Applying Recursive Sensitivity Analysis to Multi-Criteria Decision Models to reduce bias in Defense Cyber Engineering Analysis

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***Abstract*— Developing cyber engineering solutions for the Defense Department requires decisions that affect the cost, schedule, and performance of not only the constituent system but those of the combined end-to-end System of Systems. Considerable research has been conducted on the topic of decision aiding methods such as Multi-criteria and Multi-objective Decision Analysis to support results given the uncertainties within the acquisition environment. Besides the problem definition itself, the most significant contribution to a decision model's success is the identification of the correct key decision criteria to meet the stakeholder's goals. Unfortunately not all of the decision makers will agree on what is most important. In essence, the system engineer's choices and weighting may be significantly different from those of the program manager, resource sponsor, or even the user. This research focuses on the use of recursive sensitivity analysis to mitigate the uncertainty that may be introduced through the bias of the Subject Matter Experts queried for the Multi-Criteria Decision Modeling. The application of sensitivity analysis to the criteria selection and weighting process prior to and directly following the decision aiding methods could significantly reduce ambiguity and ultimately improve the quality of the decision.**

***Index Terms*— Decision making, defense acquisition, operations research, optimization, sensitivity analysis, systems engineering.**

I. Introduction

THE selection between technical alternatives to fill capability gaps identified for our warfighters is arguably the most significant decision in defense acquisition. This critical decision directly affects the cost of the program, the time necessary for development and delivery, as well as the ability to leverage technology to increase the functionality provided to the user. In light of the numerous cyber-attacks of late, many in the Department of Defense (DoD) are seeking to increase the speed at which cyber capability can be acquired and integrated into the force. The initial selection of a solution concept or an engineering alternative significantly impacts this acceleration. Georgiadis, Mazzuchi and Sarkani estimated that the requirements determination and technical alternative selection effort is only 2% of the total life cycle, but this formative decision drives the remaining 98% of the acquisition efforts [1]. Therefore, it is essential that research focuses on modeling decision criteria weighting and equilibria points to ensure the optimal alternative is selected.

A. Analysis of Alternatives

For most major defense acquisitions, significant investments in time and resources are applied to evaluate each of the feasible alternatives with respect to criteria such as life-cycle cost, technical maturity, system performance, and schedule. This is directed by both statutory and regulatory policy in the Weapons Systems Acquisition Reform Act (WSARA, Public Law 111-23) [2] and the Department of Defense Instruction on the Operation of Defense Acquisition System (DoDI 5000.2) [3]. This evaluation, known as an Analysis of Alternatives or "AOA", is an attempt to objectively offer the Milestone Decision Authority (MDA) the best alternative to meet the validated requirement. However, the U.S Government Accountability Office (GAO) reported that "AOAs have often simply validated a concept selected by the sponsor and are not used as intended to make trade-offs among performance, cost and risks to achieve an optimal weapon system concept that satisfies the warfighter's needs" [4].

This demonstrates a distinct possibility of the introduction of subjectivity and bias into the AOA results based on the criteria and importance weighting of the Subject Matter Experts (SME) conducting the evaluation. The GAO also found that "Most of the programs reviewed either did not conduct an AOA or conducted an AOA that focused on a narrow scope of alternatives and did not adequately assess and compare technical and other risks of each alternative"[5]. In 2012, the Senate Armed Services Committee's characterized this subjectivity as "cultural bias [that] produces overly optimistic cost and schedule estimates and unrealistic performance expectations" [6].

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There is an abundance of literature recommending the use of operational research methods or decision analysis tools to assist in the conduct of an AOA [7], [8], [9]. Most of these advocate the use of Multi-Criteria Decision Making (MCDM) models that can compare multiple attributes of a discrete set of alternatives offering the best ranking alternative based on the preference values. The intent of this research is to offer an evaluation of techniques that may reduce the bias of the preference values entered into these MCDM models. The assumption is that through the recursive or iterative use of sensitivity analysis techniques, overly influential criteria or mutually cancelling criteria from different experts may be balanced to optimize the recommended solution.

II. MULTI-CRITERIA DECISION MAKING TOOLS

There are many MCDM methods and supporting models available for use. The models are generally selected based upon the type of decision space being evaluated. This causes the MCDM methods to be categorized into two basic types. The first deals with decision-making given a continuous decision space such as mathematical optimization problems to find the best compromise solution amongst multiple or infinite possibilities. This is generally known as Multi-Objective Decision Making (MODM). For the most part, DoD AOAs will have a finite or discrete number of alternative solutions to evaluate and therefore use the category known as Multi-Attribute Decision Making (MADM) [10].

There are numerous deterministic methods for Multi-Attribute Decision Making; however the most prevalent in literature seem to be the Weighted Sum Model (WSM), the Weighted Product Model (WPM), the Analytical Hierarchy Process (AHP), the Elimination and Choice Expressing Reality (ELECTRE), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Each of these models have proven beneficial in their own right, some are very good when the decision criteria units of measure are the same (e.g., miles, pounds, seconds) such as WSM, WPM and AHP. Others, such as ELECTRE and TOPSIS, evaluate each criterion separately using weighted normalization and pairwise comparisons to identify the best alternatives [11], [12]. This research has selected the use of TOPSIS due to its employment of an ideal point method, where the decision alternative considered most suitable is calculated based upon the ranking of summed Euclidean distances from both the best and worst solution. The method is not necessarily complex.

$$\boldsymbol{D} = \begin{array}{c} \\ \textit{Alternatives} \end{array} \begin{array}{c} \textit{Criteria} \\ \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1j} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2j} \\ \vdots & & & & \vdots \\ x_{i1} & x_{i2} & x_{i3} & \dots & x_{ij} \end{bmatrix} \end{array}$$

Fig. 1. Decision matrix *D* – Evaluating each alternative against each criterion.

The quantitative information provided by the SMEs for each alternative creates the decision matrix ***D***, with a resultant value at the intersections given as (x_{ij}) representing the performance measure of the i^{th} alternative in terms of the j^{th} criterion as seen in Fig. 1.

TOPSIS then normalizes the information within Matrix *D* by dividing each x_{ij} by the Square Root of the Sum of the Square of each x_{ij}. This results comprise a new matrix *N* of normalized values (r_{ij}) using (1).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x^2_{ij}}}, \; i = 1, 2, \dots, m, \; j = 1, 2, \dots, n \qquad (1)$$

In addition to the SME providing their expert value of each criterion on the alternative, they provide a weighted importance to differentiate the individual criterion. The importance weight assigned to each of the criteria must equal a sum of 1. TOPSIS uses the importance weighting to calculate a weighted normalized decision matrix ***V*** e.g., multiplying the normalized values (r_{ij}) by the criterion weights ($w_1, w_2, w_3 \dots w_n$; where $\sum w_n = 1$. This matrix is depicted in Fig. 2.

Next the matrix is evaluated to calculate the best (Positive) and worst (Negative) possible solutions based on a composite of all criteria weighted values. The best and worst are determined using (2) and (3).

$$\boldsymbol{V} = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_n r_{1j} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_n r_{2j} \\ \vdots & & & \vdots \\ w_1 r_{i1} & w_2 r_{i2} & \dots & w_n r_{ij} \end{bmatrix}$$

Fig. 2. Weighted matrix *V*, Evaluating the normalized result from matrix *N* by multiply each result by each importance weighting.

$$A^* = \{(\max V_{ij} \mid j \in J), (\min V_{ij} \mid j \in J) \mid I = 1,2,3\dots n\} \qquad (2)$$
$$_i = \{v_{1^*}, v_{2^*}, v_{3^*}, \dots v_{n^*}\}$$

$$A^- = \{(\min V_{ij} \mid j \in J), (\max V_{ij} \mid j \in J) \mid I = 1,2,3\dots n\} \qquad (3)$$
$$_i = \{v_{1^-}, v_{2^-}, v_{3^-}, \dots v_{n^-}\}$$

Finally, TOPSIS evaluates the Euclidean separation distance of each alternative to the best and worst available determining a scored ranking for the outcome. This is calculated using (4) and (5). This is depicted in Fig. 3 [13].

$$S^* = \sqrt{(\sum(V_{ij} - V_{j^*})^2} \qquad (5)$$

$$S^- = \sqrt{(\sum(V_{ij} - V_{j^-})^2} \qquad (6)$$

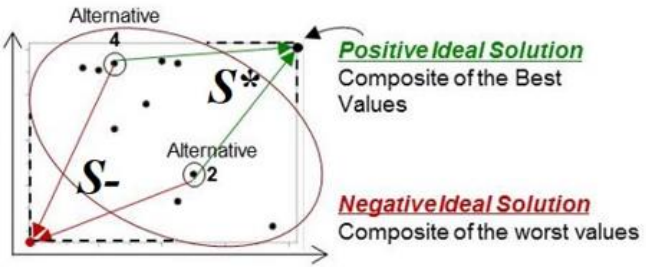

Fig. 3. Scores for alternatives are calculated using the distances from the Positive Ideal Solution (***S****) and the Negative Ideal Solution (***S***$^{-}$).

III. EXAMPLE

To demonstrate how Multi-Criteria Decision Modeling might benefit a decision maker in the selection of alternatives; an evaluation was conducted on a representative example. The scenario for the example was simply to emulate a Marine Corps acquisition that had four alternatives from which to choose a Cyber-Security system closing a high ranking gap from the Capability Based Analysis. While this example uses sample data, the exercise successfully demonstrates the impact of an expert's opinion on decision criteria's value and importance weighting with respect to the preferred alternative.

A. Decision Criteria

The first step in the assessment was to identify the key decision criteria needed to compare each of the alternatives to meet the stakeholder's goals. It is important to ensure the criteria are the same across survey population and therefore must be agreeable to all of the SMEs. In addition, the criteria must be quantifiably measurable to provide numeric values for the modeling tool. Some of the offered criteria were easily quantified, for example a vendor's offered cost or scheduled delivery time is unique to their alternative. Other criteria however required a numeric scale for use by all SMEs such as the Defense Department's Technical Readiness Level scale or a value given to the total Threshold Requirements versus the number the vendor states their alternative will deliver.

B. Communities of Interest

We next determined which specialists or communities of interest (COI) within the population were best suited to evaluate the alternatives based upon the criteria. Diversity in evaluation expertise provides the decision makers with a greater range of assessment of the alternatives. For the example, our criteria and quantification measures were distributed to a selection of SMEs from the following COI:

1. Program Managers
2. Resource Sponsors
3. Systems Engineers
4. Users

TABLE I
DECISION CRITERIA

Cost of Alternative	Delivery Schedule	Technical Maturity	Functional Maturity	Integration With Current Architecture	Contract Availability

With a little discussion, each of the SME agreed on the example's decision criteria as depicted in Table I.

C. Importance Weighting

Once the criteria were agreed upon, the SME were requested to provide importance weighting for the six criteria. Intuitively, the weighting responses were different based upon the opinions of the responding COI. Program managers lean toward the importance of cost and technical maturity. Engineers tend to favor technical maturity and integration, while the users and resource sponsors place significant importance on schedule and functional capability. Table II depicts the importance weighting of each of the COI.

TABLE II
IMPORTANCE WEIGHTINGS BY COMMUNITIES OF INTEREST

Decision Criteria	Weighted values for Program Managers	Weighted values for Systems Engineers	Weighted values for Resource Sponsors	Weighted values for Users (Warfighters)
Estimated Cost to Procure, Integrate and Deliver Alternative	25	15	10	5
Estimated Time Required to Procure, Integrate and Deliver Alternative	11	15	5	20
Estimated Technical Readiness Level of Alternative	20	20	45	15
Estimated Percentage of Functional Requirements provided by Alternative	17	20	25	45
Estimated Level of Modification Required to integrate the Alternative	12	10	10	10
Estimated ability to attain the Alternative (Contract Vehicle, Legal issues, etc.)	15	20	5	5
	100	**100**	**100**	**100**

D. Alternative Evaluation

Finally, Each SME received the exact same descriptive data of the four alternatives for the example assessment. The descriptive data was created as realistic as possible, however, with reduced complexity to simplify the value determinations for the example. Table III provides the data set used to describe the alternatives.

TABLE III
ALTERNATIVE SPECIFICATIONS

Alternatives	Estimated Cost for Alternative Rating Based on % above the mean	Estimated Completion Schedule (Months) Rating Based on % above the mean	Estimated Technology Readiness Level TRL 9…10 pts TRL 8 …8 pts TRL 7…6 pts TRL 5 or 6..3 pts TRL1 to 4…1 pt	Estimated Functionality Capability Rating Based on % of the 25 reqts provided by the Alternative	Estimated Integration Readiness Plug N Play…7-10 pts Minor Mods…4-6 pts New Interface..1-3 pts	Estimated Programmatic Accessibility Contract Avail..7-10 pts New Compete…4-6 pts New Sole Source.1-3 pts
Alternative 1	$ 550,000.00	22	8	12	Compliant Standard	New Contract Sole Source
Alternative 2	$ 710,000.00	37	7	17	New Interface Required	New Contract Compete
Alternative 3	$ 420,000.00	32	6	20	Minor Modification	Contract Available
Alternative 4	$ 630,000.00	25	9	19	Minor Modification	New Contract Sole Source

To complete the analysis, each alternative was ranked by the SMEs from the four individual COI and the values were entered into the MCDM tool TOPSIS for evaluation. To ensure differentiation between the COI, each was modeled individually maintaining the importance weighting for their community.

IV. EVALUATION RESULTS

The results of the four independent TOPSIS simulations based on the COI responses provided the decision maker with three separate recommendations. The PM and User communities both selected Alternative number 4, while the Systems Engineer and Resource Sponsor communities selected Alternatives 1 and 2 respectively. This can be seen in (4). The generally accepted method to select a best value alternative using the four TOPSIS simulations is to cumulatively sum the scores of the four COI using (7) and evaluate the results. As depicted in (5), our example analysis clearly shows Alternative 4 as the winner with 35% of the scoring value.

$$S_{(COI)} = \sum_{j=1}^{n} S_{(COI)j} \quad (7)$$

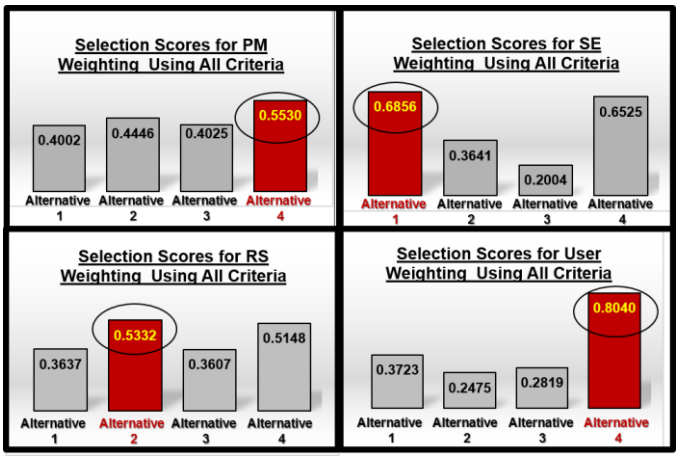

Fig.4. Alternative selections using individual COI weightings

V. Sensitivity Analysis

Conventional wisdom would suggest that this cumulative method would mediate any bias or subjectivity on the decision criteria input amongst the different COI. It also seems to justify the benefit of diversity in evaluation expertise. For example, if the decision were left to the Systems Engineers, Alternative 1 would have been recommended. However, our

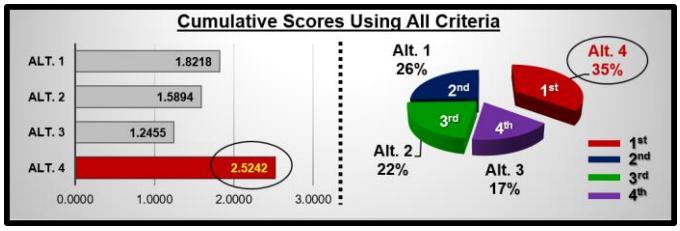

Fig. 5. Cumulative selection based on individual COI weightings

research is to investigate how sensitive the input may be to these biases and if the weightings of the individual criteria were actually causing uncertainty in the decision results. What if two or more of the criteria were to either combine to arbitrarily increase the likelihood of a preferred alternative? Or similarly, if two or more criteria offset each other to decrease a preferred alternative, would this change the results? It seems logical to hypothesize that relationships between the individual criteria could subjectively affect the outcome enough to cause a rank reversal in the recommended solution.

TABLE IV
SENSITIVITY ANALYSIS WEIGHTING NORMALIZATION

	Cost	Schedule	Technical	Function	Integ	Contracts
Cost	0.00	0.27	0.29	0.28	0.27	0.28
Schedule	0.16	0.00	0.15	0.14	0.13	0.14
Technical Maturity	0.25	0.22	0.00	0.23	0.22	0.23
Functional Maturity	0.22	0.19	0.21	0.00	0.19	0.20
Integration	0.17	0.14	0.16	0.15	0.00	0.15
Access to Contracts	0.20	0.17	0.19	0.18	0.17	0.00
Sum of Weights	1.00	1.00	1.00	1.00	1.00	1.00

To test this hypothesis, an additional TOPSIS simulation was conducted using the same alternatives, COI and weightings but insolating each of the decision criteria independently. This assessment was to identify which factors in the model contribute most to the variance in the conclusions. This evaluation is broadly defined as Sensitivity Analysis (SA) [15].

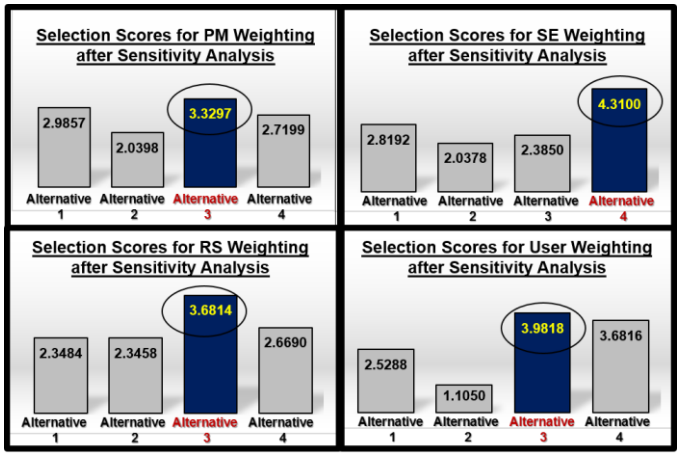

Fig. 6. Recommended alternatives based on The Sensitivity Analysis

The model isolated the interaction between criteria by removing each individually and distributing its original value proportionately across the remaining five criteria. This same method was conducted for each of the six criteria as depicted in Table IV. The TOPSIS model was conducted for each COI importance weighting rendering solution recommendation for each run. ($S_{PM}1$, $S_{PM}2 \ldots S_{PM}$ 6, $S_{SE}1$, $S_{SE}2 \ldots S_{SE}6$ and so on.) The selection scores for each COI were then calculated once again using (7).

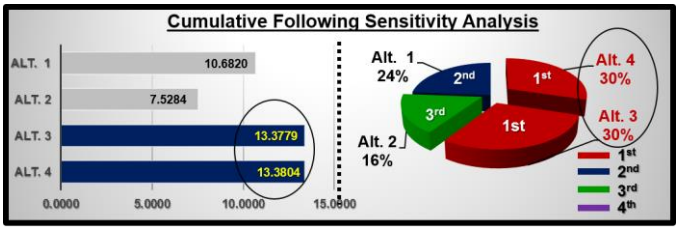

Fig.7. Recommended best value solution based on cumulative Sensitivity analysis scores.

The results of the twenty four independent TOPSIS model runs using the sensitivity analysis responses interestingly shows a dramatic increase in the selection for Alternative 3. The change was so dramatic that it rendered the distinction between Alternative 3 and 4 negligible. This is depicted in Fig. 6 and 7.

VI. Future Work

The example problem presented in this article describes an issue that suggests more research is required to identify the effects of subjectivity and bias on the input to MCDM tools. Our research will be conducted over the next year as the subject of dissertation work for George Washington University. Our objective is to coordinate with the United States Marine Corps to evaluate an actual Cyber Security acquisition decision duplicating the example methodology described. With the actual information as a basis, a comparative study can be focused on the use of these techniques to identify how sensitive the input criteria to MCDM tools are and to identify techniques to reduce the uncertainty for evaluations.

Our methodology is to utilize sensitivity analysis techniques such as regression analysis, correlation, and multicollinearity assessment to identify the change and error on the input to the model. Regression analysis evaluates if the probability distribution of a random variable *y* may depend on the value of

some predictor variable *x*. The regression analysis sets up the evaluation of this relationship using a single predictor variable (simple linear regression) or multiple predictor variables (multiple linear regressions) [16]. Correlation measures the strength or linear association of the two variables i.e., *x* and *y*. If there is a strong correlation between the two, *x* may better predict the future value of *y*, using (8) [17].

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}, x \quad (8)$$

As an example, an initial analysis of correlation amongst the decision criteria in the example problem suggests a strong linear relationship between cost and each of the other criteria. If there happens to be a high correlation such as this between many of the independent or predictor variables, the issue of multicollinearity may arise [18].

VII. Summary

Accurate decisions concerning which alternative solution to select early in an acquisition can have dramatic impact of the ultimate program cost and schedule of a Cyber Security Solution or the Cyber system of systems. Multi-criteria Decision Analysis techniques have been demonstrated as useful tools to support decision making in the DoD acquisition community. Studying the relationships between the separate inputs through sensitivity analysis is expected to reduce bias on the input criteria and increase the accuracy of the ultimate decision.

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