A Novel Cost-Benefit Analysis for Evaluation of Complex Military Systems

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This paper presents a systematic merit function approach for the comprehensive evaluation of competing military systems. In this paper, the merit function is defined to be the ratio of quantified system benefit to system life cycle cost. System benefit is measured by a unique utility function that quantifies the degree to which a given system configuration satisfies an identified set of customer requirements. This measure is derived from the information contained in Quality Function Deployment tables. The second portion of the merit function is a life cycle cost measure, which can be developed using any valid estimation technique. With this merit function approach, the cost effectiveness of complex systems can

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1995**	2. REPORT TYPE	3. DATES COVERED **00-00-1995 to 00-00-1995**

4. TITLE AND SUBTITLE **A Novel Cost-Benefit Analysis for Evaluation of Complex Military Systems**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Military Academy,Department of Civil and Mechanical Engineering,West Point,NY,10996**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Acquisition Review Quarterly Winter 1995

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**20**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

be quantified. Comparison of the quantified merit of competing systems then provides for objective and reliable decision making. This merit function approach is demonstrated by an evaluation of two attack helicopter configurations.

INTRODUCTION

According to accepted finance rules of commercial business, all investment decisions should be based upon some comparison of discounted cash inflows and discounted cash outflows (Ross,Westerfield, & Jaffe). One approach is to compute Net Present Value (NPV), which is discounted cash inflow minus discounted cash outflow. If NPV > 0, then the investment will generate a cash inflow which exceeds the cash outflow. A second approach to investment decision making uses Profitability Indices (PI). A PI is the ratio of discounted cash inflows to discounted cash outflows. For independent projects, the decision rule is to accept the project if PI > 1 and reject if PI < 1. In effect, a PI is a merit function comparing the project benefits—discounted cash inflows—to its costs—discounted cash outflows.

These traditional finance rules are applicable to a wide variety of investment decisions. However, these simple rules break down when applied by the Department of Defense (DoD) when considering procurement of military systems. The primary difficulty is that a military system seldom generates cash inflow. Instead, a military system generally represents a pure expense over its entire life cycle. Using traditional finance rules, NPV will always be less that zero and PI will always be less than one. Thus, using commercial finance rules, a military project will always be rejected as a poor investment! Obviously these are not acceptable decision rules for the DoD.

Several alternative rules have been proposed to evaluate military systems. The alternative rules focus on minimizing either acquisition costs or, more appropriately, Life Cycle Cost (LCC). In reality, however, Design To Cost (DSMC, 1986) rules are not universally applicable. Cost comparisons are only appropriate for systems with similar objectives and of equal complexity. Although these types of rules are effective tools for controlling system acquisitions and operations, decision rules based on cost alone are inadequate for evaluating competing alternatives. These rules generally ignore the benefit inherent in each military system.

The benefits of a military system are real although they typically cannot be quantified in dollars. A reasonable benefit measure must be developed in order to perform a reliable cost-benefit study. The military investment decision can then be based upon an objective merit function which compares the non-monetary system benefit to its monetary cost.

The most difficult part of the proposed merit function approach is to construct an appropriate benefit function. One common approach is to define a set of technical measures (i.e., performance parameters) that can be measured or estimated for each system. A merit function is then defined as the total score for each system; the larger the score the better. However, incomplete or incorrect formulations of such merit functions have been employed in the past. For instance, failure to normalize numerical scores between differing technical measures often leads to performance parameters of relatively large magnitude that overpower the contributions of performance parameters which are relatively small, thereby unduly biasing the overall score. Cost and risk are seldom directly incorporated into the function definition. Moreover, customer requirements, which are often difficult to associate with engineering parameters, are commonly ignored. In addition, the function is most often linear, which does not allow for diminishing marginal returns on the merit measure (Harse, 1985; Schrage, Costello, & Mitlider, (1989).

This paper introduces a newly developed function to quantify the benefits of a complex engineered system. This function overcomes previous shortcomings and it incorporates direct consideration of customer requirements. Conceptual development of this measure borrows heavily from the matrix techniques of Quality Function Deployment (Sullivan, 1986). Quality Function Development (QFD) methods, developed in Japan in the 1970s, are rooted in a product development philosophy emphasizing customer-driven design. This method employs graphical quality engineering tools that map the "voice of the customer" into product and process design characteristics. A QFD method is then used to ensure the key product development objectives of quality, cost, and timeliness are retained throughout product development and manufacturing.

The second major element of the proposed merit function is a Life Cycle Cost (LCC) measure. Life Cycle Cost is simply the summation of all expenditures required from conception of a system until it is phased out of operational use. Historically, a low initial acquisition cost has not assured a low LCC. In fact, the opposite is true. This trend is explained by the fact the majority of LCC (at least for military systems) is usually in operations and support (O&S). The greatest potential opportunity for cost reduction in the Department of Defense is now recognized as control of the cost of system support. This cost element will be invisible in the selection process and so cannot be controlled unless a LCC model is used.

With system benefit and cost quantified, an overall merit function is defined as the ratio of system benefit to its LCC. Two merit functions are developed. The first function assumes that no existing system is available. The second function assumes the systems under consideration will replace an existing system. In this case, the merit function quantifies the incremental change in benefit and cost compared with the baseline system. For the merit functions employed in this paper, the decision rule is simply to maximize system merit.

A brief outline of this paper follows. The merit function is developed and the appropriate decision rule is presented. Next, the new benefit function is developed. Construction of the QFD Tables and calculation of the benefit function are detailed. A brief discussion of the appropriate cost functions follows. Finally, application of the merit function approach is demonstrated by an actual application to the evaluation of two attack helicopters.

THE MERIT FUNCTION

The merit function is defined as a single number which, when properly determined, reflects the ratio of benefits derived to dollars spent. For the proposed merit function, the system with greatest merit is deemed the most desirable. Let M represent overall merit, B derived benefit, and C Life Cycle Cost. The absolute merit of any given configuration then is:

$$M = B/C \tag{1}$$

This function provides the means for objective comparison of two or more complex configurations when no baseline system exists. A large system merit is preferable to a small one.

This relationship between benefit and cost is graphically represented in Figure 1. In this graph, cost is plotted on the horizontal axis and benefit on the vertical. Note that merit, Eq. (1), represents the slope of the line connecting the plotted merit value and the graph's origin. Let the point labeled 1 represent the merit of a baseline system. If a configuration were introduced for which both benefit and cost are increased proportionately, overall merit remains the same. Such a point is labeled 2 in Figure 1, and will always lie on the same line connecting point 1 and the origin. If benefit were increased, but cost remained the same, the new system's merit would be larger (the new point will fall above the shaded region in Figure 1). Conversely, if benefit remained constant while cost increased, the new system's merit would be less (the new point will lie in the shaded region of Figure 1). The defined merit function becomes particularly useful when evaluating realistic problems where both benefit and cost are sensitive to system design. When such is the

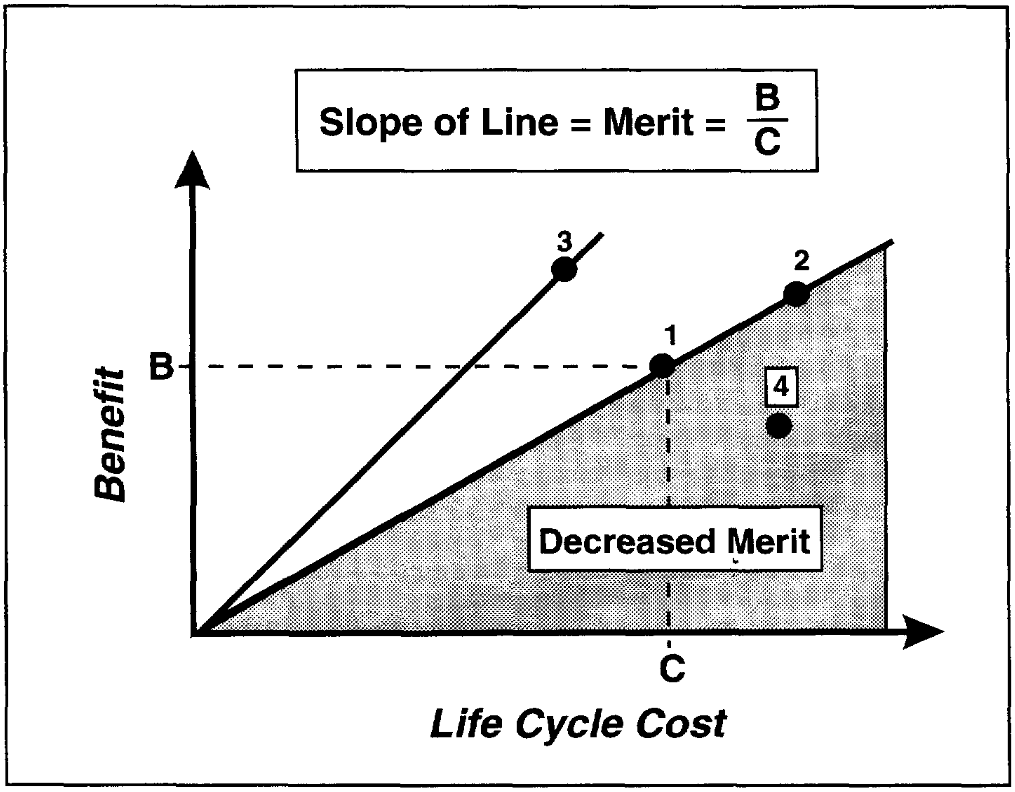

Figure 1. **Graphical Representation of the Merit Function.**

case, it is difficult to predict, a priori, the change in merit. The decision rule remains constant, however, and the system with largest merit is judged most desirable. Returning to Figure 1, points 1 and 2 have the same merit; point 4's merit is less than that of 1 and 2; and point 3 has the highest merit of all. Though the above circumstances are transparent, the problem remains to define a systematic procedure for quantifying both benefit and cost.

The merit function has direct economic interpretation. It is a measure of system benefit per dollar expended. A rational decision maker chooses to maximize the benefit obtained for each dollar spent, and selects the system with highest merit. Consider the inverse of the merit function, P.

$$P = 1/M = C/B \tag{2}$$

This function measures dollars spent to achieve a particular level of system benefit. The variable P represents dollar cost per unit of system merit. In other words, P is simply the price of a unit of system benefit.

In this case, a rational decision maker selects the system with smallest price per increment of system merit, which again is the system for which merit is greatest.

QUANTIFYING BENEFIT

In this section, a method for quantifying system benefit is developed. A Benefit Function is defined to measure the degree to which a given system configuration satisfies customer requirements. To organize the data, the methodology uses a QFD Table. The Benefit Function is derived in part from the QFD Table, which relates the engineering performance of a system to specific customer requirements.

In essence, a single measure of benefit is determined (i.e., a single number) for each candidate product design. This measure, or score, represents the degree to which each candidate balances conflicting design (i.e., customer) requirements. This measure is expressed as a percentage difference from an ideal system (i.e., a system that achieves specified target values for all of the customer's stated requirements) and evaluation is biased by the customer's stated priorities.

CONSTRUCTION OF THE PLANNING TABLE

The first step in quantifying system benefit is the construction of the *Planning Table*. The general form of the planning table is depicted in Figure 2. Four lists are compiled in order to begin construction of this table. The first is a list of the customer's requirements, that is, a list of the desired characteristics of the final system stated in the customer's own words. The second list is a set of "importance weighting factors" used to prioritize each of the requirements. These factors must also be solicited from the customer. The third is a candidate set of performance/analysis parameters to be measured or predicted and compared with their corresponding target levels. These target levels are chosen to represent the ideal system and would usually reflect state-of-the-art technology. The performance/analysis parameters are to be used to evaluate candidate system designs in relation to the stated customer requirements. The fourth list needed to construct the planning table is a list of competitive systems and/or design options.

Once these four lists are compiled, the first iteration of the *Planning Table* can be constructed. There are four primary components to the table. First is the *Relationship Matrix*, labeled Table A in Figure 2. This table is used to assess and document interactions between the customer's stated requirements and the selected performance/analysis parameters. Interactions (i.e., each entry in the matrix) are typically classified as either strong, moderate, or weak. The *Relationship Matrix*, once com-

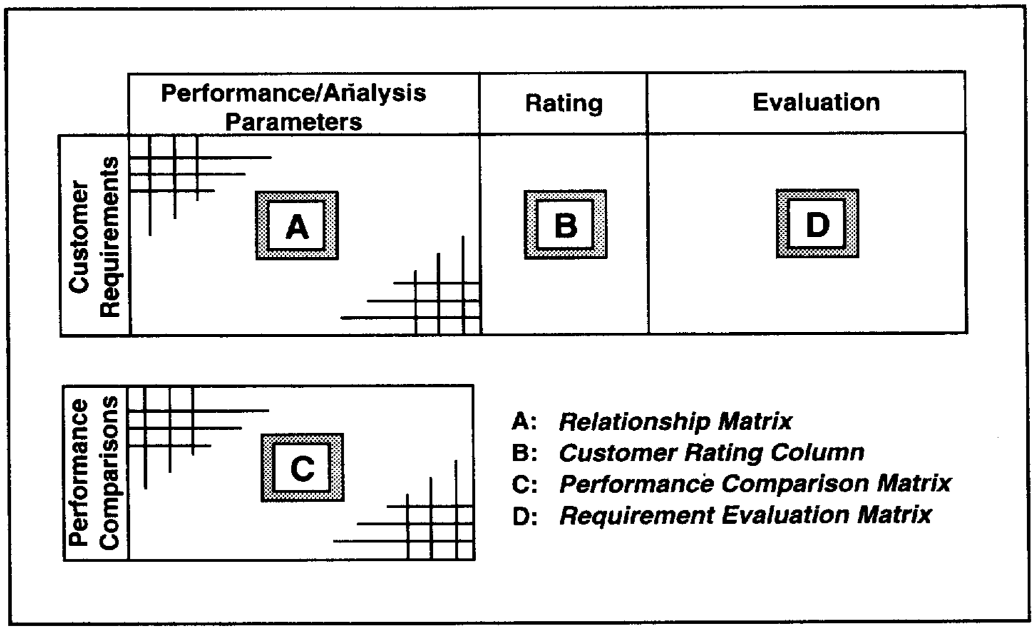

Figure 2. **QFD Planning Table Used in Quantifying Benefits.**

plete, is used to determine whether or not the selected performance characteristics can adequately measure satisfaction of the customer requirements. If relationships to a given customer requirement are predominantly weak, additional performance parameters are introduced to ensure compliance with the requirement can be evaluated. Similarly, the matrix entries can be used to identify a minimum set of performance parameters needed to be evaluated and tracked.

The second component of the planning table is the *Customer Rating Column*, labeled Table B in Figure 2. A list of "importance weighting factors" associated with the requirements list is solicited from the customer and used to fill out this column. These weighting factors are to be ordered so the largest numbers represent the most important requirements. The factors are later normalized so that their sum equals 1.0. This constraint ensures consistency between differing sets of weighting factors.

The next component of the *Planning Table* is the *Performance Comparison Matrix*, Table C in Figure 2. In this matrix, results of analytic or numerical predictions or experimentation are tabulated for the system under evaluation and its competitors. Target levels for each of the performance/analysis parameters are also tabulated in this matrix. With performance parameters tabulated, the systems are evaluated as to their satisfaction of the customer requirements. The results of this evaluation are recorded in the *Requirement Evaluation Matrix*, Table D of Figure 2. The *Planning Table* is then complete.

DERIVATION OF THE BENEFIT FUNCTION

The Benefit Function is an objective, numerical measure derived from the *Planning Table* data. This function evaluates system performance relative to the complex, and possibly conflicting, customer requirements. There are three primary components to the Benefit Function. The first component is the utility measure, which is used to compare system performance to target values in a non-dimensional format. The second component is the customer satisfaction calculation, which determines how well a system satisfies individual customer requirements. Finally, the benefit calculation combines the customer satisfaction results with the "importance weighting factors" to develop an overall score for the system. Thus, the Benefit Function measures the degree to which a system satisfies the weighted customer requirements.

The first component of the Benefit Function develops a non-dimensional utility measure from the data contained in the *Performance Comparison Matrix*. It is based upon the ratio of each performance parameter to the corresponding target level. Let the numerical entries in the performance comparison matrix be represented by the following matrix.

$$D = [d_{ij}] \qquad i = 1, \ldots, n+1 \quad j = 1, \ldots, p \tag{3}$$

where n+1 represents target data plus the number of proposed systems and its competitors, and p is the number of performance parameters measured. Note that the target levels for the performance parameters are given in the first row of the data matrix. In other words, parameter targets are represented by d_{1j}, $j = 1, \ldots, p$.

The utility measure is applied to the systems represented by the rows in the data matrix, D. The resulting utility matrix, U, is of the same dimension as the data matrix D in Eq. (3).

$$U = [u_{ij}] \tag{4}$$

where

$$u_{ij} = \begin{cases} \sqrt{d_{ij}/d_{1j}} & \text{if j-th target level is a desired lower limit} \\ \sqrt{d_{ij}/d_{1j}} & \text{if j-th target level is a desired upper limit} \end{cases} \tag{5}$$

If $u_{ij} < 1$, then the performance parameter does not meet the target level, and similarly, if $u_{ij} > 1$, the performance exceeds the target level. If $u_{ij} = 1$, then the j-th parameter is equal to its target level. The first row of the utility matrix U, is $u_{1j} = \sqrt{d_{1j}/d_{1j}} = 1$, $j = 1, ..., p$ which represents the ideal utility of each performance parameter. Note if the j-th target level is a desired lower limit, then the j-th parameter must exceed the target for $u_{ij} > 1$. Likewise, if the j-th target level is a desired upper limit, then the j-th parameter must be less than the target for $u_{ij} > 1$.

In Eq. (5), the square root function is used to provide decreasing marginal returns to the utility measure. The incremental utility gained decreases as a performance parameter approaches and surpasses its target level. It is important that diminishing marginal return behavior is ensured so the Benefit Function is consistent with traditional economic theory. Previous studies have recognized the need for diminishing marginal return behavior, but these studies were unable to achieve this property (Harse, Schrage, et al.). Using diminishing marginal returns, the benefit of a system with all the performance parameters at or near the target levels is greater than the benefit of a system where several parameters greatly exceed their targets while others fall significantly short of the desired level.

After the utility matrix is computed by Eq. (4) and Eq. (5), the **customer satisfaction calculation** is performed. This calculation determines how well the system satisfies each of the customer requirements listed in the *Relationship Matrix*, Table A in Figure 2. Specifically, the satisfaction for each requirement is a summation of the system utility components weighted by the interactions between each parameter and the specific customer requirement.

To perform the customer satisfaction calculation, the symbolic *Relationship Matrix* must be translated into a numerical matrix. For each strong interaction, a value of 3 is assigned to the matrix element; 2 to each moderate interaction; 1 is assigned to each weak interaction; finally, 0 is used to indicate no interaction. The resulting numerical relationship matrix is given by

$$X = [x_{kj}] \qquad k = 1, ..., r \qquad j = 1, ..., p \tag{6}$$

where p is defined earlier, r is the number of customer requirements and

$$x_{kj} = \begin{cases} 3 \text{ for a strong interaction} \\ 2 \text{ for a moderate interaction} \\ 1 \text{ for a weak interaction} \\ 0 \text{ for no interaction} \end{cases} \tag{7}$$

With X defined in Eq. (6) and Eq. (7), the customer satisfaction calculation can be performed. The raw customer score is computed as

$$S = XU^T \tag{8}$$

where S is dimensioned r x n+1 and the superscript T denotes the matrix transpose. Customer satisfaction is computed by

$$\hat{S} = 100\% \times S_{ki}/S_{k1} \qquad i = 1,\ldots, n+1 \tag{9}$$

where the first column of S, S_{k1}, k = 1, ..., r, represents the satisfaction of a system which identically satisfies all parameter target levels. Thus, S_{k1} is the customer satisfaction of the target, or "ideal," system for each customer requirement. The customer satisfaction results, Eq. (9), are used to construct the *Requirement Evaluation Matrix*, Table D in Figure 2. For a given requirement k, if $\hat{S}_{ki} > 100\%$, then the i-th system exceeds the satisfaction level of the ideal system. Similarly, if $\hat{S}_{ki} < 100\%$, then the i-th system falls short of the satisfaction of the target system.

The final step of the analysis is to compute system benefit. The **benefit calculation** is a summation of customer satisfaction levels, Eq. (8), weighted by the *Customer Requirement Ratings*, Table B in Figure 2. This calculation is expressed as

$$B = R^T S \tag{10}$$

where R is the vector of "importance weighting factors" for the customer requirements. As defined in Eq. (10), the benefit vector is dimensioned 1 x n+1, where n is defined earlier. The first element of B, B_1, is the benefit of the ideal system. The remaining elements of B, B_2, ..., B_{n+1}, are the benefit values of the candidate configurations.

The benefit calculation results can be conveniently expressed as a percentage of the ideal system benefit.

$$\hat{B}_i = 100\% \times B_i/B_1 \qquad i = 1,\ldots, n+1 \tag{11}$$

Note that $\hat{B}_1 = 100\%$. Any system with $\hat{B}_i > 100\%$ exceeds the benefit of an ideal system, where the ideal system matches all target levels of performance. On the other hand, if $\hat{B}_i < 100\%$, the candidate system does not meet the ideal benefit level. If target levels are selected to represent a state-of-the-art system, then $\hat{B}_i < 100\%$ will be the typical result.

QUANTIFYING COST

Life Cycle Cost (LCC) can be determined using a wide variety of techniques. Three common approaches are parametric analysis, determination by analogy, and the so called "bottom-up" technique. Choice is determined largely by the type of system being studied and the available database (DSMC, 1986).

Parametric analysis of LCC relies heavily on statistical cost estimating relationships. These relationships must either already be available or be developed from available data. In most cases, data representing a broad array of related systems must be obtained. Regressions are then constructed which relate system LCC to one or more characteristic parameters, such as vehicle and subsystem weights. This approach is most useful for conceptual design. However, it can be difficult to obtain an appropriate and up-to-date database with statistical relevance, and it is sometimes difficult to determine the statistical significance of publicly available cost estimating relationships.

Life cycle cost estimation by analogy is primarily used to calibrate the results of parametric analysis. With this approach, the LCC of a system is determined by analogy to available cost data on an existing and similar system. Adjustments are made to various cost elements to account for differences between the old and new systems. Analogy approaches are especially useful when an insufficient database exists to develop statistically significant cost estimating relationships.

The third LCC estimation technique to be discussed is sometimes referred to as a "bottom-up," or engineering data, approach. In general, the cost contributions of each subsystem component are estimated from knowledge of the component's design, material properties, and intended use. The primary drawback of this approach is that it can be labor-intensive and time-consuming.

Since there is a wealth of information available in the literature for LCC estimation, this subject will not be dealt with in any greater detail.

EVALUATION OF TWO ATTACK HELICOPTERS

Opportunities for improved AH-1W Attack Helicopter mission effectiveness, new mission capability, and improved survivability are currently being exploited by the United States Marine Corps (USMC). In particular, procurement of a night targeting system is underway, along with a navigation system upgrade and improvements in the electronic warfare suite. Evolution of the USMC AH-1 is expected to continue well into the next century. However, the many benefits of incorporating advanced technology will be offset by increased vehicle weight and a corresponding reduction in payload capability of the vehicle.

Table 1.
USMC REQUIREMENTS LIST WITH COMPOSITE WEIGHTINGS

MARINE CORPS REQUIREMENTS	RELATIVE WEIGHTING (1.0 Highest)
Improved Reliability and Maintainability	1.00
Increased Speed	0.94
Increased Maneuverability and Agility	0.90
Harder to Kill	0.87
Reduced Vibrations and Loads	0.86
Carry More	0.79
Reduced Operations and Support Costs	0.70
Harder to Detect	0.50
Operate Over the Horizon	0.49
Easier to Fly	0.49
Increased Endurance	0.39

The AH-1W manufacturer, Bell Helicopter Textron, Inc. (BHTI), in recognition of the trend toward decreasing payload capability and degraded performance, initiated an independent research and development (IR&D) program to first evaluate, and then demonstrate, the feasibility of applying available BHTI four-bladed, bearingless main rotor technology, in combination with an uprated drive system, to achieve significant improvements in AH-1W vehicle performance and payload capability. The technology demonstrator developed by BHTI is referred to as the 4BW. The evaluation of the cost effectiveness of adopting the 4BW in place of the AH-1W is an example of a complex military management decision. This problem provides an excellent opportunity for the application of the developed cost-benefit methodology. For simplicity, risk is not included in the presentation of this example. A detailed cost-benefit analysis of the two systems was documented by Corban et al. in 1991.

A survey of knowledgeable military and civilian personnel was conducted and resulted in the USMC requirements listed in Table 1. The relative weightings were obtained by averaging the weights provided by the surveyed personnel. The performance measures listed in Table 2 were used

Table 2
SELECTED PERFORMANCE MEASURES FOR BENEFIT ASSESSMENT

	Performance Measure	Target Value
(1)	Isolated Rotor Figure of Merit at Operating Blade Loading (hover, Navy hot day conditions, battle station weights, escort/anti-armor ordnance load)	0.85
(2)	Hover Ceiling (battle station weights, escort/anti-armor ordnance load, 2082 hp transmission limit (AH-1W), 2625 hp (4BW))	15,000 ft
(3)	Maximum Rate of Climb (sea level standard, battle station weights, escort/anti-armor ordnance load)	4,000 ft/min
(4)	Service Ceiling (standard day, battle station weights, escort/anti-armor ordnance load)	25,000 ft
(5)	Maximum Vertical Rate of Climb (VROC) (Navy hot day conditions, battle station weights, escort/anti-armor ordnance load)	1,5000 ft/min
(6)	Dash Speed (Navy hot day conditions, battle station weights, escort/anti-armor ordnance load, intermediate rated power)	180 knots
(7)	Cruise Speed (Navy hot day conditions, battle station weights escort/anti-armor ordnance load, max continuous power)	160 knots
(8)	Radius Ordnance Factor	4,000 lb-nm per 100
(9)	Station Ordnance Factor	5,000 lb-hrs
(10)	Maneuverability/Agility Assessment (Note overall score is the sum of tabulated scores at take-off and battle station weights	1.0
(11)	Structures (determined as the percentage difference from limits of the allowable maneuvering loads envelope)	1.0
(12)	Vibrations/Dynamic Loads (qualitative assessment)	1.0
(13)	Acoustic Signature (qualitative score based on first-order main rotor signature estimates)	1.0
(14)	Impact on Vulnerability (qualitative assessment)	1.0
(15)	Handling Qualitites (qualitative assessment)	1.0

to quantify the performance of the two candidate helicopters. This list was influenced by standard engineering practice, the identified requirements, and the engineering tools available for use in the assessment. Target values were established by a combination of military specifications, current AH-1W performance, and state-of-the-art rotorcraft technology. Those measures were subjectively evaluated based on available data, whereas the remaining were evaluated quantitatively using computer analysis tools.

Interactions:
S - Strong
M- Medium
W - Weak
N - None

Marine Corps Requirements	Normalized Weightings	① Rotor Figure of Merit	② Hover Ceiling	③ Maximum Rate of Climb	④ Service Ceiling	⑤ Maximum Vertical Rate of Climb	⑥ Dash Speed	⑦ Cruise Speed	⑧ Radius Ordnance Factor	⑨ Station Ordnance Factor	⑩ Maneuverability & Agility	⑪ Structural Design	⑫ Vibrations & Dynamic Loads	⑬ Acoustic Signature	⑭ Vulnerability	⑮ Handling Qualities
Improved Reliability & Maintainability	1.00	N	N	N	N	N	N	N	N	N	N	N	S	N	W	N
Increased Speed	0.94	M	W	W	W	W	S	W	W	W	M	M	S	S	N	W
Increased Maneuverability & Agility	0.90	W	M	S	M	S	S	W	W	W	S	S	M	M	S	S
Harder to Kill	0.87	N	N	N	N	N	M	N	W	W	S	M	N	N	S	W
Reduced Vibrations & Loads	0.86	N	N	N	N	N	M	N	N	W	S	S	M	N	S	W
Carry More	0.79	S	S	S	S	S	M	M	S	S	W	M	N	N	M	N
Reduced Operations & Support Costs	0.70	N	N	N	N	N	N	N	M	M	N	M	S	N	M	M
Harder to Detect	0.50	N	N	M	N	M	M	N	N	W	S	N	N	S	N	M
Operate Over the Horizon	0.49	W	W	W	W	W	W	W	S	S	W	N	N	N	N	N
Easier to Fly	0.49	N	N	N	N	N	N	N	N	N	M	N	M	N	N	S
Increased Endurance	0.39	M	W	W	W	W	W	W	M	S	W	N	N	N	N	N
Target Values		0.85	15,000	4,000	25,000	1,500	180	160	4,000	5,000	1.0	1.0	1.0	1.0	1.0	1.0
Configuration A - AH-1W		.701	10,250	1,169	21,562	465	157	155	524	633	.583	.966	.1	.25	.5	.75
Configuration B - 4BW		.743	12,250	2,707	24,937	1,453	171	166	861	1,076	.823	.666	.8	.75	.5	.85

Figure 3. **Planning Table for AH-1W Example.**

		Target Values	Configuration A - AH-1W	Configuration B - 4BW
Overall Benefit Score		100%	64.8%	83.6%
Handling Qualities	⑮	1.0	0.866	0.922
Vulnerability	⑭	1.0	0.707	0.707
Acoustic Signature	⑬	1.0	0.500	0.866
Vibrations & Dynamic Loads	⑫	1.0	0.316	0.894
Structural Design	⑪	1.0	0.983	0.816
Maneuverability & Agility	⑩	1.0	0.764	0.907
Station Ordnance Factor	⑨	1.0	0.127	0.464
Radius Ordnance Facotr	⑧	1.0	0.362	0.464
Cruise Speed	⑦	1.0	0.984	1.009
Dash Speed	⑥	1.0	0.934	0.975
Vertical Rate of Climb	⑤	1.0	0.557	0.984
Service Ceiling	④	1.0	0.929	0.999
Maximum Rate of Climb	③	1.0	0.736	0.823
Hover Ceiling	②	1.0	0.827	0.904
Rotor Figure of Merit	①	1.0	0.908	0.935

Figure 4. **Utility Matrix and Benefit Score for AH-1W Example.**

The customer requirements and performance parameters are assembled into a Planning Table as depicted Figure 3. The performance parameters of Table 2 are distributed horizontally across the top of the matrix. The prioritized requirements list of Table 1 is distributed vertically along the left-hand side of the upper matrix. These requirements are listed in order of importance, starting from the top, as indicated by weightings entered in the second column. Interactions between individual requirements and performance measures 1-15 are then subjectively characterized as either strong (S), medium (M), weak (W), or relatively nonexistent (N), and entered into the Relationship Matrix. Next, the candidate helicopter configurations are listed vertically in the first column of the Performance Comparison Matrix, also of Figure 3. Last, the numerical results and target values assigned to each of the fifteen performance measures are entered in the lower matrix.

With the Planning Table complete, the algorithm defined by Eq. (11) and Eq. (12) is used to construct the Utility Matrix shown in Figure 4. Next, the interaction classifications (strong, medium, weak, or nonexistent) are translated into numerical values using Eq. (13). They serve to prevent a good score for one requirement from influencing an unrelated requirement's total score. For example, the score for acoustic signature should not improve benefit attributed to a configuration that is "easier to fly" (the second-to-last requirement), since the two requirements share little relationship. The outcome of the customer satisfaction calculation, Eq. (15) and Eq. (16), is presented graphically in Figure 5. This graph represents the Requirement Evaluation Matrix: Table D, Figure 2. Note that the 4BW helicopter configuration proves superior to the AH-1W in satisfying each individual customer requirement.

Finally, the Benefit Measures for the two systems are then calculated using Eq. (17) and Eq. (18). Note in this calculation the normalized weightings have been scaled so that the sum is one. This overall score is measured relative to an ideal system which achieves all target values (i.e. the ideal system scores 100%). These overall scores are presented on the right-hand side of Figure 4. Based on this assessment, the 4BW exhibits an 18.8% improvement in benefit over the AH-1W. That is, the 4BW achieves 83.6% of the overall target level, while the AH-1W achieves only 64.8%.

Preliminary LCC estimates are generated from a generic AH-1 cost model that includes the cost elements depicted in Figure 6. Two different operating scenarios, readiness and contingency, are considered, and estimates formed for each. Readiness level assumes no combat over the aircraft life. The contingency level assumes various combat engagements over the life of the system.

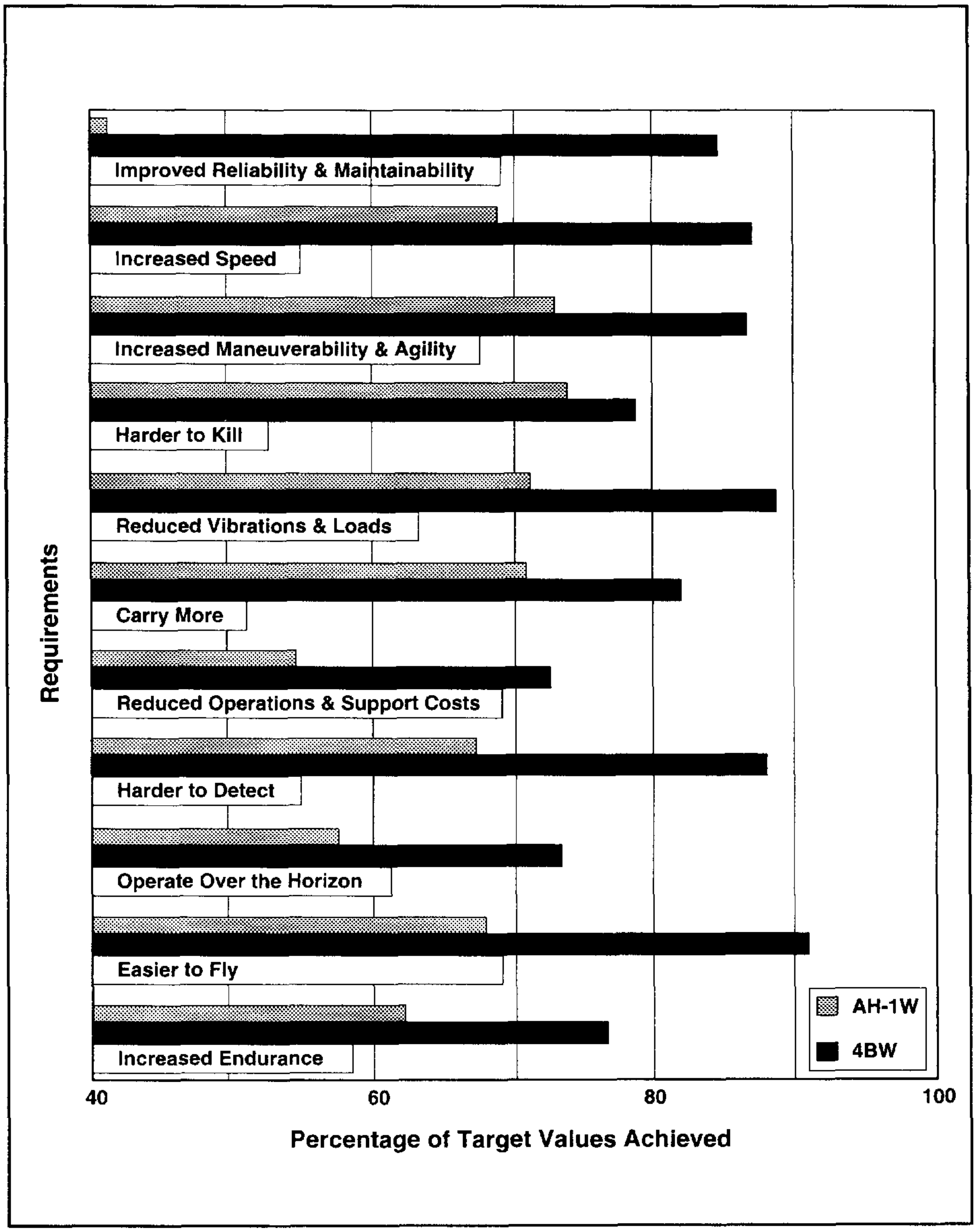

Figure 5. **Percentage of Target Values Achieved.**

Rough-order-of-magnitude estimates of LCC for the AH-1W and 4BW helicopters are presented in Table 3 in 1990 billions of dollars for both the readiness and contingency scenarios. These estimates represent a lower bound on LCC. Cost estimates for all categories of Figure 6 were not available. Acquisition of the 4BW requires approximately 200 million dollars of additional expenditure over the life of the system.

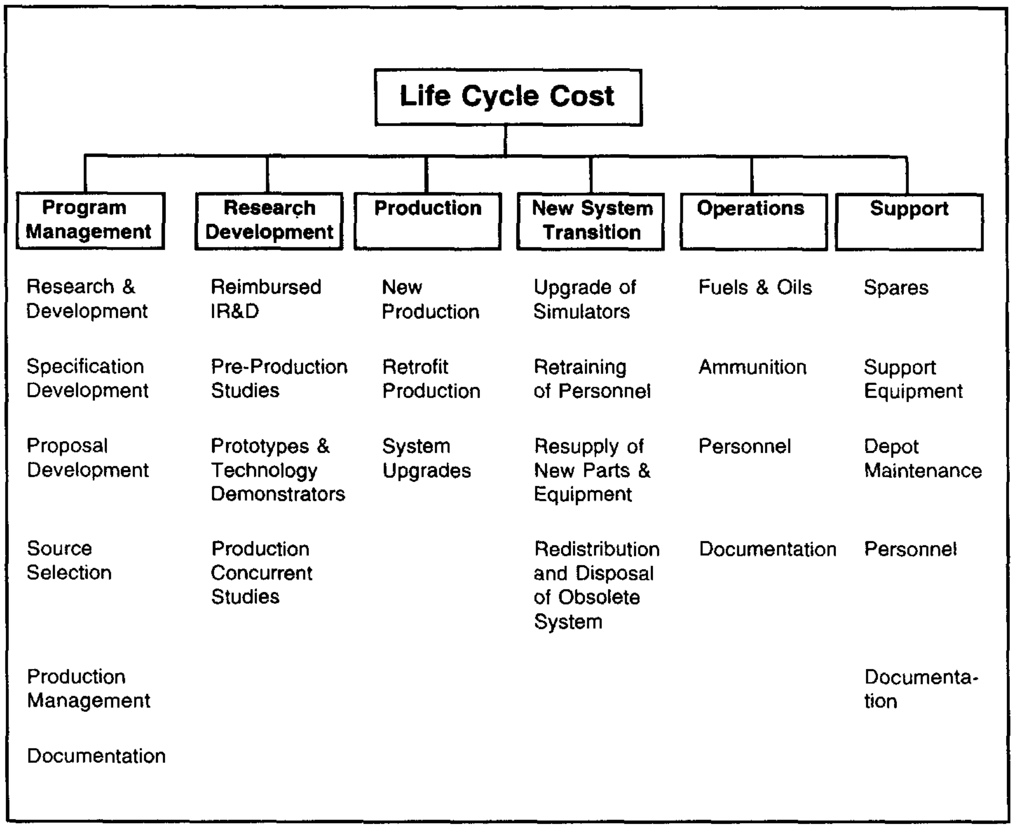

Figure 6. **Cost Categories for all AH-1 LCC Model.**

The calculation of comparative AH-1W and 4BW merit is presented in Table 3. These calculations are based on preliminary assessment of proposed four-bladed main rotor system benefit and lower bound estimates for AH-1W and 4BW life cycle cost (the 4BW is assumed to provide 5% reduction in maintenance and spares costs). Based on this preliminary assessment, the 4BW's benefit outweighs fleet conversion cost in both readiness and contingency scenarios. The 4BW's merit exceeds that of the AH-1W by 17% in the readiness scenario, and 20% in contingency. Procurement of the 4BW thus yields a 20% higher level of mission effectiveness (in the contingency scenario) per dollar spent. This preliminary positive result justifies a recommendation for further engineering development of the 4BW and more comprehensive evaluation of its potential value to the Marine Corps.

SUMMARY

This paper presents a merit function approach for cost-benefit analysis of high tech systems, which relies on a comprehensive measure of sys-

Table 3
CALCULATION OF AH-1W AND 4BW MERIT BASED ON PRELIMINARY PERFORMANCE AND COST ESTIMATES

Helicopter Configurations	Preliminary Benefit Score	Life Cycle Cost Estimated Floor In 1990 - $ Billion		MERIT	
		Readiness Level	Contingency Level	Readiness Level	Contingency Level
Configuration A - AH-1W	64.8	1.764	2.295	36.74	28.24
Configuration B - 4BW	83.6	1.940	2.466	43.09 17% Increase	33.90 20% Increase

tem utility. The benefit function is derived in part from Quality Function Deployment Tables, which allow for the measurement of both monetary and non-monetary attributes. The cost component of the merit function is system life cycle cost. Application of the methodology was demonstrated by an evaluation of two competing attack helicopter configurations. This decision example demonstrates the practical application of this methodology to the evaluation of a complex system employing advanced technology.

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