniques that are available to the analyst. The following discussion presents an overview of the most frequently used techniques. Discussed are the inherent assumptions and limitations that each criterion exhibits. Techniques under discussion include Dominance, Minimax and Maximin, Lexicography, and additive weighting.

1. Dominance Theory

Dominance theory is one of the few techniques available to the analyst that may yield a solution to the selection problem by utilizing a decision criterion for selection that considers all the original attributes. The decision criterion of dominance theory may be stated as follows:

Let

$$\underline{X} = (x_1,x_2,x_3, \ldots, x_n)$$

and

$$\underline{Y} = (y_1,y_2,y_3, \ldots, y_n)$$

where $\underline{X}$ and $\underline{Y}$ denote the overall worth of alternatives X and Y, and $(x_1,x_2,x_3, \ldots, x_n)$ and $(y_1,y_2,y_3, \ldots, y_n)$ denote vectors representing values of the alternatives over the n attributes for X and Y respectively. Then the decision rule may be stated as:

Choose X if $x_i \geq y_i$ for all i
or
Y if $x_i \leq y_i$

The decision rule allowing for the $\geq$ or $\leq$ is termed a weak dominance decision. This implies the decision was made to select one alternative even though over some attributes the system not selected was equal to the alternative chosen. If the decision rule uses only strict inequalities then the decision rule is known as strong or strict dominance. It should be noted that this decision criteria is invariant as to whether the attribute values were measured on ordinal, interval, or ratio scales. Since many of the problems associated with data have been eliminated, dominance is one of the most easily applied decision criteria. Also, a decision based on the dominance decision rule can be regarded as a very rational decision.

While dominance theory is easy to apply and the results are known to be good, rarely will the dominance criterion yield a solution to the selection problem. The best that can usually be hoped for in utilizing the dominance decision criterion is the elimination of some alternative systems from consideration. Dominance will not solve the problem of how to evaluate the remaining alternatives where dominance does not prevail.

The remaining techniques for assessing multi-attribute decision problems reduce the original dimensionality to a single dimensional problem in the attribute space. Minimax and maximin are the two decision criteria applied to multi-attribute analysis that have their origin from game theory. Because these two procedures require many common assumptions to produce a decision rule, they will be examined together.

2. Minimax and Maximin

The minimax decision rule criterion requires that alternative values across attributes be highly comparable. If comparable values can be achieved, the minimax procedure is to first obtain the maximum values of the alternatives over all attributes and then select the alternative with the smallest maximum value over all its attributes. The maximin procedure is to obtain the minimum values of the alternatives over all attributes and then select the alternative with the largest minimum value over all attributes.

While minimax and maximin decision criteria were first introduced in game theory, their results should not be interpreted in classical game theory context. Game theory requires that a payoff matrix be established. The size of the payoff matrix is dependent on the number of courses of action available to each of the players. In decision theory contexts one can view the game with the decision-maker as one player and nature as the opposing player. However, the original m alternatives to be examined and the n attributes over which each alternative must be evaluated should not be considered a payoff matrix. Nor can a payoff matrix be established unless one knows all of the different courses of action that nature may follow. Without have a payoff matrix established, the rules of game theory that ensure a player can follow either a pure or mixed strategy and maximize his expected gains, or minimize his losses, cannot be applied.

Examining the minimax decision rule for multi-attribute analysis one sees that much information is not used in arriving at a decision. The only value compared among alternatives is the maximum value each alternative receives. Thus, the decision criteria often allows a system to be chosen where alternative systems may receive higher values in the remaining n-1 attributes. The same restrictive property also holds true for the maximin technique.

3. Lexicography

Lexicography is another multi-attribute decision criterion that may be regarded as a single dimensional technique. This decision criterion requires that the list of attributes be rank-ordered in terms of their importance. Next, the values of each alternative system is measured over each of its attributes. Finally, the decision criterion may be summarized as follows. Beginning with the highest ranked attribute, select the alternative with the highest value in this attribute. If two or more alternatives have the same value in the highest ranked attribute, omit all other alternatives with lesser values. Then proceed to the attribute list and select the attribute ranked second highest. Examine the remaining alternatives and select the alternative with the highest value in this attribute. If ties continue to exist, the procedure is repeated, each time omitting alternative systems with values less than the maximum value of alternatives that remain, until an attribute is reached where only one alternative has a maximum value. If all n attributes have been examined and ties exist, the decision-maker should be indifferent as to which system is selected. An example is presented to clarify this decision criteria:

> Suppose one must choose a system to perform air surveillance and has a list of three attributes to consider. Further the weight of importance of

> the three attributes are .2, .3, .5 respectively. This information may be displayed in the following matrix:

		attribute j		
		(.2)	(.3)	(.5)
		1	2	3
alternative i	1	High	6	2
	2	Low	8	8
	3	Medium	4	6
	4	High	2	8

> Further let x_{ij} entries in the above matrix denote the value of the i^{th} alternative in the j^{th} attribute where numerical values are on an interval scale. Then lexicography decision criterion begins by selecting attribute three and examining the alternatives to obtain the maximum value. In this example alternatives two and four are tied with a value of eight. Eliminate alternatives one and three from consideration and proceed to the next most important attribute, attribute two. Examining alternatives two and three one finds that alternative two has the highest value for attribute two. Thus the selection process stops and the lexicographic decision criterion selects alternative two as the best system.

The presented example demonstrates the advantage of using lexicography. The advantage is that no requirements are placed on the analyst to obtain values that are comparable across attributes. Any form of data may also be utilized that exhibits the property of conveying a concept of worth. However to obtain the characteristic of non-comparisons across attributes the analyst relies on a fundamental assumption. This assumption is that after the solution to an n-dimensional problem has been obtained by examining m attributes, the remaining n-m attributes have no influence on the solution outcome. This implies that the original rank of attributes not only implies order, but also that each successive rank-ordered attribute is of such importance to the decision-maker that all other attributes with a lesser weight need not be considered when selecting a system. While the lexicographic decision criterion guarantees a selection outcome, much information about the various alternatives is not utilized.

4. Additive Value Function

The final multi-attribute decision technique to be discussed is the additive value function criterion. This technique assumes that the alternatives may be evaluated over each of the attributes and then the worth of each alternative may be obtained by summing the alternative values across attributes.

The concept behind the additive value function decision criterion is that the final alternative value represents a weighted average of the contribution the alternative yields over the attributes.[23] This technique has an advantage over the previously discussed decision criteria since

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[23] MacCrimmon, K.R., Decision-Making Among Multiple-Attribute Alternatives - A Survey and Consolidated Report, RAND Corp., December, 1968. P. 28-33.

each alternative is compared over all n attributes. This implies that no information was lost in arriving at a decision. Again, however, there are assumptions that the analyst should consider before applying the additive value function decision criterion.

The first assumptions that the analyst must justify is that an additive value function is the correct decision criterion. In riskless decisions the necessary and sufficient conditions that guarantee the existence of an additive evaluation function for three or more attributes are:[24]

1. Preferences must be weakly ordered
2. Monotonicity of attributes

To ensure that preferences are weakly ordered the following two properties must be examined. First the analyst must be able to express all values in the following manner. Either he is indifferent, between two outcomes x_i and x_j, he prefers x_j to x_i or he prefers outcome x_i to x_j. Secondly, transitivity must exist between outcomes. Transivity requires that for any outcomes: if x_i is preferred to x_j and x_j is preferred to x_k, then x_i must be preferred to x_k.

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[24] Fisher, p. 8.

Monotonicity of attributes is more difficult to establish. To satisfy the monotonicity requirement it must be true that preferential independence conditions are satisfied among attributes. This independence assumption may be stated as:

Let $(x_1,x_2, \ldots, x_n)$ denote the attribute vector describing the worth of system X. Further, let Y denote any subset of these attributes and Y' denote the remaining attributes. Thus $\underline{X} = (Y, Y')$. Now let Y_i and Y_j be any two states of the Y attributes and let Y'_i and Y'_j be any two states of the Y' attributes. Then it must be true that the decision-maker will prefer the outcome (Y_i, Y'_j) if and only if he prefers (Y_i, Y'_j) to (Y_j, Y'_j).[25]

The above independence or separability assumption implies that if one were examining the various alternatives' overall worth, the tradeoff values for attributes x_1 and x_2, keeping the other levels of the remaining attributes fixed, does not depend on the particular values of the fixed levels. If both the preferential independence assumption holds along with the weak ordering assumption then this guarantees the existence of an additive value function for riskless decisions.

Once the analyst has selected the additive value function as the correct decision criteria there are other

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[25] Ibid.

requirements necessary to use the proposed cost-benefit model. First, the analyst must be able to obtain values in the alternative-attribute matrix that are highly comparable across attributes. Secondly, the values obtained must possess the property of additivity. Since only ratio scale values possess this property of additivity, the analyst is forced to use ratio scale values. The implication of using ratio scale numbers is that values in the alternative-attribute matrix represents the decision-makers subjective evaluation of an alternative's worth for an attribute. Thus, if one system had a value of 3.0 in an attribute and another system had 6.0 in the same attribute, the second system is twice as valuable in the performance of the attribute.

As can be seen, all multi-attribute selection criteria require many assumptions that rarely can be verified to be valid in actual problems of choice. One problem of multi-attribute selection criteria is that no method has any internal checks that would indicate assumptions were clearly violated. Perhaps the best check that can be applied is to perform several different analyses each based on different assumptions. If the various studies all indicate the same alternative is best, this should indicate that the system selected is highly independent of the assumptions used to arrive at the decision. The proposed cost-benefit model was developed to be used in conjunction with NOSC's methodology to serve this purpose. In the next chapter a discussion of how expert judgment may be used to estimate the overall ratio-worth's of alternative systems is presented. The procedure to estimate the alternatives ratio-worth's is developed for the case where the additive functional form has been deemed appropriate.

V. METHODOLOGY TO OBTAIN ESTIMATES OF EQUIPMENT RATIO WORTH

To measure the benefits of alternative systems from Naval inventory a method comprised of several previously discussed multi-attribute decision techniques is proposed. Combining the expected benefits measured in this chapter with the previously discussed relevant life-cycle cost matrix yields a four-dimensional solution to aid the decision-maker in arriving at a rational choice. A four dimensional solution is proposed as it reduces the dimensionality of the original problem to a level the decision-maker may subjectively evaluate. This solution allows the decision-maker to use his expertise when arriving at a decision as to which system to select. A technique of this nature eliminates the requirement on the analyst to formulate an approximation to the decision-maker's functional form he uses to tradeoff such diverse items as externality costs and a system's benefit. It should be noted that this procedure does not eliminate the requirement of performing these tradeoffs. This procedure is intended to aid the decision-maker by presenting relevant information required to perform this task. What it does eliminate is having to mathematically formulate the subjective process that the decision-maker uses.

This chapter proposes the constant-sum method to arrive at an estimate of the alternative's worth. A least squares derivation of the constant-sum method is presented with emphasis placed on special cases that must be considered when using the constant-sum method to compare dissimilar alternatives. Finally, discussed in this chapter are the options the analyst has in interpreting the results.

The methodology to measure benefits was constructed for the case where the Coast Guard has incomplete knowledge of the alternative systems in Naval inventory and cannot make ratio judgements between all alternatives. Also, it has been assumed that the Navy is insufficiently familiar with actual requirements of Coast Guard peacetime missions to make ratio judgements of the system's impact on each mission. However, it is assumed that expert judges do exist within the Navy to evaluate alternative systems in each of the attributes. Possible sources of expert judges include personnel attached to Navy laboratories who are considered experts in the fields of equipments under consideration, or personnel on board vessels who have had direct experience operating several of the equipments.

Secondly, it is assumed that the ship-work-breakdown functions which will comprise the attribute list describing Coast Guard missions are performed in the same manner by the Navy. A representative list of these attributes are presented in Appendix C. Specific definitions of attributes should be utilized in obtaining subjective values from different judges to reduce the variability in judges responses arising from personal interpretation of the various attributes.

A. METHODOLOGY

To obtain ratio scale values of equipments' worth based on subjective judgement, a constant-sum method has been adopted from the psychological sciences. The basic assumption of this technique is that judges are capable of expressing the value of two competing alternatives in ratio form and there exists a concept of a natural origin among judges. An agreement on the natural origin in the case of systems comparisons implies that the judges have the same concept of when the equipment provides no worth in a given attribute and that this origin is constant over attributes.

A discussion of how the constant-sum method may be utilized to obtain an estimate of the equipments' worth for each attribute is presented. For the system selection problem under consideration 100 total points has been chosen as the value that the judges are to divide within pairs of alternatives for each attribute. In this discussion the following notation will be utilized.

Let

a_{ij} = Number of points awarded to the j^{th} alternative when compared to the i^{th} alternative, $i \neq j$

n_{ij} = Number of judges responding to the comparison of the j^{th} versus i^{th} alternative

n = Number of alternatives to be compared.

Then for each judge, his splitting of 100 points between successive pairs of alternatives may be presented in the

A matrix. The total number of comparisons each judge is required to make is $\frac{n(n-1)}{2}$ for each attribute.

A Matrix

Alternative

$$\begin{array}{llccccc}
 & & 1 & 2 & 3 & \cdots & n \\
 & 1 & a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\
 & 2 & a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\
\text{Alternatives} & \vdots & \vdots & & & & \\
 & n & a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn}
\end{array}$$

The A matrix above for each judge is then combined to form an average value matrix. Denote this matrix $\bar{A}$. Let $\bar{a}_{ij}$ denote the (i^{th}, j^{th}) entry in the $\bar{A}$ matrix. Then $\overline{a_{ij}}$ may be computed by:

$$\overline{a_{ij}} = \frac{1}{n_{ij}} \Big(\sum_{\substack{\text{All} \\ \text{judges}}} a_{ij} \Big)$$

Since $\overline{a_{ij}}$ represents the average value of Alternative j when compared to alternative i, the matrix W may now be constructed where each w_{ij} entry may be computed by

$$\begin{aligned} w_{ij} &= \frac{\overline{a_{ij}}}{\overline{a_{ji}}} & i \neq j \\ &= 1 & i = j \end{aligned}$$

Each w_{ij} entry thus becomes an estimate of the ratio between the scale value of the j^{th} versus i^{th} alternative. Thus letting s_j denote the scale value of the j^{th} alternative, the w_{ij} entries may also be denoted as

$$w_{ij} = \frac{\hat{s}_j}{\hat{s}_i} .$$

Note, however, that

$$\frac{s_j}{s_i} / \frac{s_i}{s_k} \equiv \frac{s_j}{s_i} .$$

Therefore an additional n-1 estimates can be obtained by

$$\frac{\tilde{s}_j}{\tilde{s}_i} = \frac{w_{kj}}{w_{ki}} .$$

In general $\frac{\hat{s}_j}{\hat{s}_i} \neq \frac{\tilde{s}_j}{\tilde{s}_i}$ although all are estimates of s_j/s_i. These estimates will not generally be equal since inconsistencies of judges' response can be expected to occur frequently. In order to minimize the inconsistency of a judge's response and utilize all of the information contained in the w_{ij} matrix, a least-squares approach is followed to obtain the value s_j.

The procedure begins by rewriting

$$w_{ij} = \frac{s_j}{s_i}$$

as

$$\log w_{ij} = \log s_j - \log s_i$$

or

$$\log w_{ij} - (\log s_j - \log s_i) = 0$$

Therefore, the least-squares approach implies that the values $s_1, s_2, \ldots, s_n$ are obtained by letting[26]

$$Q = \sum_i \sum_j [\log w_{ij} - (\log s_j - \log s_i)]^2$$

and then obtaining the least-squares solution for the values s_j, $j = 1, n$; which will minimize the function Q.

To minimize the function Q requires taking n partial derivatives of Q and setting each derivative equal to zero. Thus,

$$\frac{\partial Q}{\partial s_j} = -2 \sum_{i=1}^{n} [(\log w_{ij} - (\log s_j - \log s_i)] = 0$$

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[26] Torgerson, W.S., Theory and Methods of Scaling, p. 105-113.

The above equation may then be simplified to

$$\sum_{i=1}^{n} \log w_{ij} - n \log s_j + \sum_{i=1}^{n} \log s_i = 0$$

Finally, rewriting this equation as a function of s_j, one obtains

$$\log s_j = \frac{\sum_{i=1}^{n} \log w_{ij}}{n} + \frac{\sum_{i=1}^{n} \log s_i}{n}$$

Recalling that the units are arbitrary for ratio scale data, next choose the units value such that

$$\frac{\sum_{i=1}^{n} \log s_i}{n} = 0$$

Therefore, with the above simplification, which is not an assumption, the equation for s_j may be expressed as

$$\log s_j = \frac{\sum_{i=1}^{n} \log w_{ij}}{n}$$

Taking the anti-log of both sides of this equation yields the following expression for the estimate of s_j

$$s_j = \prod_{i=1}^{n} (w_{ij})^{1/n} \qquad \text{[Eq. 2]}$$

Thus, the estimate of the scale value of the j^{th} alternative, s_j, may be computed by taking the geometric mean of the j^{th} column of the W matrix. One advantageous property of the geometric mean being used as an estimate of the value of the j^{th} alternative is that the j^{th} column geometric mean is identically equal to the reciprocal of the j^{th} row geometric mean. If the arithmetic mean would have been utilized the column mean would not necessarily have agreed with the reciprocal of the row mean since in general

$$\frac{1}{\left(\overline{\frac{1}{x}}\right)} \neq \overline{x}$$

where

$$\overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

denotes the arithmetic mean.

It should be noted that when comparing highly dissimilar systems such as an air-search radar and an electro-optic device the $\overline{A}$ matrix may have entries where $\overline{a_{ij}} = 100$ and $\overline{a_{ji}} = 0$. These $\overline{a_{ij}}$ values can arise when one alternative cannot perform a given attribute while the other alternative does have some capability in the attribute. In this case values in the w_{ij} matrix will be $w_{ij} = \infty$ and $w_{ji} = 0$. To accommodate this case the following modification of the constant-sum method is suggested. Assign a value of zero to the s_i estimate of the i^{th} alternative's worth omitting the calculation of the geometric mean for the i^{th} alternative. This is deemed appropriate since it is reasonable to assume that if an alternative receives a value $\overline{a_{ji}} = 0$ then $\sum_{j=1}^{n} \overline{a_{ji}} = 0$, since the i^{th} systems inability to perform the attribute should be unaffected by its comparison with the remaining n-1 alternatives. Also a w_{ij} value of ∞ contains no information except the j^{th} alternative does have an impact in the attribute. Since this information is wholly contained in the remaining n-1 w_{ij} values, $w_{ij} \neq \infty$ then the geometric mean of the j^{th} alternative may be computed as

$$s_j = \prod_{i=1}^{n-m} (w_{ij})^{\frac{1}{n-m}}$$

for all $w_{ij} \neq \infty$, 0, where m = number of w_{ij} values = ∞.

One further special case is considered. This is the case where neither alternative has any impact on the attribute under consideration. Without specific instructions, the judges may respond to this case by dividing the points equally between alternatives. The constant-sum procedure would then produce erroneous results by calculating a positive alternative's worth when none exists. However, this problem may be eliminated by proper preparation of the questionnaire instructing judges to omit the specific comparisons where neither alternative has a positive impact on the attribute under consideration. If all judges are unanimous in leaving the a_{ij} comparison blank then $\overline{a_{ij}} = 0$ and $\overline{a_{ji}} = 0$. Thus, a value of zero is assumed for s_i and s_j.

Adopting the above procedure in the case when dissimilar alternatives are to be compared increases the importance of the analyst using a large number of judges. The constant-sum method does not take into consideration or weight the estimated s_j values by the number of judges who responded to the comparisons of the alternatives. Thus, the values of s_j are independent of the number of judges responding to the j^{th} alternative versus all remaining alternatives. As such, the constant-sum method does not require the judges to make all comaprisons on the questionnaire and encourages the judges to omit comparisons they are incapable of making. A large number of judges will reduce the probability of all judges leaving the same comparison of alternatives blank due to insufficient knowledge of the two alternatives.

The procedure yields estimates of the subjective worth of each of the alternatives for a given attribute. Let m denote the number of attributes over which the n alternatives are to be compared. Therefore, after having performed an additional m-1 replications of the constant-sum technique, i.e., once for each attribute, the following alternative-attribute matrix V may be constructed.

Alternative-Attribute Matrix

Attributes

$$\begin{array}{cccccc}
 & & 1 & 2 & \cdots & m \\
 & 1 & & & & \\
 & 2 & & & & \\
\text{alternatives} & \vdots & & & v_{ij} & \\
 & n & & & &
\end{array}$$

Thus, each column represents the outcome values s_j, $j = 1, n$ of the constant-sum technique for a single attribute.

The final step in obtaining the estimated values of the total ratio worth of alternative systems for the case of the additive function form is obtained by multiplying the V matrix by the relative weights of importance attached to the attributes by the decision-maker. Denote the attribute vector as $\lambda = (\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_m)$. Then, an estimate of the alternatives' ratio worths considered over all attributes is computed by

$$X_{1 \times n} = \lambda V^T$$

where

λ = $1 \times m$ matrix of the relative importance of attributes

V^T = the transpose of the V matrix

The finalized X matrix values are on a ratio-scale where direct comparisons between alternatives is possible. As an aid to the decision-maker, however, it is suggested that the finalized X matrix be transformed by the formula

$$X' = bx$$

where b will be the scalar value necessary to raise the equipment with the highest score to a value of 100 points. Thus, if the highest alternative has a value of 100 and another alternative has a value of 75 it is correct to interpret the results as the highest scored alternative is 1.33 times better than the other candidate. The results may also be presented as the lower-scored alternative is only 75 percent as effective over all attributes.

Appendix E presents an example of the constant-sum method of obtaining estimates of the alternative's total worth ratios for the air-search selection problem. The estimates of alternatives total worth ratios are then combined with the life-cycle cost solution to yield a four-dimensional solution. The decision-maker may use his expertise to combine the solution matrix to arrive at the selection of a single system. Table III displays the final solution in matrix form for the hypothetical air-search radar selection problem.

Table III

Four Dimensional Solution In Matrix Form

		Life Cycle Costs	Time Horizon	Externalities	Ratio-Worth
Alternative Systems	1	3.0 million	8	power weight space etc.	65.73
	2	3.5 million	12		58.04
	3	2.8 million	10		100
	4	3.3 million	8		67.8

An outline of the proposed cost-benefit methodology used to arrive at the four dimensional solution is presented in Appendix F.

B. INTERPRETATION OF RESULTS

The four-dimensional solution is to be used by the decision-maker to arrive at a rational choice. This procedure can aid the decision-maker as it presents the relevant information of the decision in a small number of variables. This small dimension will allow the decision-maker to use his expert judgement to select the best alternative based on his criteria. In many cases the solution matrix Table III may be used to directly select the best decision. In other situations more information may be required. These two cases are discussed in the remainder of this chapter. Both situations are discussed for the case where externalities and expected lifetimes would not prohibit the selection of any alternatives. Alternatives having unacceptable externalities to the decision-maker should be eliminated from the list of systems under comparison.

Case I: If one alternative has the lowest expected life-cycle cost and highest expected overall worth, then the selection criteria of dominance should be utilized. While the dominance technique is of limited value when many attributes are considered, for four attributes dominance becomes a useful criterion. If one ignores externality costs, the air-search radar example problem of Table III may very well lend itself to dominance decision criterion.

Case II: No alternative has both the lowest life-cycle cost and highest overall benefit value. In this situation, selecting the best alternative becomes much more difficult. This is due to the fact the calculated expected benefit ratio values are dimensionless. Thus, if two alternatives receive values of 50 and [illegible] respectively, it is true that the second alternative has twice the impact as the first. However, no direct estimate of how much an alternative will increase the effectiveness of the platform is obtainable from the constant-sum method. If one alternative is twice as effective as another alternative and still increases peacetime effectiveness by only two percent, costs may become the overriding decision criterion. When the final solution matrix is a case II matrix, additional information will be required. The additional information required will

be an estimate of any one alternative's overall impact on the peacetime missions. The only requirement is that the alternative chosen has a non-zero positive impact. Once the percentage of the overall impact for a single alternative is known, the remaining alternatives can be scaled accordingly. Thus, while the case II final matrix does not yield a direct solution for the analyst or decision-maker, it does eliminate the requirement of the analyst having to perform the task of conducting a separate study for each alternative to arrive at benefit values.

VI. CONCLUSIONS AND RECOMMENDATIONS

Selecting military equipments by considering their impact on peacetime missions is one alternative method of systems selection. For existing vessels with assigned peacetime mission responsibilities, the assumptions required to implement the proposed cost-benefit model are reasonable. However, even in the case of comparing existing military equipments for existing vessels it is difficult to arrive at valid estimates of the true costs and benefits associated with the various alternative systems.

Coupled with the problem of measuring the costs and benefits of the various alternatives is the task of combining these elements into a measure of effectiveness that the decision-maker may use to arrive at a rational choice. Analytical techniques that combine all selection considerations into a single, dimensionless value for each alternative are of limited value to the decision-maker since no tradeoffs can be performed. However using a technique where no attempt is made to combine any of the selection considerations also is of limited value due to the information processing limitations of the decision-maker.

Since assumptions are required to reduce the dimensionality of the system selection problem, it is appropriate to reduce the dimensionality only to a level the decision-maker may use to arrive at a rational choice which is consistent with his expert evaluation of the presented information. In the proposed cost-benefit model the solution produced is a four-dimensional solution. The individual dimensions are life-cycle costs, time horizons, externality costs, and the expected benefits of the alternatives. This dimensionality clearly falls within the maximum number of separate pieces of information that individuals may collectively evaluate when arriving at a rational choice.

The proposed cost-benefit analysis uses a life-cycle cost estimating approach to measure an expected dollar cost for each alternative system. Using a life-cycle cost approach requires that all the relevant cost elements that occur over a system's lifetime be taken into account when arriving at a cost estimate. The major cost elements that the Coast Guard must consider will undoubtedly be manpower requirements.

After the cost estimates of the alternative systems have been obtained the next step is to determine the benefits of each system. Multi-attribute theory is one technique available to the analyst that estimates the various alternatives worth over several peacetime missions. However, to use any of the available multi-attribute decision criteria requires many severe assumptions. Often the final solution produced using a multi-attribute analysis is very dependent on the specific assumptions of the criteria chosen. Thus, reliance upon subjective authoritative judgement will have to continue when arriving at the final decision.

However, since the analyst has few options other than using multi-attribute techniques to evaluate alternative systems, the most important consideration is that the analyst and decision-maker are aware of the assumptions required to use a multi-attribute analysis when evaluating alternatives.

Recommendations: No validation of the proposed cost-benefit model was possible. A validation of the model should be conducted after NOSC concludes the factor analysis of the attributes that describe Coast Guard missions. Unfortunately, a valid verification of the cost-benefit model results will be difficutl to formulate. Comparing the results of the final selection ordering of the cost-benefit model to the results of previously conducted studies must be carefully performed. The extent to which this model will aid the decision making process can only be determined by comparing the results of the cost-benefit model against previously conducted studies which produced both good and poor results.

Further analysis is also required to establish that the decision-maker correctly expresses his relative importance of the various attributes under consideration. One method that could be used to establish that the decision-maker actually selects alternatives consistent with his stated importance of attributes would be to examine past decisions of systems selected where the system's worth in each attribute is known.

Additionally, the existence of the requirements necessary to apply multi-attribute decision theory to problems involving systems selection are often unprovable. Thus, in lieu of basing a final decision or recommendation solely on the results of a single, highly detailed multi-attribute analysis, the prudent analyst may prefer to conduct several analyses on a broader level where each study uses a different multi-attribute criteria. Thus, the proposed cost-benefit model should be used in conjunction with the methodology being developed by NOSC when selecting alternative systems from Naval inventory for existing Coast Guard vessels. Since the two methodologies require a different set of assumptions, a high degree of correlation between the rank-order of the alternatives in terms of the order the decision-maker would select the systems would tend to indicate that the results are somewhat independent of the assumptions required to produce the results. If disagreement exists between the rank ordered alternatives list each methodology yields, the analyst has few options but to identify the assumptions that produce the disagreement of results.

Finally, no method currently exists to calculate a meaningful variance on the benefit ratio values calculated by the constant-sum method. However, due to the tendency of judges to respond in increments of two, five, and ten, this clearly indicates there exists a variance on the ratio values even in the case where the judges possess complete information of alternatives they compare. A Monte-Carlo simulation should be conducted to establish the extent to which this variability will affect the outcome of the final rank ordering of alternatives.

APPENDIX A

OUTLINE OF NOSC'S TENTATIVE METHODOLOGY*

1. Define all Military and Civilian Missions
2. Establish Primary and Secondary Military and Peacetime Missions
3. Establish SWBS Categories for Each Mission Area (SWBS-Mission Matrix)
4. Establish Systems for Each Category (System - Category Matrix)
5. Identify Equipment for Each System Using SCSC and Navy Inventory Listings
6. Develop Equipment Characteristics Matrix
7. List Critical Constraints for Mission-SWBS Categories (Using Mission Requirement Constraint List)
8. Subject Each Equipment to the Critical Constraints of the Appropriate Mission SWBS Category
9. Instruct Planner in Weighting System Attributes
10. Evaluate Each Equipment in terms of Each Weighted SWBS Category
11. Normalize Output Values for Each Equipment Considered
12. Take Normalized Resultant Values and Weight Each Commensurate With It's Categories Impact on the Mission (In EQ (1))
13. Weight Relative Importance of Military and Peacetime Missions (Planner)
14. Evaluate Each Equipments' Multi-Mission Capability
15. Normalize Output Values from Step 14
16. Interpret Results (Significance of Variation)

Note 1. Consider Human Factors After Final Equipment List Concluded.

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* Presented with permission of Naval Oceans System Center, Code 122, San Diego, California.

APPENDIX B

COAST GUARD VESSEL REQUIREMENTS

The "Need" column reflects the number of each class of cutter required to meet projected multiprogram cutter requirements. The "Have" column includes only those cutters in the present inventory which will not have exceeded their useful service life in the given year. The "Short" column is the difference between "Need" and "Have." The "Short" column in 1986 represents the number of cutters that must be built during the next ten years if the Coast Guard is to have the capability to execute program requirements as identified in the Cutter Plan.

CATEGORY CLASS	EST. COST PER UNIT IN MILLIONS OF 1975 DOLLARS	1977			1979			1981			1986		
		NEED	HAVE	SHORT	NEED	HAVE	SHORT	NEED	HAVE	SHORT	NEED	HAVE	SHORT
WHEC	24.6	24	17	7	24	16	8	24	13	11	25	12	13
WMEC	11.7	25	17	8	23	17	11	29	17	12	30	16	14
WPB	3.1	75	59	16	77	54	23	80	52	28	85	34	51
WLB/DB	13.3	31	28	3	31	28	3	30	28	2	30	14	16
WLI	2.9	9	3	6	6	3	3	6	3	3	6	3	3
WLM	2.9	14	5	9	14	5	9	14	5	9	14	5	9
WLIC	2.9	17	12	5	19	12	7	19	14	5	19	14	5
WLR	2.0	26	15	11	26	15	11	26	15	11	26	15	11
WAGB POLAR DOMESTIC	66.1 17.3	7	6	1	7	6	1	7	4	3	7	3	4
DI-II (WYTM)	6.2	10	1	9	10	2	8	10	1	6	10	1	9
DI-III		10	15	+5	10	15	+5	10	15	+5	10	15	+5
FERRY	7.4	3	2	1	3	2	1	3	2	1	3	2	1
WLV		4	6	+2	4	6	+2	4	6	+2	4	4	0
WAGO		2	2	0	3	3	0	3	3	0	1	1	0

Adopted from CG-380-4, Cutter Plan,
Ltr of Promulgation dtd 4 Apr 1975

APPENDIX C

GLOSSARY OF POSSIBLE ATTRIBUTES

The following is a partial list of shipboard functions that NOSC is studying to describe the peacetime missions of the Coast Guard. Their results will be the attribute list required for the proposed cost-benefit model. Definitions, whenever possible, were obtained from the Department of Defense Dictionary of Military and Associated Terms, of 3 September 1974.

Air Surveillance:	The systematic observation of airspace by electronic, visual, or other means primarily for the purpose of identifying and determining the movements of aircraft and missiles, friendly and enemy, in the airspace under observation.
Command and Control:	The exercise of authroity and direction by a properly designated commander over assigned forces in the accomplishment of his mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures which are employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of his mission.
Countermeasures:	That form of military science which by the employment of devices and/or techniques has as its objective the impairment of the operational effectiveness of unfriendly activity.
Long Range Navigation:	The systematic determination of the position of one's vessel by electronic, visual, or other means when the vessel is in excess of 10 nautical miles from chartered landmasses.

Short Range Navigation: The systematic determination of the position of one's vessel by electronic, visual, or other means when the vessel is less than 10 nautical miles from chartered landmasses.

Subsurface Surveillance: The systematic observation of subsurface areas, places, persons, or things by visual, aural, electronic, photographic, or other means.

Surface Surveillance: The systematic observation of surface areas, places, person, or things by visual, aural, electronic, photographic, or other means.

Surface-to-Air Communications: A method or means of conveying information of any kind from a surface vessel to fixed wing or rotary aircraft.

Surface-to-Shore Communications: A method or means of conveying information of any kind from a vessel to a shore communications station.

Surface-to-Surface Communications: A method or means of conveying information of any kind between two surface vessels.

APPENDIX D

EXISTING MULTI-ATTRIBUTE SELECTION CRITERIA

Item	Dominance	Satisficing	Lexicography	Maximin	Maximax	Additive Weighting	Effective-ness Index	Utility Theory	Trade-offs	Non-metric Scaling
INFORMATION REQUIREMENTS										
Numerical attribute values	not necessary	not necessary	not necessary	not necessary	not necessary	necessary	necessary	not relevant	not necessary	developed
Comparable values for different attributes	not necessary	not necessary	not necessary	necessary	necessary	necessary	necessary (implicitly)	not relevant	not necessary	developed
Minimal acceptable values (i.e., goals) for each attribute	not relevant	necessary	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant
Ordering of the relative importance of each attribute	not relevant	not relevant	(possibly) necessary	not relevant	not relevant	necessary	necessary (implicitly)	not relevant	not relevant	developed
Numerical assignment to the relative importance of each attribute	not relevant	not relevant	not necessary	not relevant	not relevant	necessary	necessary (implicitly)	not relevant	not relevant	no
INDEPENDENCE OF ATTRIBUTES	not assumed	not assumed	implied	implied	implied	assumed	not assumed	not relevant	not assumed	assumed
DIMENSIONALITY CONSIDERED										
Single--one of the original n	--	--	x	x	x	--	--	--	--	--
Single--numerical scale	--	--	--	--	--	x	x	x	--	--
Intermediate (between 1 and n)	--	--	--	--	--	--	--	--	x	x
Full (all n attributes)	x	x	--	--	--	--	--	--	--	--
PROCESSING ORDER										
Comparison across attributes (for a given alternative) and then across alternatives	--	--	--	x	x	x	x	not relevant	x	x
Comparison across alternatives (for a given attribute) and then across attributes	x	x alternatives compared with goals	x	--	--	--	--	--	--	--
FREQUENCY WITH WHICH THE PROCEDURE YIELDS A UNIQUE FINAL CHOICE	seldom unique	depends on stringency of goals	probably unique	probably unique	probably unique	probably unique	probably unique	probably unique	by itself does not yield final choice	probably unique
RELATIONSHIP AMONG THE FINAL ALTERNATIVES WHEN THE PROCEDURE DOES NOT YIELD A UNIQUE CHOICE	not necessarily indifferent	not necessarily indifferent	indifferent	indifferent	indifferent	indifferent	indifferent	indifferent	indifferent	indifferent

Adopted from: <u>Decision Making Among Multiple-Attribute Alternatives: A Consolidated Approach</u>, by K.R. MacCrimmon, p. 44.

APPENDIX E

EXAMPLE OF APPLYING THE CONSTANT-SUM METHOD

An example of using the constant-sum method is presented for the reader. The problem presented obtains ratio benefit values for the original air-search radar selection problem previously discussed.

Let the following matrices denote the responses of judges' whose task was to divide 100 total points within each pair of alternatives. Each judge was instructed to divide the points in terms of the alternatives positive impact on the performance of the specified attribute. Further, the judges were informed that the awarding points as (50,50) implied that both alternatives were equally effective within the attribute while (75,25) point split indicated that the first alternative had three times the positive impact on the attribute as the second alternative. All judges were also instructed to omit comparisons where they were unfamiliar with one or both alternatives.

The results of the judges' response are presented below. Omitted entries indicate a judge chose not to make specific comparisons.

ATTRIBUTE 1

		Alternative System			
		1	2	3	4
	1	-	40	60	55
Alternative System	2	60	-	70	55
	3	40	30	-	25
	4	45	45	75	-

Judge 1

	1	2	3	4
1	-	45	55	50
2	55	-	65	60
3	45	35	-	40
4	50	40	60	-

Judge 2

	1	2	3	4
1	-		75	
2		-		50
3	25		-	
4		50		-

Judge 3

ATTRIBUTE 2

		Alternative System			
		1	2	3	4
	1	-	55	70	20
Alternative System	2	45	-	55	45
	3	30	45	-	25
	4	80	55	75	-

Judge 1

	1	2	3	4
1	-	60	60	50
2	40	-	55	45
3	40	45	-	35
4	50	55	65	-

Judge 2

	1	2	3	4
1	-		50	35
2		-		
3	50		-	
4	65			-

Judge 3

ATTRIBUTE 3

		Alternative System			
		1	2	3	4
	1	-	45	45	60
Alternative System	2	55	-	50	55
	3	55	50	-	60
	4	40	45	40	-

Judge 1

	1	2	3	4
1	-		40	70
2		-		
3	60		-	
4	30			-

Judge 2

	1	2	3	4
1	-	50		
2	50	-		70
3			-	
4		30		-

Judge 3

Each entry in the above matrices represent a_{ij} values. Thus, the a_{i2} entry for judge 1 in attribute 1 implies that the second system received 40 of the original 100 points divided among the first and second alternatives.

After obtaining the a_{ij} values the next step is to construct the $\bar{A}$ matrices for each attribute. Each entry in the $\bar{A}$ matrices is computed by

$$\overline{a_{ij}} = \frac{1}{n} \sum_{\text{judges}} a_{ij}$$

The results of this computation leads to the following:

		ATTRIBUTE 1					ATTRIBUTE 2			
		Alternative Systems								
		1	2	3	4		1	2	3	4
	1	-	42.5	63.3	52.5	1	-	57.5	60	35
$\bar{A}$ = Alternative Systems	2	57.5	-	67.5	55	2	42.5	-	55	45
	3	36.4	32.5	-	32.5	3	40	45	-	33.3
	4	47.5	45	67.5	-	4	65	55	66.7	-

	ATTRIBUTE 3			
	Alternative Systems			
	1	2	3	4
1	-	47.5	42.5	65
2	52.5	-	50	62.5
3	57.5	50	-	60
4	35	37.5	40	-

Using the above values in the $\bar{A}$ matrices the next step of the constant-sum procedure is to construct the W matrices for each attribute. Each element in the W matrix is computed by

$$w_{ij} = \frac{a_{ij}}{a_{ji}}$$

The results of this computation leads to the following:

ATTRIBUTE 1

		Alternative Systems			
		1	2	3	4
	1	1	.74	1.72	1.11
Alternative Systems	2	1.35	1	2.08	1.22
	3	.58	.48	1	.48
	4	.90	.82	2.08	1

ATTRIBUTE 2

	1	2	3	4
1	1	1.35	1.5	.54
2	.74	1	1.22	.82
3	.67	.82	1	.50
4	1.86	1.22	2.0	1

ATTRIBUTE 3

	Alternative Systems			
	1	2	3	4
1	1	.90	.74	1.86
2	1.11	1	1	1.67
3	1.35	1	1	1.5
4	.54	.6	.67	1

Continuing the example the scale values s_j are now calculated for each attribute. To calculate the s_j values use the following formula:

$$s_j = \prod_{i=1}^{4} (w_{ij})^{\frac{1}{n}} .$$

These s_j values for each alternative in each attribute are presented in the following matrix (V):

ALTERNATIVE-ATTRIBUTE MATRIX

		Attribute 1	Attribute 2	Attribute 3
Alternative Systems	1	.92	.98	.95
	2	.73	1.08	.86
	3	1.65	1.38	.84
	4	.90	.69	1.47

Next, assuming that the decision-maker has expressed the relative importance of increasing the capability of performing attributes 1, 2, and 3 as 0.6, 0.2, 0.2, respectively, an overall estimate of the alternatives ratio-benefits may be calculated by combining the weights of the attributes and values in the alternative-attribute matrix as follows:

$$X_{1 \, x \, n} = \lambda V^T$$

where:

λ = A vector of the relative weights of attributes

V^T = Transpose of the alternative-attribute matrix

Performing this calculation on the example of measuring the benefits of the four air-search radars the following results are obtained:

$$X_{1 \times n} = (.6\ .2\ .2) \begin{matrix} .92 & .73 & 1.65 & .90 \\ .98 & 1.08 & 1.38 & .69 \\ .95 & .86 & .84 & 1.47 \end{matrix}$$

$$= [.94 \quad .83 \quad 1.43 \quad .97].$$

Each x_i value above represents an estimate of a ratio-benefit value of the i^{th} alternative. However, to aid the decision-maker it is recommended to transform the values on a scale where the maximum x_i value equals 100. Thus, a transformation of the x_i values by

$$x_i' = bx' \quad \text{where} \quad b = 69.93$$

yields the following:

$$X'_{1 \times n} = [65.73 \quad 58.04 \quad 100 \quad 67.8]$$

Finally, these values are combined with the life-cycle cost vectors to obtain the final four-dimensional solution matrix.

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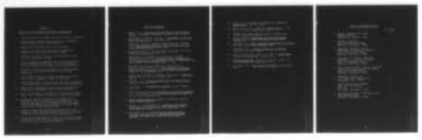

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APPENDIX F

OUTLINE OF THE PROPOSED COST-BENEFIT METHODOLOGY

1. Obtain alternative systems list from the Navy's inventory.
2. Eliminate any systems which could not be installed after reasonable vessel modifications.
3. Identify peacetime missions of the platform.
4. Identify all attributes required to perform the peacetime missions [Results of NOSC study].
5. Determine relevant life-cycle and externality costs for each alternative system.
6. Utilize subjective judgement from systems experts to obtain expected benefit ratios of each alternative. This will require the preparation of a questionnaire.
7. Establish the relative importance the decision-maker places on increasing performance of the various attributes.
8. Obtain final estimates of each alternatives overall ratio value by combining steps six and seven.
9. Combine the results of steps five and eight to construct a four-dimensional solution vector for each alternative.
10. Remove from consideration any system with completely unacceptable externality costs or time horizons.
11. Apply the dominance criterion on the remaining alternatives. If a solution is produced, select that system.
12. In the case where no solution is produced using dominance, further analysis must be conducted. The analyst must arrive at an estimate for any non-zero, positive alternative of the percent of overall impact it will have on peacetime missions.
13. Scale the remaining alternatives benefits once one system's benefit has been obtained to arrive at direct estimates of the benefits for all alternatives.
14. Allow the decision-maker to arrive at a rational choice of the best system using his expertise to subjectively tradeoff values in the solution matrix.

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