Standard Approach to Trade Studies:
A Process Improvement Model that Enables Systems Engineers to Provide Information to the Project Manager by Going Beyond the Summary Matrix

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ABSTRACT

The model for the trade study process described in this paper is based on the 'Standard Approach to Trade Studies' [1][*]. The process modeled herein describes the steps for performing and documenting a **trade study (trade-off study)**, developing products for the Decision-Making Authority (DMA), and guidelines in tailoring the study to meet the needs of the program. This trade study process model is a series of steps used to transform subjective data to more quantitative information for the DMA in the decision-making process. Each step in this process model is designed to alleviate problems identified in past trade study models. This process model presents a framework and structure centered on the familiar summary matrix to help document the thinking process in more quantitative decision-making terms. Within this process model, standard terms and definitions are used, roles and responsibilities of the participants and decision-makers are documented, and a suggested flow is illustrated. This trade study process meets Level 3 'Decision Analysis and Resolution' requirements of the Capability Maturity Model Integration (CMMI®)[**].

INTRODUCTION

In the past, previously used trade study models have been blamed for giving the incorrect answer when trading criteria traits among viable alternatives. In hind-site, many of the past trade study models typically did not properly present the data in a more comprehensible format to the decision-maker.

The complete trade study process model is divided into four phases. Many aspects of each phase are overlapping, but in moving from one phase to the next, specific products (summary matrix) or reviews (gates) are mandated. Within each phase, specific responsibilities are assigned to the Trade Study Lead (TSL), Trade Study Team (TST), and the DMA.

The <u>significant developments</u> introduced in this paper are identified in the paper where they appear.

#1. Defining a 'Framework and Structure' for seven often used trade study types.
#2. Removing 'Cost' and 'Risk' from the tradable criteria list.

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[*] "Standard Approach to Trade Studies"; Patent Pending 10/980,838; dated 12 July 2004
[**] Capability Maturity Model Integration (CMMI®) -Copyright 2003 by Carnegie Mellon University

#3. Defining a 'Baseline/Optimum solution(s)' to anchor criteria utility curves.
#4. Presenting 'Uncertainty (Lack of Confidence)' considerations in criteria evaluation
#5. Presenting the 'Cost-Benefit chart' for use in final (Gate 3) evaluation
#6. Presenting the 'Risk-Benefit chart' for use in final (Gate 3) evaluation

Each trade study executed is ultimately dependent on time, resources, or data. This trade study process model can be tailored to meet the program time, resources or data constraints. The simpler tailored trade study process models are direct subsets of the more complete trade study process model.

The trained TSL, TST, and the DMA can follow this process model to achieve the optimum systems solution with confidence that their decision can be backed up and defended by the program and each team member. When trade studies are executed using this process model, technical and managerial personnel can review and re-assess trade studies used in decision-making and revise each with expedient and immediate results when updated information on alternatives becomes available. This can only be accomplished when the systems engineering community universally accepts the model developments highlighted in this paper and applies this process through all levels of their organization.

This process utilizes the information from the 'Summary Matrix' for the development of the 'Cost-Benefit' and 'Risk-Benefit' charts. In both cases, we treat Cost As an Independent Variable (CAIV) and Risk As an Independent Variable with respect to benefits derived from each alternative under consideration. When the 'ilities are assessed as tradable criteria, and the time horizon is moved from the present to the operational future, there will be little or no need to address Reduction of Total Ownership Costs (RTOC) because those considerations will have been properly addressed. Especially since the purpose of RTOC is to 'fix' the decisions made earlier in the acquisition process did not originally take the 'ilities into account.

PHASED APPROACH

The complete trade study process is defined by four phases. In moving from one phase to the next, gate reviews or specific products (summary matrix) are mandated. Figure 1 displays the trade study process (*significant development #1*).

Within each phase, specific responsibilities are assigned to designated personnel. They are:

- TSL – responsible for the trade study. This responsibility starts with initiating the trade study through final presentations to the DMA for approval and release.
- TST – responsible for supporting the TSL by gathering/developing data for the trade study as directed by the TSL. This information is required for the products and presentations to the DMA.
- DMA – responsible for making decisions on the trade study. These decisions are made at each of the mandated gate reviews. The DMA is often the program/project manager or the customer that funds or supplies resources for the trade study and is dependent on the results for subsequent program execution.

Phase I – Initiate Trade Study

TSL initiates the trade study by documenting the Purpose/Need Statement, identifying membership of the TST for support, and developing the program plan for the execution of the proposed trade study. Phase I ends as the DMA decides approving the viable alternatives, criteria, baseline/optimum solution, and priorities/weighting during the Gate 2 Review.

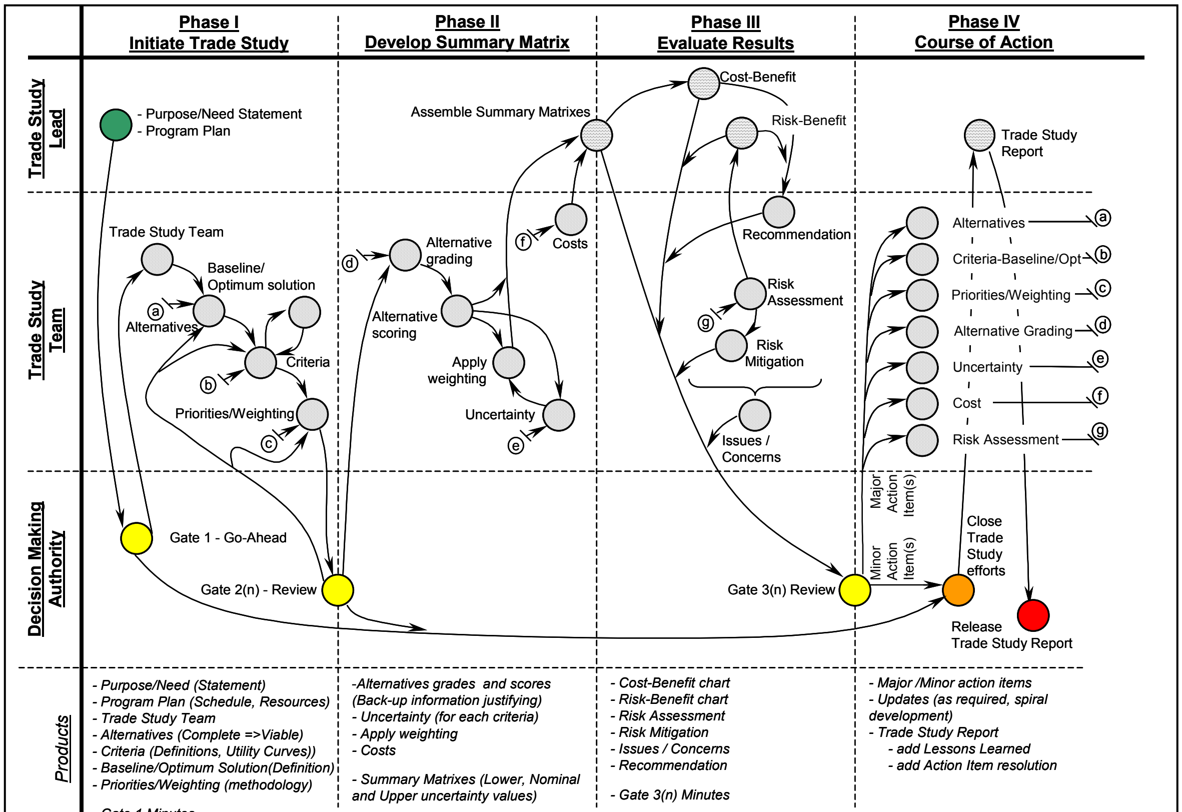

Figure 1. Trade Study Process Framework & Structure

Purpose/Need Statement, Program Plan – The TSL documents the specific Purpose/Need of the proposed trade study and the expected results of the selection, consequence of no action, and major program constraints. The TSL also develops a draft program plan for the trade study.

Gate 1 – Go Ahead – The TSL presents to the DMA the Purpose/Need Statement, Program Plan, and any ground-rules and assumptions that are relevant to this trade study. The DMA can authorize the start of the trade study, stop work on all activity, or ask the TSL to start work with resources assigned contingent upon completion of specific action items. All presentation materials and minutes shall be documented in the trade study report.

TST – The prospective members are presented to the DMA at the Gate 1 Review. The DMA shall finalize the program plan and the membership / responsibilities of the TST at that review.

Alternatives – This section develops two groups of alternatives. First is the more inclusive group of alternatives identified. The second group is the list of viable alternatives used in the trade study. The down select of alternatives in the trade study comes through using Go/No-Go (hard) constraints. The Go/No-Go constraints are absolute in that the alternatives can or cannot meet those specific constraints. A manageable list of viable alternatives is from three to five alternatives. More than five viable alternatives may consume valuable program resources in the trade study.

Criteria – The TST establishes the criteria to be used in assessing the viable alternatives. The establishment of the criteria includes their definition and scoring functions (Utility Curves). The utility curve relationships (see Figure 2) can take the form of curves, linear relationships, or step functions. These relationships are developed by the TST and TSL. The criteria used for criteria grading are not the hard constraints previously used for Go/No-Go down-selection. There are two basic points that need to be made in this section of the trade study. First is that we are assuming that each of the criteria are independent of one another for grading purposes. The second is that we want to reserve the use of cost and risk for the final evaluation of the viable alternatives in Phase III, and not use cost and risk as part of the 'tradable' space in the trade study (*significant development #2*). The importance of cost and risk are reserved for review and judgment by the DMA at the Gate 3(n) Review. The minimum number of criteria used for a trade study should be set to 3. The maximum of criteria considered should follow an often-quoted rule of thumb is that people can pay attention to seven plus-or-minus two things at a time. Therefore, nine should be the upper limit to tradable criteria used for trade studies.

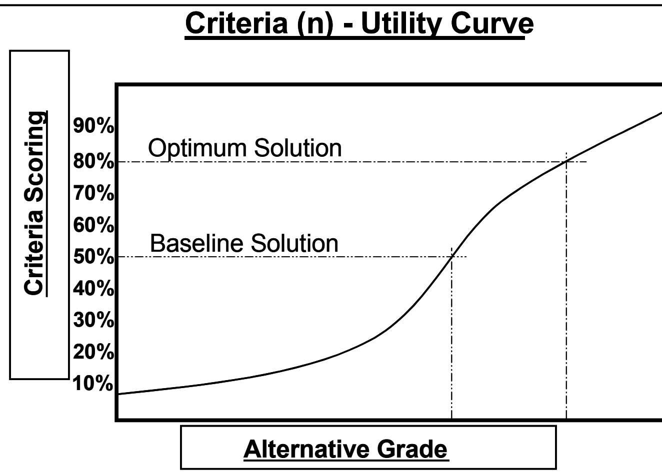

Figure 2. Sample Utility Curve - Each tradable criterion is scored for each alternative independently of the other criteria

In the development of the criteria being considered for evaluation, the respective 'ilities need to be addressed with their respective time horizon. Most acquisition trade studies only focus on the development type of criteria which is a very short time horizon, while in actuality, they should also be addressing the fielded operational systems with the respective 'ilities as tradable criteria. When these concerns are addressed in the early developmental trade studies, there will be a direct cost avoidance in the out years, thereby Reducing Total Ownership Costs.

Baseline/Optimum Solution – The Baseline/Optimum solution is used to anchor the utility curve (*significant development #3*). The baseline solution is typically used when evaluating replacements for an existing baseline. An optimum solution is used when a balanced optimum solution has been defined that meets system and programmatic constraints. For the baseline, the utility curves are adjusted to show the scores of the baseline solution at the 50 percent mark (based on experience). This allows trading space for the criteria above and below the baseline. When the optimum solution is used, the utility curves are adjusted to locate scores at the 80 percent level (based on experience). The expectation is that each of the criteria may not be able to meet the 80 percent value in all criteria grades. This also allows room for improvement, but significant improvement beyond the 80 percent value enters the area of diminishing returns. These steps in generating the utility curves may be an iterative process within the TST facilitated by the TSL.

Priorities/Weighting – Priority/Weighting of criteria are handled in a single tier or a two-tier fashion. A single tier method puts each of the criteria on equal footing or importance for consideration. A two-tier method groups the criteria into groups that can be individually prioritized within the group, while the groups can be prioritized against each other (See Table 1). This method has helped in sorting out the criteria under consideration. Values shown are for illustrative purposes only. All percentages and weightings are defined and substantiated by the TST and TSL. Further details on their derivation are reserved for another paper. Both the priorities/weighting and the method used in developing those weightings should be documented for presentation to the DMA for their understanding and future reference.

Criteria	Sub-Criteria		Percentages		Ratios	
Performance	-----	-----	50.0%	-----	3.3	-----
- - -	speed		- - -	15.0%	- - -	3.0
- - -	acceleration		- - -	15.0%	- - -	3.0
- - -	payload		- - -	10.0%	- - -	2.0
- - -	fuel consumption		- - -	5.0%	- - -	1.0
- - -	ceiling		- - -	5.0%	- - -	1.0
Reliability	-----	-----	15.0%	-----	1.0	-----
- - -	MTBF		- - -	15.0%	- - -	1.0
Safety	-----	-----	15.0%	-----	1.0	-----
- - -	Safety		- - -	15.0%	- - -	1.0
Logistics	-----	-----	20.0%	-----	1.3	-----
- - -	Supply Lines		- - -	5.0%	- - -	1.0
- - -	Spare Parts		- - -	5.0%	- - -	1.0
- - -	Crew Training		- - -	10.0%	- - -	2.0
			100.0%	100.0%		

Table 1: Sample Two-Tier approach - Used for Criteria/Sub-Criteria Prioritization/Weighting

Gate 2(n) Review – This is the line of demarcation between the set-up work and the evaluation of the viable alternatives. This review is used by the TSL to present products generated in Phase I to the DMA. The establishment of viable alternatives, criteria, utility curves, baseline/optimum solutions, and priorities/weighting are reviewed and approved by the DMA before proceeding on to the actual grading and scoring of the viable alternatives. The DMA may approve the products and signal the continued efforts in the trade study, stop the trade study efforts, or assign actions that require reassessment of the products and another review at a later date. The latter choice would require another gate review before proceeding. The products and the Gate 2(n) minutes are included in the trade study report.

Phase II – Develop Trade Study Matrix (es)

Phase II starts when the DMA decides to continue with the trade study after approving the Gate 2(n) Review. Phase II ends when the TST has developed each of the viable alternatives to generate the scores for each grading criterion and the TSL has assembled those scores into the summary matrix (es). The information in the summary matrix (es) is the basics used for Phase III activities. The completion of the summary matrix (es) is a pseudo gate that the TSL uses to signify the completion of Phase II. It is important to understand that this process model uses the data from the summary matrix (es) and graphically displays relational information to the DMA. We are not comparing the virtues of the summary matrix with this process/model. We are in fact using that data in the summary matrix for further review and action by the DMA. Therefore, this model enables the systems engineer to provide information to the DMA by going beyond the summary matrix

Alternative Grading – The viable alternatives are assembled for evaluation. Each alternative is evaluated and assessed per the pre-defined criteria. The TST is responsible for gathering and assembling that information. Again, the importance of grading in the correct time horizon is of up-most importance. The value of some of the criteria may actually change over time. It would be worthwhile to consider those changes in the first trade study than to have to explain those changes in the updates/revisions to the trade study in the future.

Alternative Scoring – The utility curve translates the criteria grade to a resultant score. This process is repeated for the minimum-maximum grades developed in the section entitled Uncertainty (Lack of Confidence).

Apply Weighting – That score generated above, is subsequently prioritized / weighted for a weighted score for each criterion. The current process uses the same weighting on the minimum-maximum scores developed due to uncertainty (lack of confidence). Further research beyond the scope of this paper is required to determine if and how different priorities / weightings should be applied to the minimum-maximum scores.

Uncertainty (Lack of Confidence) – In the evaluation of the viable alternatives, the TST has the responsibility of not only generating a nominal value of the criteria grade, but also determining the 'uncertainty' or 'lack of confidence' of that value (*significant development #4*). This relationship shows that the alternative value of low confidence, it is expected to have a wider uncertainty in the grade. This process lends itself to a minimum-nominal-maximum grading (or a $+3\delta$ value if probabilistic methods are used). In the past, several trade studies used a uniform deviation around the criteria score, typically +1 resultant score count for a sensitivity study. Using this type of sensitivity study shows lack of understanding of the uncertainty of the alternative grades. In this process, the uncertainty of each criteria grade is individually evaluated on the merits of the viable alternative being assessed. This means that each individual criterion will almost always have a different uncertainty spread based on the merits of that criterion for each viable alternative assessed in the trade study.

Costs – The costs for each alternative is collected for each viable alternative for the TSL. The TST is responsible for generating/defining the minimum-nominal-maximum costs for each alternative.

Assemble Summary Matrix (es) – The TSL compiles the assembled scores for the viable alternatives into a summary matrix (es) used to tabulate the information (See Table 2). The process is repeated for the upper and lower values (or $+3\delta$) of the score based on uncertainty in the criteria grade.

Summary Matrix			Alternative A Cost $____		Alternative B Cost $____		Alternative C Cost $____		Alternative D Cost $____	
Criteria	Sub-Criteria	Weighting	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Performance		**3.3**	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	speed	3.0								
	acceleration	3.0								
	payload	2.0								
	fuel consumption	1.0								
	ceiling	1.0								
Reliability		**1.0**	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	MTBF	1.0								
Safety		**1.0**	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	Safety	1.0								
Logistics		**1.3**	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	Supply Lines	1.0								
	Spare Parts	1.0								
	Crew Training	2.0								
TOTAL			- - -	#1 Score	- - -	#2 Score	- - -	#3 Score	- - -	#4 Score

Table 2: Sample Summary Matrix - Used to tabulate the weighted criteria scoring for each Viable Alternative studied using the two-tier method

Phase III – Evaluate Results

Phase III starts with the TST completing the summary matrix (es), and now must develop the Cost-Benefit chart, Risk-Benefit chart, Risk Mitigation Plan(s), Issues and Concerns, and the

Recommendations to the DMA for the Gate 3(n) Review.

Cost-Benefit – This graphical representation of the data in the summary matrix (es) (See Figure 3) shows the relative relationships of cost and benefit of each viable alternative. In this graphical representation, the X-axis is the relative worth (final tabulated scores from the summary matrix) and the Y-axis is the cost of each viable alternative. The preferred quadrant is in the lower right hand quadrant being the quadrant that has the highest benefit with the lowest cost (*significant development* #5).

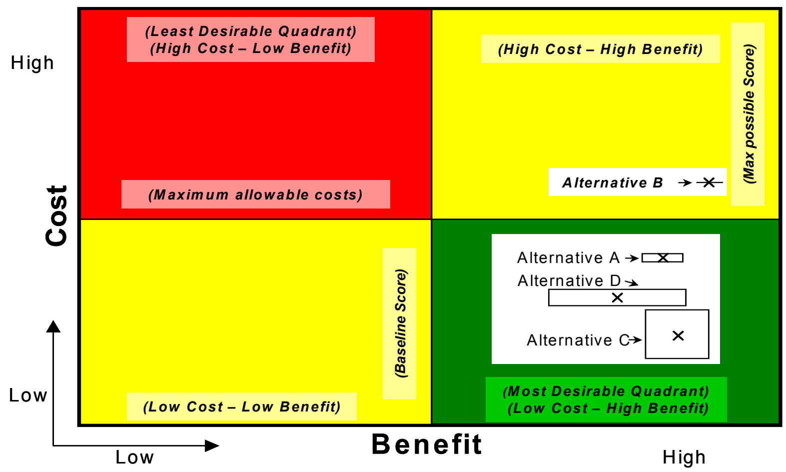

Figure 3. Cost-Benefit Chart - Showing the spread on the X axis due to the uncertainty in the Criteria scoring and the spread in the Y axis due to uncertainty in Costs

In developing the Cost-Benefit chart, cost is treated as an independent variable. The DMA can now relate the additional benefit he/she is getting for the relative increase in incremental costs.

The variation in the final score due to uncertainty of alternative scoring causes the spread along the X-axis. The uncertainty in the cost of the alternative would cause a spread in the Y-axis. The mid-point of the Cost-Benefit chart X-axis is the point in which all scores are set to the mid-point of the utility curves. The mid-point of the Y-axis is the maximum allowable cost assigned by the program for a viable alternative to be further considered. The relative relationships of the alternative's Cost-Benefit show how uncertainty plays a significant role in determining the next course of action.

X-axis overlaps indicate that there is a probability of an incorrect winner of the trade study that increases with the amount of overlap, so that the final scoring positions of the alternatives can change positions. Increased overlap indicates increased ambiguity in the final solution positions. Therefore, when there is overlap, it is caused by the cumulative build-up of high levels of uncertainty in criteria grading. With that overlap, there is no clear winner in the trade study solution. Further action is required to minimize with the objective of negating the overlap. This may be focused effort on specific select criteria that significantly reduce the uncertainty of the results, thereby decreasing the overlap. The value added due to this Cost-Benefit analysis would be lost if cost were included as a tradable criteria for evaluating the viable alternatives.

If there is any overlap in the Cost-Benefit chart due to uncertainty, the author recommends that no decision be made at this time until the overlap is addressed with additional action. The uncertainty must be reduced as a matter of good business practice. If the DMA attempts to make a decision with the outstanding overlap in the Cost-Benefit chart, then he/she is unnecessarily assuming risk that can be avoided with the additional focused effort.

Risk Assessment – Each of the viable alternatives in the trade study is assessed for risk. History of past performance may significantly reduce the risk of alternatives being successful. Again this is not a "tradable criterion".

Risk-Benefit – This graphical representation of the risk assessment shows the risk as compared to the benefit (See Figure 4). The X-axis is the relative worth (final tabulated scores from the summary matrix) and the Y-axis is the cost. The value added due to Risk-Benefit analysis would be lost if risk were included as a criteria for evaluating the viable alternatives (*significant development #6*).

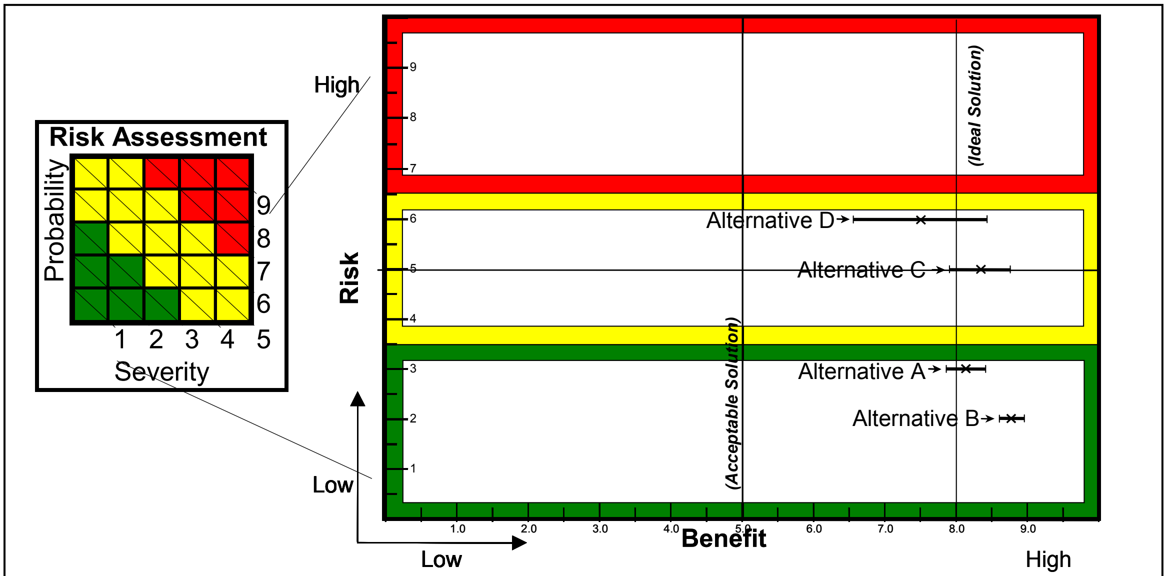

Figure 4. Risk-Benefit Chart

Risk Mitigation – The TST generates a mitigation plan for each moderate or high risk assessed. In that mitigation plan, the direction of further resources shall be planned so that the end result can be the definition or characterization of a viable alternative that meets the systems needs.

Recommendation – The TSL shall present the team's recommendation to the DMA in the Gate 3(n) Review.

Issues / Concerns – During the development of the trade study, issues and/or concerns are generated that are not classified as risks, but do need to be documented and brought to the attention of the DMA.

Gate 3(n) Review – This review is the gate in which the basic trade study activities are complete. The primary presentation products are the summary matrix showing the nominal data along with the lower limit (minimum or -3δ type values) and the upper limit (maximum or +3δ type values) due to uncertainty, Cost-Benefit chart, Risk-Benefit chart and the team's recommendation for the next plan of action.

The DMA can decide to either cancel (or place a stop-work) the trade study, collecting the work completed to date, or, to approve the recommended alternative with minor action items. Finally the DMA day decide to reiterate the trade study by revising some of the significant steps previously approved. These are major action items that will require another review by the DMA upon completion. The point is that any change in the previous steps will alter the final score of the viable alternatives. This would require the respective gate review(s) before proceeding. The products and Gate 3(n) minutes of this phase are incorporated into the trade study report.

Phase IV – Course of Action

Phase IV starts when at the end of the Gate 3(n) Review, the DMA has made a decision. This can be either to (1) close the trade study by accepting the data and making a decision on the winner of the trade study based on that data, or (2) repeat any of the previous steps (major actions) to reassess the data presented.

Close Trade Study Efforts – The DMA may make the decision contingent on completing minor action items. At that point, the TSL finalizes the trade study report for final release.

Major Action Items(s) – The DMA may assign major action items to the TST. The trade study process lends itself to this type of spiral development for updates and refinement of current and pre-existing trade studies.

- Trade Study Report – This report contains the summation and explanation of all the activity concerning the trade study and an explanation of the products developed during each phase. Minutes from each of the DMA gate reviews should be included in the report.

Release – Releasing the trade study report is contingent on the final approval of by the DMA. The released trade study report will reside in the program's repository for decision-making.

Major Action Items – The DMA at their discretion, may require that one or more of the major steps in this trade study be re-assessed and possibly revised for another Gate 3(n) Review in the future.

TRADE STUDY SUBSETS

Circumstances arise when the complete trade study process is not applicable, the program may then direct/request a less complex subset of the trade study process. The following are short descriptions of those subsets, which are a tailored version of the complete trade study process. Each of the trade study subsets below generally fit in the Structure and Framework identified in Figure 1. The only changes required are some tasks and products in Phase I and II. The steps in Phases III and IV are the same for all trade study subsets. Therefore, once the general concepts of the trade study process are learned, they can be applied to all trade study subsets with confidence and accurate results for the program.

Single Criterion Choice – This is the simplest of all subjective decision-making methods. This method is used when there is only one criterion available for the DMA for decision-making. The DMA makes the decision among viable alternatives based on the merits of a singular criterion.

Pros/Cons Trade Study – The Pros/Cons method of trade study is when each viable alternative is judged by a listing of Pros/Cons. This method can be used when more than one criterion is known. This type of trade study can be divided into two major groupings. The first is when the pros and cons are independent and unique from alternative to alternative. The second is when each of the alternatives listed contains (and are judged by) the same characteristics (criteria).

Multiple Criteria Selection – In using Multiple Criteria method, the selection is based on text that shows how alternative can satisfy criteria.

Pugh Controlled Convergence – The Pugh Controlled Convergence requires a defined baseline/optimum solution that the alternatives are to be compared. Each criteria being evaluated is judged being better or worse than the baseline. The alternative with the most positives is considered the winner in this selection (or iterative) process.

Relative Comparison (Basic) – In Relative Comparison (Basic), text is used to document the difference between the alternative being considered, and the baseline. The magnitude of the qualitative difference shows the amount of "goodness" that alternative brings to the system solution. A weighting/priority is given to the criteria to be used in the selection process.

Relative Comparison (Advanced) – In this more advanced comparison method the evaluation needs to add the priority or weighting of the specific criteria being assessed. The weighting shows the programmatic importance of each criterion. At this step, a complete utility curve is required to graph the importance of the criteria grade as it relates to a standard scoring system. At this level, a generic sensitivity study is performed.

Complete Trade Study – The elevation of the more advanced relative comparison to a complete trade study is the use of a Go/No-Go filter in selecting the viable alternatives subset from the complete set of alternatives, and uncertainty (lack of confidence) is used to define a minimum-nominal-maximum grade.

The use of the Cost-Benefit chart, Risk-Benefit chart, and the Risk Assessment at the end of the trade study are recommended for all trade study types.

SUMMARY

This paper described the trade study process and various subsets of that process. A TST, and DMA knowledgeable in the complete trade study process will understand the direction and the need for completing all of the steps and products required, thereby mitigating many if not all of the shortcomings in the past. This phased process supports a program's needs with a process that can be monitored, documented and repeated.

The trained TSL, TST, and DMA can follow this process to achieve the optimum systems solution with confidence that their decision can be backed up and defended by the program and each team member. When all technical and managerial personnel are trained, each can review and re-assess previous trade studies used in decision-making and revise each with expedient and immediate results. This can only be accomplished when the Systems Engineering community universally accepts the developments highlighted in this paper and applies this process through all levels of their organization. The significant developments presented in this process are the:

Introducing defined Framework and Structure for all trade study types

1. Removing cost and risk from the tradable criteria list
2. Define Baseline/Optimum solution to anchor criteria utility curves.
3. Introducing Uncertainty (Lack of Confidence) considerations in criteria evaluation
4. Introducing the Cost-Benefit chart for use in final evaluation
5. Introducing the Risk-Benefit chart for use in final evaluation

The following topics were briefed but not covered in the detail needed for deeper understanding and acceptance. Each will be discussed in future publications and forums. Those subjects are:

- Detailed description of each of the trade study subsets
- Criteria dependence and independence.
- Weighting methodologies for trade studies
- Priority/Weighting philosophy for uncertainty values

The author is currently taking the steps to patent the process described in this paper.

REFERENCE

[1] Felix, A, "Standard Approach to Trade Studies", Technical Paper presentation at INCOSE 2004 - 14th Annual International Symposium Proceedings, 20-24 June 2004

BIOGRAPHY

Arthur Felix works for the Avionics Department at the Naval Air Systems Command – Weapons Division, Point Mugu, California. In a previous position, Art was a Systems Engineer for Boeing and part of their Best Practices Assessment team. In that role, Art was the Systems Engineering Subject Matter Expert on trade studies.

Art comes from California, having received his Bachelors of Science in Electrical Engineering from California State University, Long Beach, and a Masters of Science in Systems Management form the University of Southern California, Los Angeles. With over 27 years of engineering experience, Art has worked for several major Aerospace employers. Art is also serving as a Commander in the Navy Reserves as an Aeronautical Engineering Officer. His breadth of experience and knowledge has exposed him to various aspects of Systems Engineering and ultimately trade studies.