Component-Oriented Trade-Off Analysis (COTOA)

by

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ABSTRACT

The decision process may occur at various points during the life cycle of a program/project. Incorporating various statistical techniques allows for the creation of multiple views of supporting data. The main purpose of Trade-Off Analyses is to provide a record including quantitative data to support decisions. This report discusses a Trade-Off Analysis process and a tool capable of being used for various types of Trade-Off Analyses. With the current computing power at our desktops and the flexibility of many software packages and suites, we are able to create automated process and analysis tools that saves time and thus saves money. By following the methodology and approach documented here, many other tools may be developed from existing processes.

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NOMENCLATURE

COTOA – Component-Oriented Trade-Off Analysis

TPM - Technical Performance Measures

TOA – Trade-Off Analysis

CHAPTER I.

INTRODUCTION

Component-Oriented Trade-Off Analysis (COTOA). COTOA is a process tool that can be tailored to accommodate any type of trade-off decision analysis. COTOA contains various types of reusable components for creating Trade-Off Analysis reports. The components will be based on various types of evaluation criteria and contain the necessary formulas for specific parameters used in the evaluation process. An engineer may choose these components as if selecting parts from a parts bin. If a particular component does not satisfy the necessary evaluation criteria, then one may be created and added to the repository of components. This method is less time consuming then creating every component every time a Trade-Off Analysis report is required. The COTOA process tool uses the components to generate the required Trade-Off Analysis tables and graphs necessary for the formal Trade-Off Analysis report.

1.1 Scope

The scope of this project is to develop a Trade-Off Analysis process tool. The reusable components consist of common predetermined evaluation criteria and associated algorithms, and templates for the required tables, graphs, and reports. The COTOA may be tailored so those newly developed components may be added to the COTOA tool database for use on future trade-off analyses. The COTOA will consist of a report generator for producing the Trade-Off Analysis reports that contain the Trade Table, Utility Curves (Graphs), Sensitivity Analysis, Adverse Consequences Analysis (Risk Analysis), and a Final Selection Recommendation. The COTOA will also be capable of interfacing with other commonly used tools, such as a Rough Order of Magnitude (ROM) Tool used for cost estimating. The Specific ROM Tool results may be included as specific evaluation criteria, in this case the cost evaluation criteria can be linked directly to the specific COTOA through Object Linking and Embedding (OLE) or Dynamic Data Exchange (DDE) interfaces. These are some of the many time saving capabilities of the COTOA.

Disclaimer:

1. This report does not address the configuration management effort required to deploy the COTOA tool.

2. This tool does not interface directly to modeling, simulation or test equipment.

CHAPTER II.

BACKGROUND

During the development of systems, various design approaches may be considered, but only the most viable cost-effective approach is desired. Also, customers of these systems are moving away from Military Standard or Government specified equipment, more often they are requiring the use of Commercial Off The Shelf (COTS) products in the development of their systems, which in many cases allows the customer to obtain a quality system for a much lower cost. When COTS products are used, it will be necessary to choose the best candidate product from several products on the market.

In my research on Trade-Off Analyses, my references only provide high level guidance in preparing Trade-Off Analyses, by describing the various tables and graphs required for the Trade-Off Analysis report. The difficulty with this is that it does not provide the necessary detail required to prepare the Trade-Off Analysis tables or graphs, nor do they provide sample Trade-Off Analysis reports or suggest a data repository where previously performed Trade-Off Analyses are available to use as guidance. After inquiring about the Trade-Off Analysis repository, the Process Group began to gather Trade-Off Analysis reports from previous programs in an effort to build a repository, but these were not consistent and did not appear to completely follow the current processes. Engineers expend a great deal of time and effort determining how to evaluate criteria and how to create the required components of a Trade-Off Analysis.

We as engineers don't have the luxury of picking up a book or magazine with reviews and product comparisons, such as PC Magazine, Consumer Reports or Edmunds. If we are able to find previously performed reviews or product comparisons, the results do not reflect what is actually important to us – some or all of our evaluation criteria were not used in the comparisons. Much of what we do is unique; we need a way to evaluate products according to what's important to our customers and us.

CHAPTER III.

TRADE-OFF ANALYSIS

As a method for formal decision analysis, Trade-Off Analyses can be used to solve any complex problem where there is more than one selection criterion, and provide documented decision rationale for review by a higher authority. These analyses are equally necessary for establishing system configurations and for accomplishing detailed design of individual components. The Trade-Off Analysis method is equally applicable to budgeting, source selection, test planning, logistics development, production control, and design synthesis.

Engineers, whether engaged in research, design, development, construction, operations, or a synthesis of these activities, are concerned with the efficient use of limited resources. When known opportunities fail to hold sufficient promise for the employment of resources, more promising opportunities are sought. This view accompanied by initiative leads to exploratory activities aimed at finding the better opportunities. In such activities, steps are taken into the unknown to find new possibilities that may then be evaluated to determine if they could be superior to those now known (Blanchard et al., 1997).

Trade-Off Analyses provide a standard method to use in evaluating and documenting the relative merits of specific technologies, design configurations, components and material selection, manufacturing process selection, etc. The goal is to quantitatively support selection of the best approach to satisfying requirements while maintaining a balanced design, as defined by the customer. They evaluate alternative solutions in order to narrow the list of candidates and ultimately select an optimum or balanced solution. The Trade-Off Analysis method may be tailored to a project's needs, especially for: criteria, solutions, cycle-time, and cost (Raytheon 1997).

Trade-Off Analyses are performed throughout the design and development process to select the design approach that best satisfies program requirements, and document the reason for the selection. The best design is achieved after iterating the design, based upon the results of Trade-Off Analyses that consider all reasonable design approaches. Trade-Off Analyses are equally necessary for establishing each level of the system design (Raytheon 1999).

The principal benefit derived from Trade-Off Analyses is twofold. First and formost, the use of Trade-Off Analyses forces the designer to consider multiple approaches to the problem and helps to avoid the tendency to go directly to a point-design. Second, the Trade-Off Analysis provides the supporting data necessary to enable a meaningful evaluation of the design. The overall result should be the selection of the best approach a higher percentage of the time and an implementation that best satisfies the overall program requirements of cost, schedule, performance, risk, and producibility (Raytheon 1999).

The role of Trade-Off Analyses evolves with the phases of the program. During the Concept Development and Functional Design phases, a primary focus of Trade-Off Analyses is to establish the system configuration. During the Detail Design phase, Trade-Off Analyses are employed in the detailed design of individual configuration items to determine the most cost-effective designs. As the design enters the implementation phase, Trade-Off Analyses support make-or-buy, process, rate, and location decisions and the evaluation of design changes (Raytheon 1999).

Trade-Off Analyses can be performed in the order of hours to months and even years depending on the complexity of the problem to be solved. The systems engineer has the responsibility for defining the scope of the effort based on the customer's expectations, time & budget available, and resources required.

All data is captured and recorded in a final report. This is important for two fundamental reasons: it is a mechanism for communicating the results and recommendations of the Trade-Off Analysis and most importantly it provides a decision history for the product development process. This allows for later modification of the Trade-Off Analysis results and recommendations if key assumptions, models, requirements, or criteria change.

It is important that the engineer performing the Trade-Off Analysis include subject matter experts, the customer(s), and supplier(s). It is the responsibility of the engineer to ensure that the individuals affecting and affected by the Trade-Off Analysis be involved throughout its execution.

In order to ensure that a rational and unbiased selection is made, a structured process is employed. Section 3.1 illustrates the steps required to complete a Trade-Off Analysis. The study objectives and the evaluation criteria are defined based on the overall program and performance requirements. Weights for each criterion are then assigned based on program priorities to obtain a weighted score for each candidate. Candidate approaches are defined, followed by evaluation of the performance of each candidate. The resulting data is entered into the trade table. Each candidate is assigned a performance score for each evaluation criterion. A sensitivity analysis is then performed to assess the sensitivity of each candidate to small changes in its performance or in the requirements. This information is used to further adjust the candidate performances and to assess the robustness of the scores.

The best candidate is selected based on the final weighted scores, and the adverse consequences of selecting that candidate are examined to ensure that the program will not be detrimentally affected by its selection. If the candidate is acceptable, it becomes the baseline approach and the Trade-Off Analysis is documented in a report. If the candidate is not acceptable, it is discarded, after documenting the results, and the remaining candidates are reconsidered.

It is best to structure the Trade-Off Analyses to reduce their complexity to the lowest practical level. This allows enough information for decision support. Large Trade-Off Analyses should be broken into a number of smaller ones to reduce the number of combinations of performance that must be considered. As with most things, it is best to have a number of simple trade-offs rather than one large, complex one.

Trade-Off Analyses are the vehicles for evolving cost-reductions strategies and mitigating program risks (Michaels et al., 1989).

3.1 Trade-Off Analysis Process

The Trade-Off Analyses process is necessary to ensure that all of the required, necessary, and appropriate steps are accomplished. Prior to attempting a Trade-Off Analysis, it must be determine that there is a genuine valid need for a Trade-Off Analysis effort. Unless there is a real need, the effort may be futile and wasteful.

Briefly the Trade-Off Analyses process may be described as follows and in detail in the following sections. The Trade-Off Analysis objectives and the evaluation criteria are defined based on the overall project and performance requirements. Weights for each criterion are then assigned based on project priorities to obtain a weighted score for each candidate. Candidate approaches are defined, followed by evaluation of performance of each candidate. Each candidate is assigned a performance score for each evaluation criterion. The resulting data is entered into the trade table. A sensitivity analysis is then performed to assess the sensitivity of each candidate to small changes in its performance or in the requirements. This information is used to further adjust the candidate performance and to assess the robustness of the scores. The best candidate is selected based on the final weighted scores, and the adverse consequences of selecting that candidate are examined to ensure that the project will not be detrimentally affected by its selection. If the candidate is acceptable, it becomes the baseline approach and the Trade-Off Analysis is document in a report. If the candidate is not acceptable, it is discarded, after documenting the results, and the remaining candidates are considered.

All data is captured and recorded in a final report. This is important for two fundamental reasons: it is a mechanism for communicating the results and recommendations of the Trade-Off Analysis and most importantly it provides a decision history for the product development process. This allows for later modification of the Trade-Off Analysis results and recommendations if key assumptions, models, requirements, or criteria change (Raytheon 1997).

The result is the design approach that best satisfies the overall project requirements of cost, schedule, performance, risk, and producibility.

3.1.1 TOA Process Phases

Phase 1 - Planning

1. When a Trade-Off Analysis is required by the SEMP (or equivalent), the IPT must review the Trade-Off Analysis requirements expressed by the SEMP with other potentially affected IPTs to ensure that the expectations established are properly interpreted and applied. If there is any possibility of an inadequate understanding of customer requirements or priorities, these must be resolved prior to planning the Trade-Off Analysis. This is a critical step since it aligns everyone to the same goal and provides the bounds within which the Trade-Off Analysis will be performed.

2. A Trade-Off Analysis Kick-Off Meeting is used to communicate the need for the Trade-Off Analysis among the stakeholders and other key personnel. If there is any possibility of an inadequate understanding of customer requirements or priorities, these must be resolved prior to planning the Trade-Off Analysis. This is a critical step since it aligns everyone to the same goal and provides the bounds within which the Trade-Off Analysis will be performed.

3. Create a Trade-Off Analysis plan based on the understanding of the problem to be addressed. The plan must include a schedule of events in the performance of the Trade-Off Analysis, a Budget, and other required resources (e.g., computational resources, models and prototypes, test equipment, subject-matter experts, etc.)

Phase 2 - Perform Trade -Off Analysis Phase

1. Define The Problem. The Trade-Off Analysis standard method begins by defining the problem. Define the need, the user, and the availability of resources bounding the scope of the analysis. Constraints that apply to the Trade-Off Analysis must be identified including budget and schedule. If the Trade-Off Analysis is associated with a deficiency in meeting specific requirements, then that deficiency should also be stated along with other related requirements, which could be affected by the Trade-Off Analysis.

2. Establish Evaluation Criteria. This step defines the set of evaluation criteria on which the Trade-Off Analysis is based. The evaluation criteria reflect all of the technical and programmatic requirements of the product, which could be impacted by the study. The evaluation criteria should be traceable to a program document. For each of the evaluation criteria a corresponding system impact is identified.

3. Weight the Criteria. This step weights the evaluation criteria in terms of relative importance, in accordance with the customers' priorities.

4. Identify Alternative Solutions. This step identifies the set of alternate solutions to be considered in the Trade-Off Analysis. These alternate solutions will be predetermined (in the case of a design competition, they will be the various proposed designs) or developed specifically for the analysis. Alternate solutions should reflect the widest possible range of distinctly different solutions in order for the overall goal of optimized design to be achieved.

5. The set of alternate solutions that are subjected to the full analysis may go through a process of elimination that considers ability to solve the problem, affordability, technology or other screening criteria established by the IPT.

6. The IPT defines the set of subject matter experts needed to brainstorm a set of candidate solutions.

7. Quantify the Evaluation Criteria. This step ensures that each of the evaluation criteria is quantified and quantifiable. For evaluation criteria that have their origins in the product specification, they should already be stated in quantifiable terms as represented in those requirements. The criteria will include quantitative goals and thresholds (specification limits) beyond which the characteristic is unsatisfactory.

8. However, evaluation criteria for which quantitative data is not available, any qualitative data is converted into quantitative data via a rating scale developed by the IPT conducting the Trade-Off Analysis.

9. Develop Criteria Evaluation Functions. This step identifies models to apply in characterizing each alternative solution based on the evaluation criteria. The models/functions selected represent the fidelity necessary to distinguish among competing alternatives. These models provide the characteristics for each alternate solution as required based on the constrains previously defined (e.g., schedule, budget, customer expectations, etc.) .

10. Prepare Utility Functions. This step calculates a parameter used to account for non-linearities in the benefit derived from improvements to a given Evaluation Criteria . Most parameters have a utility function value of 1. This technique allows for the translation of diverse criteria to a common scale (0-1) for direct comparison.

11. Evaluate Alternatives. This step consists of doing the mathematical evaluation of the Evaluation Criteria using the evaluation functions and applying the weights to arrive at an initial cumulative assessment of each Trade-Off Analysis alternative.

12. Performance estimates/predictions are produced by evaluators from testing, vendor sources, parametric analysis, simulation, experience or other available, affordable, and dependable methods.

13. Perform Sensitivity Analysis. This step determines the sensitivity of the Trade-Off Analysis selection to the specific weighting of the selection criteria and the selection criteria itself.

14. Where the total weighted scores of several alternatives are proximate, a small change in the estimated/predicted performance or weight of any alternative against any criterion may change the decision.

15. Perform Risk Analysis. Risk analysis is performed to identify potential risks associated with the Trade-Off Analysis results and recommendations.

<u>Phase 3 - Prepare Report Phase</u>

1. Generate a Trade-Off Analysis report at the conclusion of the last step of the Trade-Off Analysis process and placed under configuration management/distribution control. This report must include all the data generated at each step with associated assumptions, rationale, and sources. The Trade-Off Analysis report shall conform to the Trade-Off Analysis Report format.

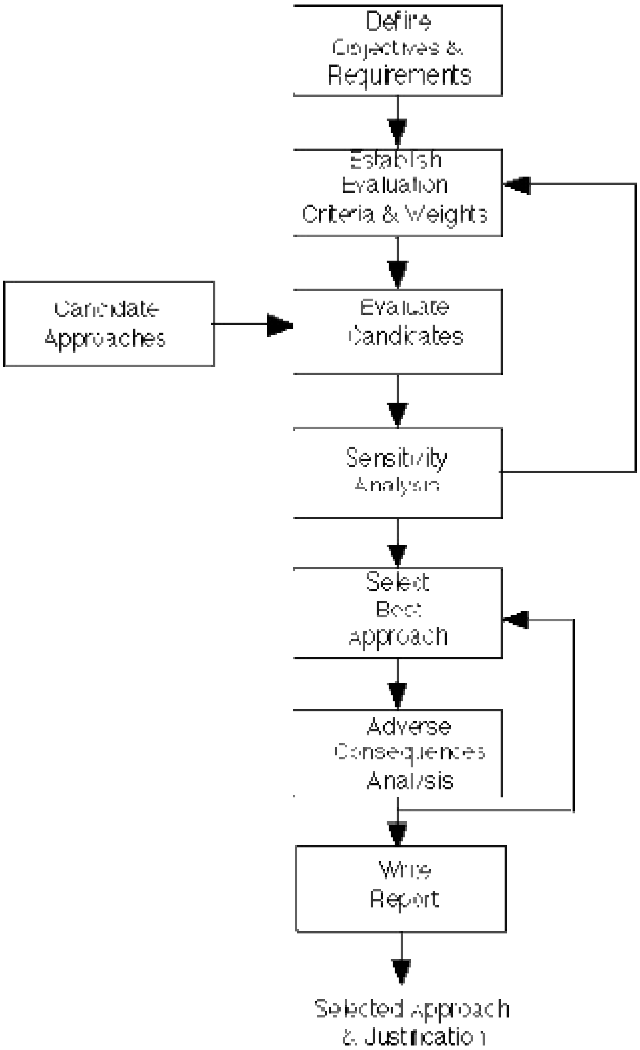
2. Review the report within the IPT (including any customers or suppliers). Distribute finale copies of the report and place in the integrated database.

Phase 4 - Follow-On

1. If the Trade-Off Analysis results are inconclusive or there is not enough data to make a decision within acceptable levels of risk, re-evaluate the Trade-Off Analysis approach, identify weaknesses and replan to resolve.

2. If the customer rejects the results and recommendations, summarize the rationale for rejection.

Figure 1 - Trade-Off Analysis Process Major Components



3.1.2 Trade-Off Analysis Kick-Off Meeting

The Trade-Off Analysis Kick-Off Meeting is a focused and structured initial brainstorming activity that consists of a Design Team or Working Group. Follow-up brainstorming sessions are conducted as deemed necessary by the design team. The meeting participants consist of a facilitator (specialist trained in facilitation and in the methodologies of Trade-Off Analyses), specifically identified stakeholders (customers, suppliers, program management, engineering, etc.) domain experts, departmental experts and experts from various disciplines. It is the responsibility of the technical lead to ensure that the individuals affecting and affected by the Trade-Off Analysis be involved throughout its execution. The brainstorming session creates a vast set of options from "very simple" to "state of the art." The goal is to generate ideas that provide the most efficient and cost-effective solution. During the kick-off meeting, it may be revealed that there is only one worthwhile solution, in which case there is no need to proceed with the complete Trade-Off Analysis. If this is the case, the results of the meeting are documented in the Trade-Off Analysis report.

During the Trade-Off Analysis Kick-Off Meeting, several candidate solutions will be generated. Of these solutions, the most practical candidates are selected to be included in the Trade-Off Analysis. Discarded candidates are documented in the Trade-Off Analysis report as being discarded and why.

Since the group of participants is engaged in a focused and structured dialogue, the brainstorming sessions provide the framework for a real and deep understanding of the situation that is under consideration. The people engaged in the brainstorming activity are exposed to a real sharing of ideas and information, and thus are actively learning about the issue at hand. Because of the fact that the definition of the situation, the design, and choice of alternatives are made participatively, the decisions taken by the group are their own decisions; only through this kind of approach can a genuine commitment be achieved. In turn this commitment leads to a better basis for the implementation of the decision within the organization (Warfield 1990).

3.1.2.1 Stakeholder Responsibilities

Along with participating in brainstorming sessions, the following responsibilities also apply.

Technical Lead:

- Review Lessons Learned from previous, similar Trade-Off Analyses for relevance to the present Trade-Off Analysis.
- Capture Lessons Learned in the performance of the present Trade-Off Analysis.
- Tailor the Common Trade-Off Analysis process with cooperation from process owners to the unique aspects of the program using the common process tailoring process.
- Plan for the use of Trade-Off Analyses to meet contract and engineering requirements.
- Prepare a Trade-Off Analysis Report tailored to the program/customer.

- IPTs apply Trade-Off Analyses at any time during a product life cycle as part of the program plan, in response to an identified problem, or changed conditions.

Functional Organization:

- Train personnel in the Trade-Off Analysis process.
- Provide skilled resources when needed by the IPT.

Project Configuration Management:

- Places the Trade-Off Analysis report under configuration control, and manages changes to it during the remainder of the program.

Process Owners:

- Collect and report metrics for Trade-Off Analysis process performance.
- Capture and report Lessons Learned as change requests to the common Trade-Off Analysis process.
- Document a follow-up report to the original to provide the rationale for rejecting the results and recommendations when Trade-Off Analysis results and recommendations are not adopted or implemented.

Program Managers:

- Provide budget to perform planned Trade-Off Analyses.
- Include Trade-Off Analysis results in Technical Performance Measures.

3.2 Trade-Off Analysis Objective

The Trade-Off Analysis objective must be expressed in precise, explicit terms to serve as the basis for sound decisions. They should define the need, the user, and the availability of resources bounding the scope of the analysis. The source for these objectives will be requirements and design documents. This will provide a firm foundation for identifying the range of alternatives and the decision criteria.

The Trade-Off Analysis begins by defining the problem. Define the need, the user, and the availability of resources bounding the scope of the analysis. Constraints that apply to the Trade-Off Analysis must be identified including budget and schedule. If the Trade-Off Analysis is associated with a deficiency in meeting specific requirements, then that deficiency should also be stated along with other related requirements, which could be affected by the Trade-Off Analysis (Raytheon 1997).

This step identifies the system configuration or critical item that is the subject of the Trade-Off Analysis. It includes the objective of the Trade-Off Analysis or a statement of the problem to be addressed and must be expressed in precise, explicit terms to serve as the basis for a sound decision. Identification of the specific requirements being addressed helps to narrow the scope of the study. This step is accomplished by key personnel on the program as a result of their efforts to define the system configuration or critical item implementation. They should define the need, the user, and the availability of resources that bound the scope of the analysis. When defining the objective of the Trade-Off Analysis, the Systems Engineer must determine the root of the problem being addressed (Raytheon 1999).

It is best to structure the Trade-Off Analyses to reduce their complexity to the lowest practical level. This allows enough information for decision support. Large Trade-Off Analyses should be broken into a number of smaller ones to reduce the number of combinations of performance that must be considered. As with most things, it is best to have a number of simple trade-offs rather than one large, complex one (Raytheon 1999).

3.3 Candidate Approaches

Alternatives for consideration will be either predetermined (in the case of a design competition, they will be the various proposed designs) or developed specifically for the analysis. Candidates may be the product of systems engineering synthesis activities and represent existing (standard), modified, or original designs. Candidates should reflect the widest possible range of distinctly different solutions if the overall goal of optimized systems design is to be achieved.

Next, candidates identified through unconstrained synthesis or brainstorming may be screened based on their ability to solve the problem. This ensures that the analysis effort does not waste time on nonproductive solutions. A second screening may be performed on the basis of attainability/affordability, where the candidate solutions are achievable within time and budgetary constraints.

Remaining candidates become the decision alternatives. These alternatives are described fully and carefully. Sufficient detail must be available to judge the relative worth of each workable, attainable alternative. If an insufficient number of candidates survives the screening process, the study constraints should be reexamined and all candidates rescreened, or the synthesis and possibility functional analysis activity must be reinitiated.

Quite often, the candidates have been defined before the trade study begins. There is no magic way to select the candidates for a trade study. Some methods which engineers normally use singly or in combination are listed below:

- Experience with similar problems
- Consultation with senior personnel in the division
- Consultation with experts outside the division
- Researching the problem in books, journals, etc.

3. Studying the problem, being creative and inventive

   - Brainstorming
   - Soliciting proposals from companies who claim to have a solution

All feasible approaches within reason should be considered. They should reflect the widest possible range of distinctly different solutions if the overall goal of identifying the best system design which meets requirements is to be achieved. Candidates identified through unconstrained synthesis or brainstorming should be screened based on their ability to solve the problem. This ensures that the analysis effort does not waste time on nonproductive solutions. A second screening should be performed on the basis of attainability and affordability. Are the candidate solutions achievable within time and budgetary constraints?

The sensitivity of the criteria that were used to eliminate any approach should be checked to ensure that candidates are not wrongly eliminated at this point. If an insufficient number of candidates survives the screening process, the study constraints should be reexamined and all candidates re-screened, or the design synthesis and possibly the functional analysis activity must be reinitiated (Raytheon 1999).

3.4 Evaluation Criteria

This step in the process is to generate ideas. The idea set that is desired is a set of Evaluation Criteria. These Criteria will be used as part of a systematic approach to the choice of a single Alternative. This set may be developed through brainstorming or other methods that produce ideas in response to a suitable overview or triggering question (Warfield 1990).

Criteria may be of two types: standard and non-standard. The standard criteria are those for which numbers are available that arise from a process of enumeration against accepted standards. For example, cost in dollars, area in acres, board-feet of timber, inches of topsoil, length of an artifact, number of horsepower, etc. The non-standard criteria are those criteria for which no suitable, accepted standard exists (Warfield 1990).

The non-standard criteria may be of two types: quantifiable and non-quantifiable. The former are those for which numerical values can be attained that reflect subjective opinion on a scale. The latter are those for which numerical values do not appear to have significance on any interpretable scale (Warfield 1990).

Then the criteria also can be said to fall into two other types: quantifiable and non-quantifiable. The former include both the standard criteria and the non-standard criteria which can be suitably quantified (Warfield 1990).

Evaluation Criteria are standards for judging achievement of required operational effectiveness/suitability characteristics, or resolution of technical or operational issues. The criteria may include quantitative goals (desired value of the attribute), where possible, and thresholds beyond which the characteristic is unsatisfactory (specification limits). Good evaluation criteria must .

1. Differentiate meaningfully between alternatives without bias.
2. Relate directly to the purpose of the Trade-Off Analysis, including established requirements and high-interest concerns.
3. Be stated as broadly as possible.
4. Be able to be measured or estimated at reasonable cost.
5. Be independent of each other at all levels.
6. Be universally understood by evaluators.

Evaluation criteria may be drawn from systems engineering documentation based on program requirements; military and department guidance and standards; and design-for and specialty requirements. These sources vary in importance based on the stage of program development and design maturity. Regardless of the sources used and the advice obtained, final selection must be made by the decision-maker. The value of the Trade-Off Analysis effort is proportional to the decision-maker's ability and willingness to include all objective and subjective decision criteria. Regular, efficient guidance on appropriate decision criteria is one of the primary products of the systems engineering organization.

The evaluation criteria against which the candidates will be traded off must be identified and listed in the trade table. They must be pertinent to the trade study, quantified whenever possible, and based on the program requirements and the performance specifications. The use of a "high, medium, low" type assessment should be minimized. The value of the trade-off analysis effort is proportional to the ability and willingness to include all objective and subjective decision criteria. Good evaluation criteria must (Raytheon 1999):

1. Differentiate meaningfully between alternatives without bias

2. Relate directly to the purpose of the trade-off analysis, including established requirements and high-interest concerns

3. Be stated as specifically as possible

4. Be able to be measured or estimated within reasonable cost, schedule, and performance

5. Be independent of each other at all levels to a reasonable extent

6. Be universally understood by the evaluators

3.4.1 Typical Evaluation Criteria

The evaluation criteria used for conducting a Trade-Off Analysis will depend to a great extent on the particular problem under study. While the evaluation of cost, schedule, and performance must always be considered, the operational performance evaluation criteria will be unique to each study. Parameters should be selected that are neither so broad that their sensitivity is masked by a large number of inputs, nor so narrow that the list becomes to long (Raytheon 1999).

Evaluation Criteria may either be Predefined or Newly Defined for a particular Trade-Off Analysis. Categorized below are various types of evaluation criteria. This listing may serve as stimulus in developing other evaluation criteria. It is also a good idea to capture the exact definition or interpretation for a particular evaluation criterion being used in a specific Trade-Off Analysis. Many of the Common Evaluation Criteria in Table 1 below are defined in Appendix A.

Table 1 – Common Evaluation Criteria

Programmatic
- Cost
- Initial Cost
- Life Cycle Cost
- Maturity of the Technology
- Reputable Vendor
- Preferred Vendor
- Recommended Vendor
- Risk
- Schedule
- Acceptable Delivery

Hardware
- Cooling Requirements
- Environmental Requirements
- Electrostatic Discharge Sensitivity
- Heat Dissipation
- Memory Constraints
- Power Consumption
- Producibility
- Shape
- Size
- Storage Life
- Volume
- Weight
- Ease of Upgrade
- Upgradability

Hardware Performance
- Accuracy
- Bus Loading
- Data Integrity
- Response Time
- Throughput

Specialty
- Reliablility & Maintainability
- Availability
- Maintainablity
- Reliability
- Mea Time Between Failure (MTBF)
- Meat Time To Replacement (MTTR)
- Human Factors
- Safety
- Operator
- Operability
- Operator Interface
- Obsolescence Analysis

Development & Program Support
- Documentation Support
- Technical Manual/Users Guide
- Sustainment Planning
- Sustaining Engineering
- Logistics
- Government Property Management
- Logistic Services
- Spares Analysis
- Operations & Maintenence
- End-User Training Development

Software
- Size
- Ease of Upgrade
- Upgradability

Software Performance
- Accuracy
- Bus Loading
- Data Integrity
- Response Time
- Throughput

System Performance
- Accuracy
- Bus Loading
- Data Integrity
- Response Time
- Throughput

3.4.2 Weighting Evaluation Criteria

The Evaluation Criteria are weighted by the Trade-Off Analysis Team according to their relative importance in determining the effectiveness of alternatives. To ensure the objectivity of the subsequent analysis, weighting factors developed by the Trade-Off Analysis Team may be withheld from the analysts who do the performance evaluation.

Weighting follows a logical breakdown such as the one illustrated in Figure 8-5 for a ship design program. Essentially, the numerical scale used is coincidental, provided that it is consistently distributed down the criteria tree. In contribution to mission capability including speed/endurance, logistics, cargo capacity, safety, and cargo capability. First, effectiveness measures are examined for their contribution to objectives for the system; then each criterion is weighted according to its perceived contribution to the effectiveness measures. The extent of the breakdown required is determined by:

- The level at which performance evaluation is possible.
- The level at which separate performance specifications have been established.

Numerical weights are given to reduce the effect of evaluator bias on the analysis. Numerical weighting allows the Trade-Off Analysis Team to obtain an objective assessment of the alternatives. In addition, numerical treatment facilitates comparison among criteria that are not related. For instance, in this example, cargo capacity is twice as important as speed capability. The advantages in relative simplicity, efficiency, and objectivity of this approach far exceed the effort required to assign numerical weights. Decision makers who claim that they cannot assign numerical weights to the criteria should realize that decisions are based on quantified criteria whether that quantification is subconscious (therefore, unsystematic and undocumentable) or objective/numerical (therefore, systematic and documentable).

Where a program maintains an overall system effectiveness model and has operational data, this weighting process can be very objective. In cases where such a foundation is not available, decision support techniques can be used to render subjective evaluations more reliable. The analytic hierarchy process sets criteria weights using a paired comparison technique. Engineers and managers from the design team were asked to prepare data input sheets that compared attributes at each level on a one-to-one basis. A typical input sheet is shown in Table 2. Data were entered into a computer for analysis, consolidation, and normalization into matrix form. The mathematical technique of eigenvector analysis was then applied to the normalized matrix to determine the relative weightings of all components at each level. Once the weighting factors of all elements of hierarchy were derived, the "contributing weight" of any one attribute could be calculated by multiplying the weights of its associated category headings by its weighting factor. Data from respondents were summarized and, with minor adjustments, resulted in the priorities shown in Table 5. This technique of paired comparisons has been shown to give more repeatable weighting than direct estimation of the relative attribute priorities.

Once the evaluation criteria have been defined, they are weighted according to their relative importance in determining the effectiveness of the candidates. This ensures that the most important attributes have the most influence on the decision. In order to increase the objectivity of the candidate performance scoring, these weights are applied after the raw scores have been assigned, but before adjustments are made in the candidate performance or the system requirements to optimize the scores. The relative importance of the evaluation criteria should be given to the systems engineers prior to the study as an aid in structuring the trade study.

The numerical scale used in weighting is coincidental, provided that it is consistently distributed. While it is not a necessity that the weights add up to a value of 100, it makes for simpler evaluations. Weighting is necessary, since decisions are based on quantified criteria, whether that quantification is subconscious (therefore, unsystematic and undocumentable) or conscious (therefore, systematic and documentable).

Where a program maintains an overall system effectiveness model and has operational data, this weighting process can be very objective. In cases where such a foundation is not available, two approaches may be used. In the first approach the engineers and managers who are aware of the relative importance of the requirements discuss the evaluation criteria and assign the weights directly based on their perceptions. This approach can be made more rigorous by applying Quality Function Deployment techniques. QFD is a process for discovery and estimation of the relative "worth" and costs of different attributes of an object. The process is formalized to remove as much individual bias as possible. The output of a QFD analysis will produce the weights needed for the trade study.

The second approach is more time consuming, but is also more reliable and repeatable. The analytic hierarchy process is used to calculate the weights using a paired comparison technique. Key engineers and managers evaluate pairs of attributes at each level on a ranking chart.

3.4.2.1 Calculating Weights Using Paired Comparison

Estimating the weights for the evaluation criteria in the trade table may be mechanized using a technique that compares the relative value of each combination of evaluation criteria taken two at a time. This section describes a method for estimating the weights and for calculating the consistency of the estimate.

The first step is to construct a ranking chart with all paired combinations of the evaluation criteria. Next, those engineers and managers who have the best insight into the relative importance of the criteria pick the more important of each pair and rank the relative preference of the one selected on a scale of 1 to 9. Whenever possible, the customer technical and user personnel should also be used to rank the criteria for which they have unique experience. The scale shows the relative preference of one criterion over the other as follows:

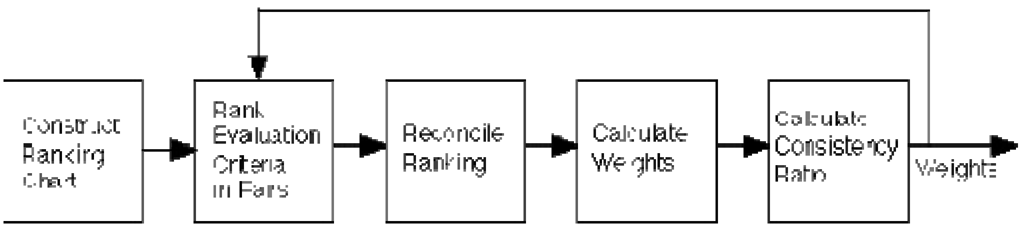
1 - The two criteria are approximately equal.

2 - The selected criterion is twice as important.

3 - through 9 - The selected criterion is 3, 4, 5, etc., times as important.

The scale may be adjusted if a small range of values is required and intermediate values may be used. For example, a scale of 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5 may be used.

Figure 2 – Paired Comparison Calculating Weights



The pair ranking estimates should be reconciled to attempt to arrive at a common estimate for each pair of criteria. This may be accomplished by discussion among the participants, or the Delphi process may be used. The Delphi process is designed to produce a more accurate result by avoiding peer pressure when all the participants are equally knowledgeable. Group discussions are quicker and work better when the participants are not equally knowledgeable and exchange of information is desirable.

It is usually not possible to arrive at a complete consensus and the ranking estimates will have to be averaged. Since the 9 to 1 to 9 scale is non-linear, it should be temporarily converted to a linear scale from 1 to 17; the scores should be averaged and the result converted back to the 9 to 1 to 9 scale.

The next step is to form a matrix using the pair ranking estimates from the ranking chart. The mathematical technique of eigenvector analysis can be applied to a normalized matrix of data values to determine the relative weighting factors of all components at each level. The Systems Engineering Management Guide published by the Defense Systems Management College provides a good description of this process.

During the Trade-Off Analysis Kick-Off meeting or another brainstorming session, several evaluation criteria are established. These evaluation criteria are placed in a table similar to Table 2 and members of the Trade-Off Analysis Team are surveyed - asked to rank the criteria according to importance. In order to eliminate influence among the Trade-Off Analysis Team members, this ranking is done individually. Depending on the scope of the Trade-Off Analysis, the logistics and size of the Trade-Off Analysis Team, and the Trade-Off Analysis Schedule, the individual ranking survey may be accomplished during the current meeting or accomplished individually and returned to the Trade-Off Analysis Team Leader at a specified later date.

The ranking scheme used is from 0 – 100 %, 1 % being least important and 100 % being most important. If a criterion has no impact its ranking is 0 %. After ranking all criteria the total of all criteria is $\cong$ 100 %.

A statement of Rationale for Criteria Weight should be entered on the surveys by the individual evaluators. This rationale explains why a score/weight was given to a particular criterion. These rationale statements may then be compared when the final consolidated weighted criteria is complete and an overall rationale statement may be written for each criteria in the final list.

Table 2 – Criteria Evaluation Survey

Weight	*Criteria*	*Description*	*Rationale for Criteria Weight*
	Architecture Cost	Includes all cost related to utilizing the specific architecture option (i.e. integration of existing control software, SDDS ports, SDN ports, shipping, site integration, hardware and software maintenance costs).	
	Product Quality	Total BER performance in the complete signal path of the specific architecture option.	
	Schedule Risk	The dependency of the specific architecture option on the delivery schedules of SDDS, DSMs, and cabling.	
	Product Quantity	The impact to the number of tapes made per day for the specific architecture option and whether the high volume SPS users are affected.	
	Single Point Of Failure	The amount of recording capability lost for the specific architecture option.	
	Architecture Transition Support	The capability of each architecture option to use any DCR function for any purpose within the system.	
	Availability	The amount of additional downtime experienced within a year due to the specific architecture option.	
	Operator Impacts	Distance of equipment or controls, more/fewer commands required, more/fewer displays (i.e. the addition of the DSM has increased the number of displays/windows).	
	Facilities Impacts	Floor space, cabinet space, power, and environmental conditions.	
	Software Control Complexity	Complexity of the architecture control scheme of controlling resources limited to the complexity of the task and not any other characteristic (e.g. SLOC) that translate directly to colst.	
	Fault Diagnosis Fault Detection	Percent of connection status logged. How to track a TFR (caused by data routing) that may be a month old. Whether failure logging is accessible to maintenance personnel. If software is required ensuring that such logging is available for all switches in the specific architecture option. Whether fault detection blind spots exist due to the specific architecture option.	
	Industry Standard Compliance	Compliance with hardware and software development standards.	
100	***Total***		

Once the evaluation criteria ranking surveys are received or the evaluation criteria survey deadline has passed, the received results may be entered into a table similar to Table 3. Letters are used to provide evaluator anonymity during this phase of the Trade-Off Analysis. Only the Trade-Off Analysis Leader should have the record of names corresponding to the letters given in the Evaluation Criteria Ranking Survey Table. Various statistical and mathematical methods may be used to test for abnormalities or bias tendencies in the rankings. For example, evaluator F in Table 3 appears to have a strong bias towards Cost (69) and Schedule (20) and considers all other criteria to have the least value (1). In order to eliminate these extremes, the highest and lowest values of each category can be thrown out in order to remove these biases instead of completely throwing out evaluator F as shown Table 4.

Table 3 – Evaluation Criteria Ranking Survey Initial Results

Evaluation Criteria	Evaluators										
	A	B	C	D	E	F	G	H	Avg	Var	Std Dev
Architecture Cost	12	5	10	15	6	69	19		19.43	430	21
Product Quality	10	15	13	10	16	1	15		11.43	23	5
Schedule Risk	12	0	8	10	10	20	7		9.57	31	6
Product Quantity	10	5	13	10	13	1	12		9.14	18	4
Single Point Of Failure	10	15	5	10	8	1	7		8	17	4
Architecture Transition Support	6	0	5	15	6	1	12		6.43	25	5
Availability	10	15	5	5	8	1	0		6.29	23	5
Operator Impacts	6	10	12	5	6	1	4		6.29	12	3
Facilities Impacts	2	10	12	5	6	1	4		5.71	14	4
Software Control Complexity	4	0	4	10	7	1	12		5.43	17	4
Fault Diagnosis	6	10	10	3	3	1	4		5.29	11	3
Fault Detection	8	10	0	0	10	1	4		4.71	18	4
Industry Standard Compliance	4	5	3	2	1	1	0		2.29	3	2
Total	100	100	100	100	100	100	100	0	100.01		

Table 4 – Anti-Bias Evaluation Criteria Ranking Survey

	Evaluators										
	A	B	C	D	E	F	G	H	Avg	Var	Std Dev
Architecture Cost	12		10	15	6		19		12.4	19	4
Product Quality	10	15	13	10			15		12.6	5	2
Schedule Risk	12		8	10	10		7		9.4	3	2
Product Quantity	10	5	13	10			12		10	8	3
Single Point Of Failure	10		5	10	8		7		8	4	2
Architecture Transition Support	6		5		6	1	12		6	12	4
Availability	10		5	5	8		0		5.6	11	3
Operator Impacts	6	10		5	6		4		6.2	4	2
Facilities Impacts	2	10		5	6		4		5.4	7	3
Software Control Complexity	4		4	10	7	1			5.2	9	3
Fault Diagnosis	6	10		3	3		4		5.2	7	3
Fault Detection	8	10	0			1	4		4.6	15	4
Industry Standard Compliance	4	5	3	2	1	1	0		2.29	3	2
Total	100	65	66	85	61	4	88	0	92.89		

During the preparation and data gathering stage, prior to the performance evaluation phase, certain criteria may be determined as non-discriminating or may be considered as part of other evaluation criteria. These evaluation criteria may be discarded and their weight zeroed out. After the weights of the discarded criteria have been removed, the weights must be adjusted in order to achieve a total ranking or $\cong$ 100% again as shown in Table 5.

Table 5 – Final Criteria Evaluation Results

Adjusted Weight	***Avg***	***Criteria***	***Description***	***Rationale for Criteria Weights***
25	19.43	Architecture Cost	Includes all cost related to utilizing the specific architecture option (i.e. integration of existing control software, SDDS ports, SDN ports, shipping, site integration, hardware and soft ware maintenance costs).	
15	11.43	Product Quality	Total BER performance in the complete signal path of the specific architecture option.	
12	9.57	Schedule Risk	The dependency of the specific architecture option on the delivery schedules of SDDS, DSMs, and cabling.	
0	9.14	Product Quantity	The impact to the number of tapes made per day for the specific architecture option and whether the high volume SPS users are affected.	
10	8	Single Point Of Failure	The amount of recording capability lost for the specific architecture option.	
8	6.43	Architecture Transition Support	The capability of each architecture option to use any DCR function for any purpose within the system.	
8	6.29	Availability	The amount of additional downtime experienced within a year due to the specific architecture option.	
8	6.29	Operator Impacts	Distance of equipment or controls, more/fewer commands required, more/fewer displays (i.e. the addition of the DSM has increased the number of displays/windows).	
7	5.71	Facilities Impacts	Floor space, cabinet space, power, and environmental conditions.	
0	5.43	Software Control Complexity	Complexity of the architecture control scheme of controlling resources limited to the complexity of the task and not any other characteristic (e.g. SLOC) that translate directly to colst.	
7	5.29	Fault Diagnosis	Percent of connection status logged. How to track a TFR (caused by data routing) that may be a month old. Whether failure logging is accessible to maintenance personnel. If software is required ensuring that such logging is available for all switches in the specific architecture option.	
0	4.71	Fault Detection	Whether fault detection blind spots exist due to the specific architecture option.	
0	2.29	Industry Standard Compliance	Compliance with hardware and software development standards.	
100	***100.01***	***Total***		

3.5 Evaluating Candidate Performance

The performance for each candidate is evaluated for each criterion and entered into the Trade Table, Table 7.

The performance estimates are developed using analysis, rapid prototyping, simulation, vendor data, actual measurements, engineering estimates, or other affordable and dependable methods. Data from these sources are plotted on utility curves. Utility curves associate the performance of an attribute with a score using graphical or tabular methods.

The table entries should be quantitative whenever possible so that performance can be easily compared to the requirements and subjectivity is reduced. For example, schedules should be developed to the point where a time can be estimated, rather than merely selecting which is longer or shorter. This is necessary in order to check schedule sensitivity; e.g., what if the schedule requirement is changed from 20 to 24 months?

Each of the candidates is scored for each of the evaluation criteria based on the performance that has been entered into the table. The maximum possible score for each evaluation criterion must be identical to prevent inadvertently weighting the scores. Utility curves may be used to provide a convenient means for selecting or adjusting the scores based on performance. Utility curves are discussed in more detail later in this section.

When scoring is done without the benefit of measured data, the uncertainty in the estimate may be significant. In this case a useful technique is to indicate a range of performance values. This may complicate the final selection process, but will give a truer indication of relative worth. An alternative technique is to describe the range as a function and run a Monte Carlo simulation. Monte Carlo simulations use probability distributions for each "assumed" value and produce an output "forecast" value associated with it. This reduces a "what if" scenario into a range of possible outcomes and the likelihood of their achievement by creating a statistical picture.

Every attempt should be made to keep the scores objective. Since the scores will always be at least partly subjective, they should be estimated by several knowledgeable key personnel and a consensus arrived at for the final number.

Once the scores have been assigned, the predetermined weights are entered into the table. The weighted score is determined by multiplying the raw score for each requirement by its weight.

Table 6 – Evaluating Candidate Performance

Cost ($k)	System Integration	Hardware Cost	Cables	Shipping & Installation	Maintenance Cost	Total Cost
Candidate A	500	1000	400	500	400	2800
Candidate B	400	1000	200	500	500	2600
Candidate C	300	1200		700	400	2600

3.5.1 Trade Table

The trade table is the structure into which the data is entered to define the evaluation criteria and the candidates' performance. The trade table is best implemented as a template using a spreadsheet program. This facilitates the sensitivity analysis by allowing rapid computation of scores as a result of postulated performance changes. The trade table is set up to record the following:

- Evaluation criteria
- Relative weights of the evaluation criteria
- Candidate approaches
- Quantitative performance for each candidate's evaluation criterion
- A raw score for each candidate's evaluation criterion, relative to the other alternatives, to quantify the performance of that evaluation criterion
- A weighted score for each candidate's evaluation criterion
- A total weighted score for each candidate

These items are discussed in more detail in the following sections. A sample Trade Table is provided in Table 7.

Table 7 – Trade Table

Evaluation Criteria							Candidates								
			Rqm't Limit				A			B			C		
Item	Description	Rqm't / Limit Type	L_{Max}	L_{Min}	UM	WT	Performance (P)	Utility Score (U)	WTD Score (U x WT)	Performance (P)	Utility Score (U)	WTD Score (U x WT)	Performance (P)	Utility Score (U)	WTD Score (U x WT)
1	Architecture Cost	Range Min	2800	2000	$ k	17	2800	0	0	2000	10	170	2600	2.5	43
2	Architecture Transition Support	Range Max	100	0	%	9	0	0	0	60	6	54	100	10	90
3	Availability	Greater Than	99.5	99.3	%	9	99.3	0	0	99.5	10	90	99.5	10	90
4	Facilities Impacts	Less Than	100		%	6	50	5	30	0	10	60	0	10	60
5	Fault Detection	Greater Than	80	30		0	45	3	0	80	10	0	30	0	0
6	Fault Diagnosis		0			6			0			0			0
7	Industry Standard Compliance								0			0			0
8	Operator Impacts	Less Than	100		%	9	50	5	45	25	7.5	68		10	90
9	Product Quality	Range Min	3E-08	1E-08	BER	18	2.00E-08		0	1.00E-08		0	1.476E-08		0
10	Product Quantity								0			0			0
11	Schedule Risk	Less Than	100	0	Days	13	50	5	65	33.3	6.67	87	33.3	6.67	87
12	Single Point Of Failure	Less Than	100	0	%	12	91.5	0.85	10	52.4	4.76	57	100	0	0
13	Software Control Complexity								0			0			0
14									0			0			0
15									0			0			0
16									0			0			0
17									0			0			0
18									0			0			0
19									0			0			0
20									0			0			0
	Total Weighted Score					99			150.2			585.33			459.21

3.5.2 Modeling Performance Utility

Although not necessary for every Trade-Off Analysis application, utility curves are a good technique for translating diverse criteria to a common scale.

There is a distinction between three approaches to establishing utility scales:

7. Absolute Scaling,
8. Ration Scaling, and
9. Relative Scaling.

Absolute scaling is most desirable, for it assumes that by analysis or initiative, it is possible to conceptualize a “perfect” system and to predict a level of performance with respect to each attribute for each alternative being evaluated.

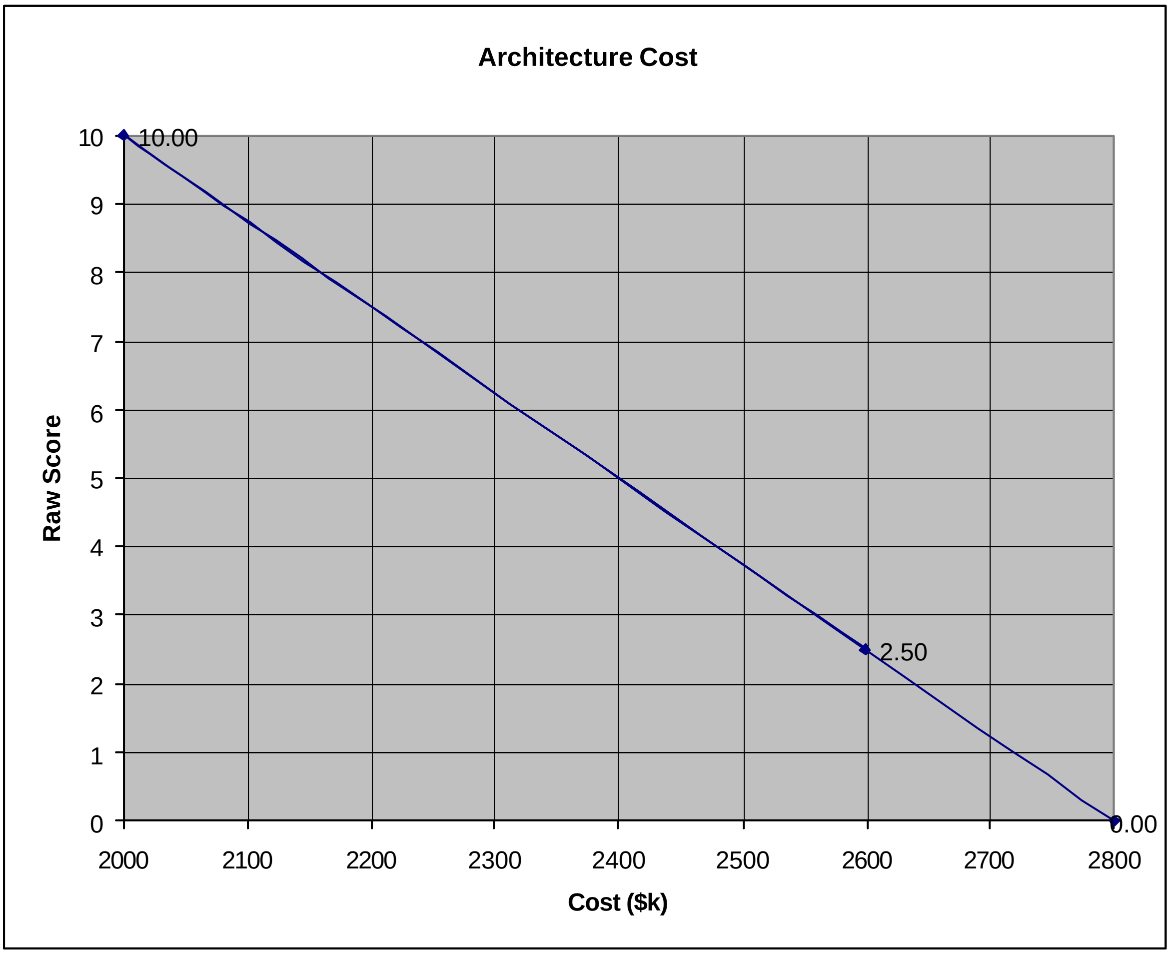
In cases where an attribute is difficult to quantify or measure, the evaluation might establish a ratio scale or use the analytic hierarchy process to establish a relative scale for utility values. The ratio and relative scaling approaches identify the “best” alternative through a structured comparison of alternatives. These approaches are most valuable in considering nontechnical parameters (such as cost, development time, political saleability) where only subjective (high, medium, low) evaluation is possible. For example, if safety was an essential Trade-Off Analysis criterion, if could be included as a relatively scaled attribute using a paired comparison process and scaling methodology.

Utility curves are a technique for translating performance into a numerical score. They also:

- Improve the consistency of scoring between the candidates.
- Provide a means to adjust the score in a controlled manner if the performance is changed.
- During the sensitivity analysis, facilitate adjusting the score based on postulated changes in performance.
- Provide translation of non-linear data into linear space, i.e. a Transfer Function.

Utility curves associate the performance of an attribute with a score using graphical, tabular, or mathematical methods. The score ranges from 0 to 10, with the lower bound on the useful value of an attribute being assigned a score of 0 and the upper bound being assigned a score of 10. Other scales may be used provided they are consistent with other scoring methods used on the program. An example utility curve is illustrated in Figure 3.

Figure 3 – Sample Utility Curve



Utility curves for a given Trade-Off Analysis must use consistent scales (for example, between 0 and 10) so as not to inadvertently weight the scores. These models also must assume the independence of criteria. The "zero point" of each curve indicates the level of performance that no longer provides value to system performance or effectiveness. The zero may be set below minimum acceptable specification values, since minimum acceptable values are usually the cut-off beyond which alternatives are "not worthwhile to pursue," rather than "without value."

Graphic utility curves are not necessary for every criterion. Where linear relationships are assumed between utility and performance, simple tables can be established. Tabular scoring plans could replace graphic charts for any criterion; however, some fixed plan for scoring performance evaluations must be established before the evaluations are conducted.

Developing utility curves has two important benefits. First, it forces the analyst to think seriously about the importance of various levels of performance. This results in a better understanding of the performance benefits and a more accurate scoring rule.

The second benefit is that the scoring rule is documented. This is very important, since the trade study often extends over several days or weeks. If not documented, the analyst's perception of the value of the levels of performance can change over time. The scoring would then not be consistent between the initial candidates and a candidate added near the end of the study. Furthermore, the accuracy of the sensitivity analysis could be adversely affected. Using utility curves, the scoring remains consistent for the duration of the study even if the original reasoning is forgotten.

The following is a recommended procedure for constructing a utility curve:

- Determine the useful range of performance and plot it on the abscissa. The scale for the utility score on the ordinate is always the same, and should be 0 to 10.

- Estimate the performance or range of performance that has the maximum and plot it at a value of 10 (or 0 depending on the criteria). Be careful not to set the maximum value higher than necessary, because that may increase the cost unnecessarily. The maximum value must include any value established by a system requirement.

- Estimate the performance below which there is no value to the program, per the requirements, and plot it at a value of 0. This point may be below the minimum acceptable specification values, since performance below specification is not necessarily without value. However, selection of a configuration with performance below the specification value may require a compensating change in another part of the system to maintain the overall system performance. It may also require a change in the system performance requirements.

3.5.2.1 Utility Curves/Graphs

Utility Curves are a technique for translating performance into a numerical score. They also:

- Improve the consistency of scoring between the candidates.

- Provide a means to adjust the score in a controlled manner if the performance is changed.

- During the sensitivity analysis, facilitate adjusting the score based on postulated changes in performance.

- Provide translation of non-linear data into linear space (i.e. transfer function).

- Utility curves associate the performance of an attribute with a score using graphical, tabular, or mathematical methods.

The utility score ranges from 0 to 10, with the lower bound on the useful value of an attribute being assigned a score of 0 and the upper bound being assigned a score of 10. Other scales may be used provided they are consistent with other scoring methods used on the project.

Developing utility curves has two important benefits. First, it forces the analyst to think seriously about the importance of various levels of performance. This results in a better understanding of the performance benefits and a more accurate scoring rule. The second benefit is that the scoring rule is documented. This is very important, since the TOA often extends over several days or weeks. If not documented, the analyst's perception of the value of the levels of performance can change over time. The scoring would then not be consistent between the initial candidates and a candidate added near the end of the TOA. Furthermore, the accuracy of the sensitivity analysis could be adversely affected.

By using utility curves, the scoring remains consistent for the duration of the TOA even if the original reasoning is forgotten.

The recommended procedure for constructing utility curves is as follows:

1. Determine the useful range of performance and plot it on the abscissa. The scale for the utility score on the ordinate is always the same, and should be 0 to 10.

2. Estimate the performance or range of performance that has the maximum and plot it at a value of 10 (or 0 depending on the criteria). Be careful not to set the maximum value higher than necessary, because that may increase the cost unnecessarily. The maximum value must include any value established by a system requirement.

3. Estimate the performance below which there is no value to the project, per the requirements, and plot it at a value of 0. This point may be below the minimum acceptable specification values, since performance below specification isn not necessarily without value.

Selection of a configuration with performance below the specification value may require a compensating change in another part of the system to maintain the overall system performance. It may also require a change in the system performance requirements.

3.5.2.2 Utility Scores

The Utility Score is a technique for translating diverse criteria into a common scale, which provides a mediating capability. The utility score ranges from 0 to 10, with the lower bound on the possible value of an attribute being assigned a utility of 0, and the upper bound being assigned a utility of 10.

The range of the utility score encompasses the range of acceptable or realistic alternatives. The "zero point/value" indicates the level of performance, which no longer provides value to the system performance or effectiveness. The "zero point/value" may be set below minimum acceptable specification values, since minimum acceptable values are usually the cut-off point beyond which alternatives are "not worthwhile to pursue," rather then "without value."

3.5.2.3 Subjective Method

In cases where an attribute is difficult to quantify or measure, the evaluation might establish a ratio scale or use analytic hierarchy process to establish a relative scale for utility values. The ratio and relative scaling approaches identify the "best" alternative through a structured comparison of alternatives. These approaches are most valuable in considering non-technical parameters, where only subjective (high, medium, low) evaluation is possible. A subjective parameter could be included as relatively scaled attribute using a paired comparison process and scaling methodology. This approach counts explicit, physical items that might have and impact. The assumption is that each item counted will have the same potential impact as every other item. This approach is used because there is no clear method to customize the impact of each individual item in a defensible way. If the approach assumed that the risk impact of Candidate B is higher than that of Candidate A, the Candidate B supplier would more than likely want to dispute that claim . . . and vice versa.

3.5.2.4 Calculations

Given the following, utility scores can be developed for the various types of evaluation criteria in the trade table.

Limits established by requirements or the maximum and minimum performance between all evaluated candidates for the specific criterion.

L_{Max} = Upper Limit
L_{Min} = Lower Limit
L_{Mid} = Mid Point between L_{Max} and L_{Min}; $L_{Mid} = \frac{(L_{Max} + L_{Min})}{2}$ (3.5.2.4-1)

Performance of the specific candidate's criterion being evaluated.

P = Performance

Maximum criterion performance of all candidates being evaluated.

P_{Max} = Performance Max

The score from 0 to 10, given to the performance of the specific candidate's criterion evaluated.

U = Utility Score

3.5.2.4.1 Calculation Methods

Less Than – Use this method when performance must be below a specific limit, such as weight and cost, where the parameter is not to exceed a certain amount/level, but may be as low as possible. The lowest performance value receives the highest score.

$$\text{Less Than} \longrightarrow U = 10\left(1 - \frac{P}{L_{Max}}\right);\ \text{where}\ 0 \le U \le 10 \qquad (3.5.2.4.1\text{-}1)$$

Greater Than – Use this method when performance must be above a specific limit ant there is no upper limit, such as processor speed, disk storage capacity and memory size. The highest performance value receives the highest score.

$$\text{Greater Than} \longrightarrow U = 10\frac{(P - L_{Max})}{(P_{Max} - L_{Min})}\text{; where } 0 \le U \le 10 \qquad (3.5.2.4.1\text{-}2)$$

Nearest To – Use this method when performance must be the closest to a specific value, but may not be achievable by current technology, such as disk storage, memory, processor speed, etc.

$$\text{Nearest To} \longrightarrow U = 10\frac{P}{L_{Max}}\text{; where } 0 \le U \le 10 \qquad (3.5.2.4.1\text{-}3)$$

Range Max - Use this method when performance must be within a specific limit range, such as fuel capacity or reliability, where the parameter is not to exceed or go below a certain amount/level. Being closest to the maximum is desired.

$$\text{Range Max} \longrightarrow U = 10\frac{(P - L_{Min})}{(L_{Max} - L_{Min})}\text{; where } 0 \le U \le 10 \qquad (3.5.2.4.1\text{-}4)$$

Range Min – Use this method when performance must be within a specific limit range, such as fuel consumption, where the parameter is not to exceed or go below a certain amount/level. Being closest to the minimum is desired.

$$\text{Range Min} \longrightarrow U = 10\frac{(L_{Max} - P)}{(L_{Max} - L_{Min})}\text{; where } 0 \le U \le 10 \qquad (3.5.2.4.1\text{-}5)$$

Range Mid – Use this method when performance must be within a specific limit range, such as temperature, where the parameter is not to exceed or go below a certain amount/level. The mid-point is the most desired, allowing leeway on both sides of the mid-point parameter.

$$\text{Range Mid} \longrightarrow \begin{cases} \text{If } P < \text{Mid Point} = \dfrac{(L_{Max} + L_{Min})}{2} \text{ then, } U = 10\dfrac{(P - L_{Min})}{(L_{Max} - P)}; \text{ where } 0 \le U \le 10 & (3.5.2.4.1\text{-}6a) \\[2ex] \text{If } P = \text{Mid Point} = \dfrac{(L_{Max} + L_{Min})}{2} \text{ then, } U = 10; \text{ where } 0 \le U \le 10 & (3.5.2.4.1\text{-}6b) \\[2ex] \text{If } P > \text{Mid Point} = \dfrac{(L_{Max} + L_{Min})}{2} \text{ then, } U = 10\dfrac{(L_{Max} - P)}{(P - L_{Min})}; \text{ where } 0 \le U \le 10 & (3.5.2.4.1\text{-}6c) \end{cases}$$

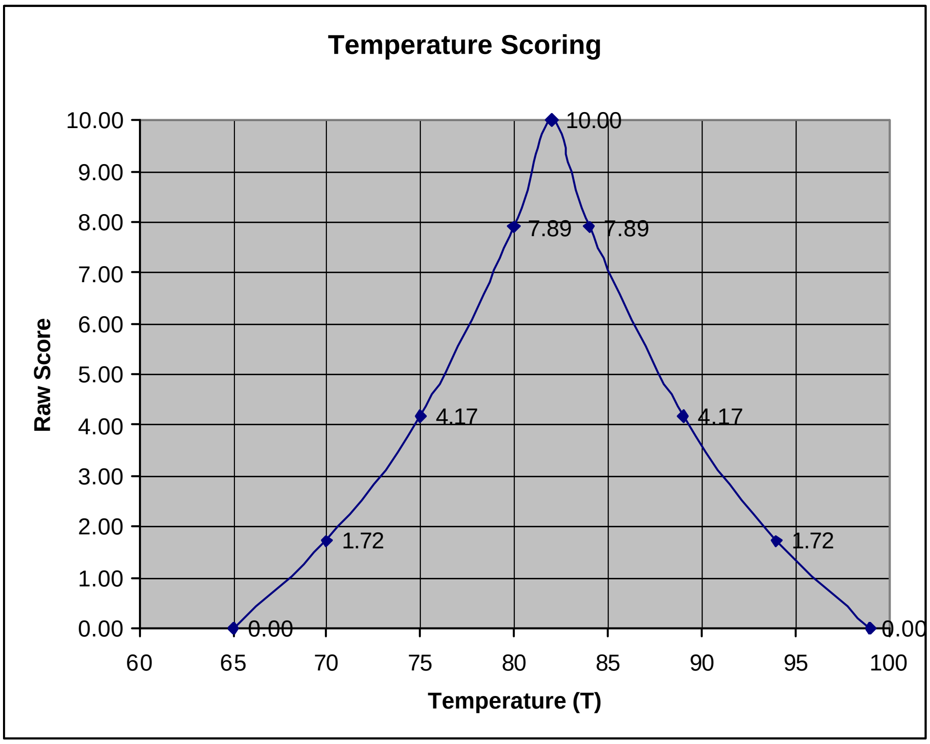
Range Mid Example:

A unit shall operate within the temperature range 69°F < T < 95°F, not below 69°F and not above 95°F. The unit nominal values of 65, 70, 75, 80, 82, 84, 89, 94 and 99 would appear as graphed below. The mid-point of 82 would achieve the highest score since it falls closest to the mid-point of the utility curve.

Table 8 - Temperature vs. Raw Score

Temp	Raw Score
65	0.00
70	1.72
75	4.17
80	7.89
82	10.00
84	7.89
89	4.17
94	1.72
99	0.00

Figure 4 - Temperature Utility Curve



3.5.3 Sensitivity Analysis

It is important to understand how the results of the analysis are affected by changes in the input factors such as scoring, weighting, requirements, capabilities, assumptions, or other subjective estimates. Sensitivity analysis is a tool for indicating the quantitative significance of these changes,thus giving the systems engineer confidence in the results of the trade study. Candidates should be evaluated in both stress and nominal conditions.

Varying the candidate performance up and down by 20 percent should uncover those areas which are too sensitive. When sensitive criteria are uncovered, the differences between the candidates must be examined carefully. The differences may not be as significant as the numbers indicate and additional reasoning may be required to make the selection. The predicted performance should be examined to determine if it is robust and can reasonably be met. If not, the score should be adjusted.

The evaluation criteria must also be examined to determine if a small reduction in the requirement will make a significant improvement in the scores of one or more candidates. If the reduction in performance is acceptable to the customer, or if it may be compensated for somewhere else in the system, then a significant cost saving may sometimes be obtained.

3.6 Select Best Candidate

The difference in scores may be small (a total weighted score difference between candidates of less than 10 percent is not significant) or the results of the sensitivity analysis may result in no clearly superior approach. It is, therefore, important that the key personnel on the program review the evaluation criteria and the scoring, and take part in the final decision. The final decision may have to be made based on the most important evaluation criteria such as:

- Risk, Cost, or Performance In A Particular Area
- Major Advantages and Disadvantages
- Political or Strategic Considerations.

As an example, if the final total weighted scores of two or more alternatives are proximate and additional data is unavailable to discriminate between them, then either candidate may be chosen. The choice may be based on any criterion that makes sense. Whenever a single criteria becomes the deciding factor, a detailed explanation is to be included in the trade study report

Where the accuracy limits of the performance evaluation affect the decision, several options are available:

- Delay the decision until additional information is available.
- Acquire additional data or refine the analysis to reduce uncertainty.
- Review criteria and weights for modification.
- When all else is inconclusive, make the selection based on advantages and disadvantages, or on political considerations.

3.6.1 Adverse Consequence Analysis

The final step is to examine the selected candidate to determine what, if any, undesirable consequences might happen if this candidate is selected. The adverse consequence analysis is used to overcome the natural tendency to only characterize the positive features of selected alternatives. An example would be a technically superior alternative that has a high risk of not being able to meet delivery deadlines.

An additional benefit of the adverse consequences analysis is that it highlights the need for the creation of contingency plans to prevent or minimize the impact of any adverse consequences which may develop. Also, it allows the comparison of negatives for each alternative as well as positives (i.e., it completes the evaluation job).

Table 9 – Adverse Consequences

Posible Adverse Condition	Candidates								
	A			B			C		
	Probability (P)	Seriousness (S)	P x S	Probability (P)	Seriousness (S)	P x S	Probability (P)	Seriousness (S)	P x S
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0
			0			0			0

3.7 Create TOA Report

The following is the recommended format for the Trade-Off Analysis Report including section headings and a brief description of the sections.

Title Page

Program/Project Name
Trade-Off Analysis Report

< date >

Team Members
Team Member 1 (leader)
Team Member 2
Team Member 3
.
.
.
Team Member n

1.0 ABSTRACT

This section should be only one paragraph generally describing the trade study. Conclusions need not be given explicitly in the abstract unless they can be included very compactly. The abstract should allow the reader to make an informed decision about reading further.

2.0 SUMMARY

The summary capsulizes the report's entire content. Most readers will only read through the summary, so great care should be taken in structuring the summary and in choosing the most concise, accurate, and descriptive words and figures for inclusion. Included in the summary should be the following:

a) the purpose of the trade study

b) a brief list of the criteria and their relative weights

c) a brief list of the alternatives considered

d) a brief list of any assumptions made in performing the trade study

e) a short discussion of the major considerations that affected the outcome of the study

f) a brief description of the recommended alternative

3.0 Introduction

The primary purpose of the introduction is to provide the necessary background information and description of the motivation behind conducting the trade study. At a minimum, this section must include the following:

a) purpose of the trade study

b) evaluation criteria

c) weighting of evaluation criteria

4.0 Discussion

4.1 Configuration Alternatives

This section documents the trade study alternatives identified.

4.2 Quantification of Evaluation Criteria

This section documents how the evaluation criteria is to be quantified for the alternatives identified in the previous section.

4.3 Utility Function(s) (Optional)

This section documents any utility functions used to account for nonlinearities in the benefits derived from a given parameter.

4.4 Costing Function(s)

This section documents the criteria costing function(s) used to determine how costs are assigned to the trade study alternatives.

4.5 Evaluation of Alternatives

This section documents the evaluation of the trade study alternatives against the evaluation criteria defined in section 3.0 and using the quantification defined in section 4.2, the utility function(s) (if any) defined in section 4.3, and the costing function(s) defined in section 4.4.

4.6 Sensitivity Checks

This section documents the results of the sensitivity checks performed to ensure insensitivity to evaluation criteria weighting and balance.

5.0 Conclusion

This section will document the recommendation of the trade study.

CHAPTER IV.

COTOA APPLICATION DEVELOPMENT

Following the creation of the COTOA concept, the COTOA concept must be decomposed into requirements. Requirements define what a product or system must do. Requirements mandate that something must be accomplished transformed, produced or provided. Table 10 is the Requirements Allocation Matrix (RAM) lists the requirements for the Component-Oriented Trade-Off Analysis Project along with methods to verify each requirement.

Table 10 – Requirements Allocation Matrix

Req ID	Requirement Text	Verification Method
10	Sample Trade-Off Analysis application tables shall be created.	Demonstration
20	Sample Trade-Off Analysis application graphs shall be created.	Demonstration
30	Sample Trade-Off Analysis application screens/displays shall be created.	Demonstration
40	Sample Trade-Off Analysis reports shall be created.	Demonstration
50	Reusable Trade-Off Analysis components shall be created.	Demonstration
60	A Component-Oriented Trade-Off Analysis process shall be created.	Demonstration
70	Sample Evaluation Criteria shall be created.	Demonstration
80	A process for developing new Trade-Off Analysis components shall be created.	Demonstration
90	A demonstration of the timesavings of the new Component-Oriented Trade-Off Analysis process versus the manual method of creating Trade-Off Analysis components every time a Trade-Off Analysis Report is required.	Demonstration
100	A demonstration of how components are used to generate the tables required for the Trade-Off Analysis Report shall be performed.	Demonstration
110	A demonstration of how components are used to generate the graphs required for the Trade-Off Analysis Report shall be performed.	Demonstration
120	Three sample Trade-Off Analysis Reports shall be manually created and timed.	Inspection
130	Three sample Trade-Off Analysis Reports shall be created using the Component-Oriented Trade-Off Analysis process and timed.	Inspection
140	A comparison analysis shall be performed between the manual method of creating Trade-Off Analysis Reports in order to validate the new Component-Oriented Trade-Off Analysis Process.	Demonstration
150	The manual Trade-Off Analysis Process shall be decomposed in to components.	Inspection
160	Results from previous Trade-Off Analysis Reports shall be used to verify the Component-Oriented Trade-Off Analysis Process.	Inspection/Demonstration
170	A Trade-Off Analysis Component Repository shall be created.	Inspection/Demonstration
180	Microsoft Office applications shall be used and linked together in order to provide portability of the Component-Oriented Trade-Off Analysis Process.	Inspection/Demonstration

4.1 Domain Specific Analysis & Modeling

The term domain is used to denote or group a set of systems or functional areas, within systems, that exhibit similar functionality. COTOA may be viewed as a domain by defining the Domain Model, its components, component protocol, and creating a methodology.

Components are structural pieces that are tangible. They are independently defined, but when put together, they construct the desired system. The same components could be used to build different systems.

The COTOA Domain consists of components from the Microsoft Office suite of applications as follows:

Microsoft Word is a word processing program that can be used to write letters, memos, reports, and all the documents an organization needs.

Microsoft Excel is a spreadsheet program that can be used to organize, calculate, and analyze data in worksheets, charts, and reports.

Microsoft Access is a database program that can be used to link data in useful ways, perform queries, and create forms and reports. Access helps manage data efficiently.

Microsoft PowerPoint is a presentation program that can be used to create professional slide shows and handouts. Enhancing the appeal of a presentations may be accomplished by adding charts, graphics, sound, and animation.

4.1.1 Interface Protocols

In today's workplace, it's likely that you need to do more than simply create a document in Word or manage data in Access. The Microsoft Office suite of programs have been designed to work together in and integrated environment, providing the ability to go beyond the limits of the individual programs. With Microsoft Office, you can do the following:

- Embed information from one file type into another, to allow editing without altering the source information.

- Create links between files so when information is updated in one file it is automatically updated in the other file.

- Merge an Access database with a form letter, report or other type document in Word to quickly create a large volume document merge or segregated document merge.

Dynamic Data Exchange (DDE) - An established protocol for exchanging data between Windows-based programs. The active link between applications is called a DDE channel. A form of interprocess communication used in Microsoft Windows, providing exchange of commands and data between two applications. DDE was used principally to include live data from one application in another - for example, spreadsheet data in a word-processed report. After Windows 3.1 DDE was replaced by object linking and embedding. DDE links between files rely on the files remaining in the same locations in the computer's directory.

Object Linking and Embedding (OLE) - A protocol by which an object, such as a chart (graph) in an OLE server or file, can be linked or embedded (inserted) in a OLE container file, such as a Microsoft Access form or report. OLE is the protocol for drag and drop or linking and embedding data and objects is accomplished through the Microsoft OLE standard. OLE allows a user or another program to communicate with other programs, usually for the purpose of exchanging information. An enhancement to dynamic data exchange, which makes it possible not only to include live data from one application in another application, but also to edit the data in the original application without leaving the application in which the data has been included.

Open DataBase Connectivity (ODBC) - A database programming interface from Microsoft that provides a common language for Windows applications to access databases on a network. ODBC is made up of the function calls programmers write into their applications and the ODBC drivers themselves. For client/server database systems such as Oracle and SQL Server, the ODBC driver provides links to their database engines to access the database. For desktop database systems such as dBASE and FoxPro, the ODBC drivers actually manipulate the data. ODBC supports SQL and non-SQL databases. Although the application always uses SQL to communicate with ODBC, ODBC will communicate with non-SQL databases in its native language. ODBC is a standard method of sharing data between databases and other programs. ODBC drivers use the standard Structured Query Language (SQL) to gain access to data from outside sources. MS Office provides a Driver Manager and a set of ODBC drivers for popular database formats. ODBC is a standard protocol for accessing information in SQL database servers, such as Microsoft SQL Server. You can install ODBC drivers that enable Microsoft Access to connect to these SQL database servers and access the data in the SQL databases.

Data Access Objects (DAO) - A programming interface for data access from Microsoft. DAO/Jet provides access to the Jet database, and DAO/ODBC Direct provides an interface to ODBC databases via RDO. DAO is a COM object.

These component protocols are required and must be obeyed to guide new component development.

A methodology is similar to a process model, the only difference is that the methodologies include a lot more detail than process models. Methodologies are step-by-step definitions of how engineer. A methodology is a well-defined set of practices and tools. The basic premise behind a methodology is that ist will give users a predictable and repeatable process. Only at the point its repeatable and predictable, can we begin to think about how to improve on the methodology and optimize it.

4.1.2 Domain Methodology

A simple methodology for locating, adapting and integrating components to build applications in the domain is to locate components that add value to the COTOA by providing additional capability, efficiency, accuracy and/or speed. In order to adapt and integrate components, the components must comply with the interface protocol standards described in section 4.1.1.

There are a variety of approaches to domain analysis and modeling, each with its advantages and disadvantages. Which domain analysis and modeling approach is best is dependent on the issues and constraints of each application. The application should be discussed with a researcher who is knowledgeable in all appropriate methodologies before an approach is selected.

4.2 COTOA Application Features

The COTOA may be used for any application where a Trade-Off Analysis is required, it may be necessary to create separate COTOAs for a specific area. COTOA contains generic templates for the following COTOA components:

- Trade Table
- Utility Curves/Graphs
- Sensitivity Analysis Table
- Adverse Consequences Table

COTOA MS Access templates have been created for many common Trade-Off Analyses.

4.2.1 Starting COTOA

Create a new COTOA

To create a new COTOA, double click on one of the existing COTOA MS Access Templates as follows to :

- Generic COTOA.mdz – Creates a generic COTOA
- Software COTOA.mdz – Creates a software COTOA
- Hardware COTOA.mdz – Creates a hardware COTOA
- Automobile COTOA.mdz – Creates a automobile COTOA
- Home Purchase COTOA.mdz – Creates a home purchase COTOA

Open an existing COTOA

Double click on the COTOA file name or open the file through the MS Access file menu.

4.2.2 COTOA Application User Interface

Splash Screen

After opening the COTOA, you will see a splash screen with information and disclaimers. Click the OK button to go to the main menu.

Figure 5 – COTOA Splash Screen

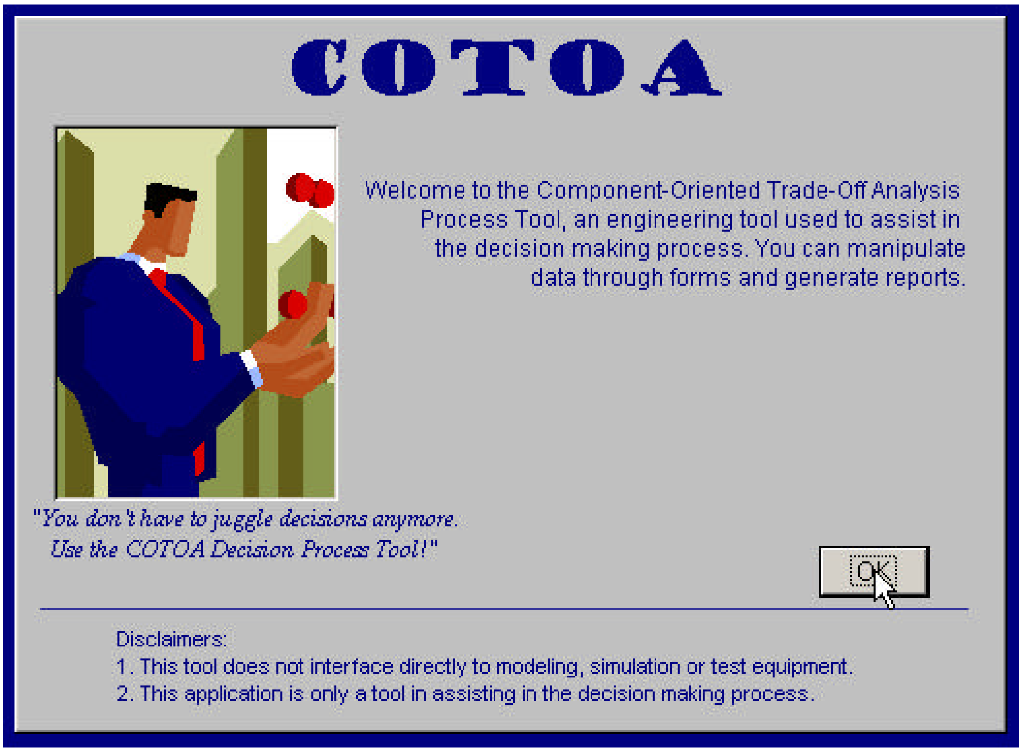


Figure 6 – COTOA Main Menu

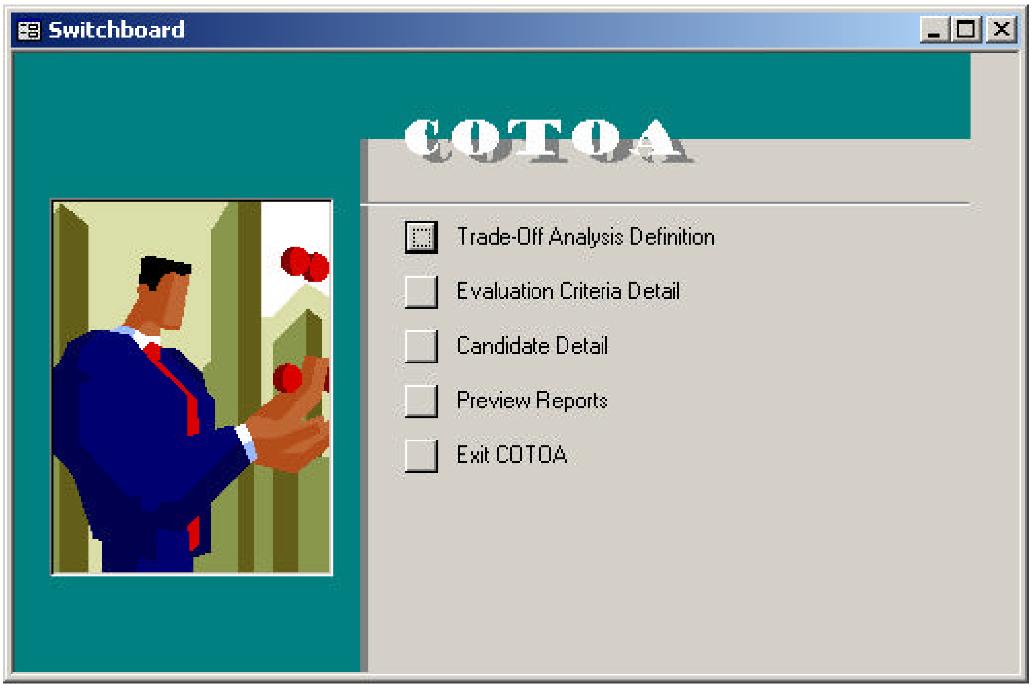


Figure 7 – Evaluation Criteria Input Window

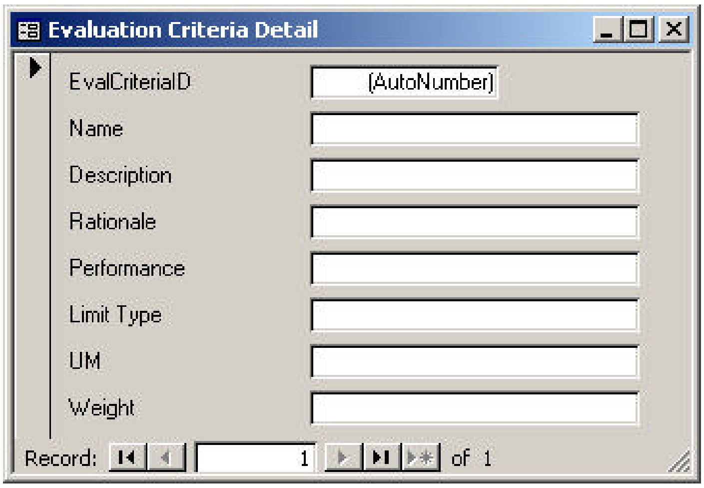


Figure 8 – Candidate Input Window

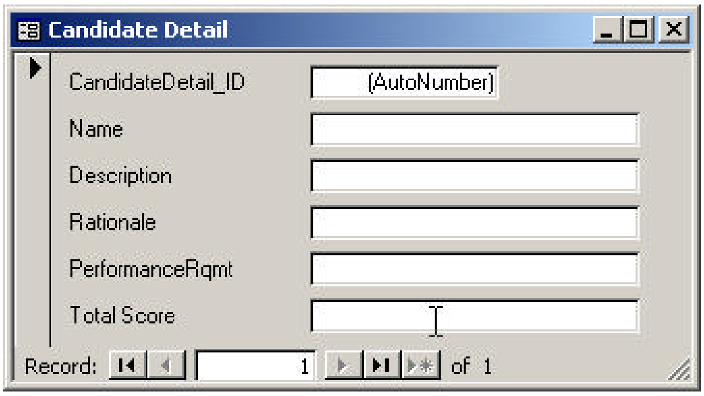
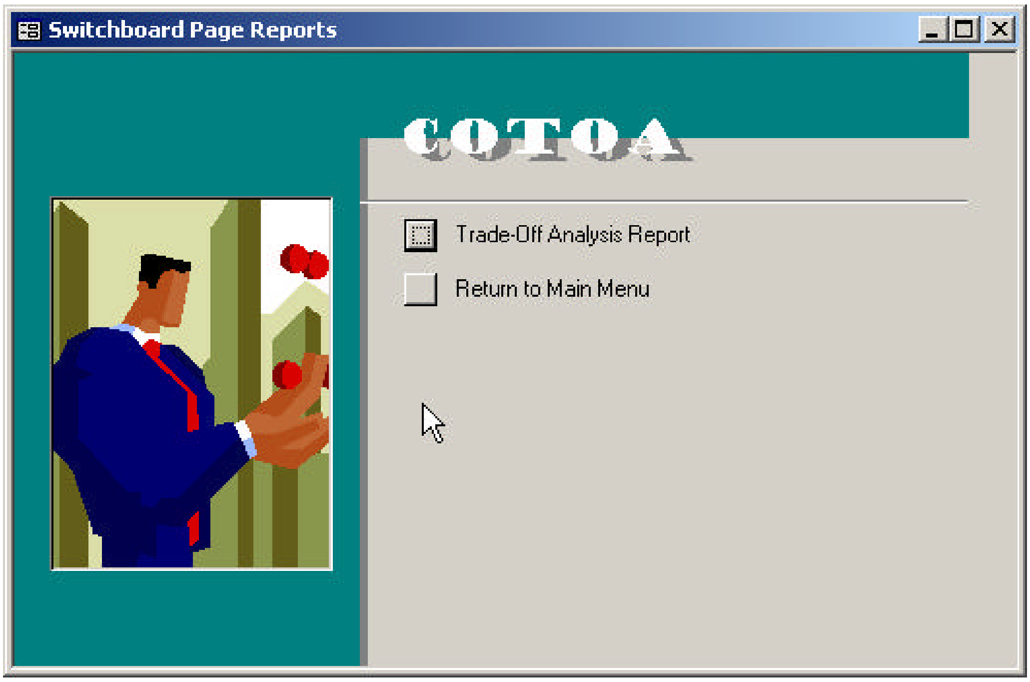


Figure 9 – Reports Menu



4.3 Future Enhancements

The Component-Oriented Trade-Off Analysis will consist of an object-oriented database management system (OODBMS) that manages objects, which are abstract data types. Some examples of these objects are:

- Data with complex relationships that are difficult to model and process in a relational DBMS.
- Multimedia data types (images, audio, and video)
- Complex data types
- Arrays of values
- Nested tables and methods.
- User-defined objects.

The OODBMS stores the complex data objects and relationships among the data elements directly in a database instead of trying to map the information to relational rows and columns as opposed to the relational database management system RDBMS, which is designed to only handle numbers, alphanumeric text and dates. The RDBMS may also support a Large Object (LOB) field. A LOB field is a database field that holds any binary/digitized information including text, images, audio and video, but the database program does not manipulate the LOB directly, another application has to be written or some middle-ware has to be used to process the LOB. In an OODBMS, a picture or video clip object can include the routine to display the picture of video that is dynamically invoked by the OODBMS.

Object databases bring back the navigational access of hierarchy databases, a performance benefit RDBMSs gave up. The OODBMS uses object inheritance to capture all the relationships that affect decisions and the OODBMS is aware of class hierarchy, so there is one schema and one model. The OODBMS retains the data integrity and control features of traditional database models, while adding the modeling features of object technology.

Some OODBMSs are entirely object oriented and are accessed from an application program written in an object-oriented programming language. Others allow access via a SQL-like language or derivative the common database language between client and server. The OODBMS functions as both a RDBMS and OODBMS. Object programming cuts development time considerably by object reuse. For database structures with inheritance mechanisms at work, nothing has the speed of an OODBMS.

Overall, OODBMS technology has many benefits, including more data abstraction; encapsulation; data hiding, code reuse, inheritance, actual OO database programming functions, full integration with OO programming languages, and all other defining characteristics of OO software.

An object database makes it easy to view the data in a number of ways without having to write highly complex queries for each view. The OODBMS models real world objects placing emphasis on nouns, instead of verbs and creates a real time, distributed system. The OODBMS has strong server functions, security, integrity, concurrency, high-volume processing, reliability, high performance, and broad-based availability. Dealing with multimedia and multiple data formats that exists today or that come tomorrow and object technology are the key reasons for using an OODBMS.

The OODBMS provides industry-leading performance, unlimited scalability from 10 gigabytes to more than 100 terabytes, seamless connectivity and low administration requirements. The OODBMS is capable of legacy data transformation and movement, metadata management, application building and information access. The OODBMS has backup and incremental backup features, along with the ability for backing up and restoring huge databases; or for storage and retrieval of data that does not fit well into standard relational tables.

The OODBMS has security and access control, which include locking, which prevents two users from changing the same data simultaneously; or rollback, which restores a database to its original state if a transaction is interrupted in midstream.

The OODBMS will efficiently process the daily Trade-Off Analysis task and also provide sufficient horsepower for decision support. The OODBMS operation is also split into different databases, one for daily work (normal operations), and the other for ad hoc or advanced queries and capabilities (administrator activities).

The OODBMS uses intelligent-agent technology as a built-in decision support tool or data mining capability. There can be a lot of parameters that influence decisions, using intelligent agents provides a variety of statistics to base these decisions on, in an easy-to-understand interface. Each decision is the end result of a series of very complex relationships. In the OODBMS, the decision-making capability is built in to the relationships.

Functionality is built in to the database so that actions would be taken based on the stored information and user input. The OODBMS organizes and sets up the necessary Trade-Off Analysis in response to requests and pre-planned input. It will balance the plan and capabilities. The system knows what data are required and what capabilities are necessary to set up a given Trade-Off Analysis.

CHAPTER V.

RECOMMENDATIONS & CONCLUSION

When creating any type of analysis tool similar to the Component-Oriented Trade-Off Analysis, an Engineering Notebook should be used to capture all ideas, problems, problems and successes. The engineer or developer should perform progress estimates – sample time to complete a particular task in order to estimate tasks completion throughout project time period.

It is also advantageous to select the Master's Report topic as early as possible, in order to gain project topic approval and to attempt to base course group and individual projects on the final project topic.

Other process tools that I may venture into creating are a Requirements Management Database Tool, an Electromagnetic Compatibility Analysis Tool and an Electrical Load Analysis Tool.

While the philosophy behind the Component-Oriented Trade-Off Analysis Process and Tool is quite robust, the actual process steps, as well as this documentation describing that process, and the COTOA application, are always subject to correction and/or improvement. Questions, suggestions or comments concerning this project may be directed to:

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APPENDIX A

EVALUATION CRITERIA DEFINED

As mentioned previously in section 3.4, evaluation criteria are defined based on the overall project and performance requirements, in addition to evaluation criteria that the domain experts have established as important and having merit. This section defines various types of evaluation criteria and may serve as stimulus in developing other evaluation criteria. It is also a good idea to capture the exact definition or interpretation for a particular evaluation criterion being used in a specific Trade-Off Analysis.

Architecture Flexibility - Flexibility is often stated. Most if not all candidates advertise compliance to some acceptable set of standards. That is a necessary but not a sufficient condition. Even within standards, individual products may be so tightly coupled that one cannot be removed and replaced without impacting several. Such coupling can also complicate product enhancements, technology insertion, and buyer extensions. Examples are: a) proprietary use of portions of a VME bus, b) software using a low level interface to hardware, c) products that contain their own database or GUI rather than one that could be shared by all products in the system, d) direct coupling of software components rather than using wrappers and a software bus with standard message formats (e.g. a state vector is always the same on the bus no matter what the individual application does internally), e) the over use of non-portable languages included with a product such as an expert system.

Performance & Functionality - The real issue is not whether or not but rather, how does one determine what the product can and cannot do. The only way to know for sure is to execute the system under realistic operational conditions. The greatest problem is the ability to perform a function at the (often high) expense of operability and supportability.

Documented Specifications - Experience is that COTS products and systems seldom do what they are advertised to do and there is generally no written understanding between the seller and buyer as to what capabilities and performance are provided. A written specification of some form indicating the functional and performance capabilities should be provided by the seller. It should be in terms that allow a quantitative assessment of the product. Risk to the buyer is inversely proportional to the quality and comprehensiveness of the specification.

Reliability & Maintainability Analysis - RMA data is often proprietary for COTS products making it difficult to assess the performance of the individual product. Multiple integrated products complicate the situation. While the performance of individual products may be known, how they are used collectively determines RMA performance. In this case, the supplier should provide a system level RMA assessment and certify it.

Availability (Capabilities) - The advertised capabilities of COTS products or integrated products are often allocated to some future version. That version may not be available soon enough to meet the buyer's needs, may be delayed, or may never happen. If a required capability is not currently in the product, then there should be a written agreement as to when the supplier will provide that capability.

Customization - To what extent, if any, will the supplier make specific modifications to the product and within what kind of pricing structure? There are many requirements that can vary from trivial to almost difficult and expensive depending on where they are implemented. COTS, of course, constrains the implementation options. It is often the case that the most obvious and cost effective place to implement functions is through the use of a COTS product. It also generally occurs in niche areas as opposed to broad based areas. Fortunately, niche products tend to be provide by smaller companies willing to make special upgrades and modifications for a price. If it is likely that upgrades or special modifications will be beneficial, then companies willing should be sought and written agreements established prior to product selection.

Product Support - What role will the supplier perform during product support? What response time will the supplier guarantee for critical problems? For main line (large market) commercial products the support available from suppliers is generally well documented and often offers a menu of options. For smaller suppliers it can become more vague and for suppliers of integrated products there is a major opportunity for misunderstood roles and responsibilities. Examples illustrate the need for clearly defined roles and responsibilities:

If the symptom of a problem appears in Product X, what does the buyer expect of the supplier if the problem is inside X or outside X but manifests itself in X?

If the product is an integrated set of products or contains second tier products, is the integrating supplier responsible or must the buyer assume responsibility for the overall system and manage the interface with each individual product supplier.

There is no right or wrong answer as long as it was reached through a deliberate assessment of the cost/benefits of the alternatives.

Benchmark/Operational Senerio - A comprehensive operational scenario should be defined and all candidates evaluated against that scenario in real or pseudo (simulation driven) test cases. Test cases should encompass:

- functional and performance requirements.
- database generation process and labor costs.
- configuration management needs.
- adequacy/ability of provided facilities to meet training needs and support personnel.

The buyer should assess the cost and operational impacts of resolving discrepancies either through a contract with the seller or by extending the system after delivery.

- The database architecture/design allows substitution without a major re-specification and generation of the database. This can be done in two ways:
    1. utilize products that can access a standard DBMS.
    2. define and maintain the master database in a standard DBMS and translate from that to the specific structure of the product currently in use.

Performance - The performance of integrated COTS products often is not easily projected from the specifications or even the performance of the individual products. The seller/integrator of the product should provide information to help the buyer assess the overall system performance. It should track to hands-on evaluations that the buyer may later perform. The existence of a parametric performance model is indicative of a supplier who understands and can describe the performance of the product in a variety of environments.

Upgradability - Does the supplier have a formal process for incorporating upgrades of included COTS products on a regular basis? If the product contains included COTS or if the seller of the system is essentially a COTS integrator with limited added function through developed product, then the seller should:

- have a formal process for incorporation of COTS upgrades on a regular cycle such that the resultant product is current with the state of the contained products.
- have a process for evaluating alternative products and incorporating them if appropriate.
- perform a reasonable and documented level or regression testing.

Product Robustness - Is the system designed to accommodate future product and/or technology substitution/insertion? The life expectancy of a government is generally very long compared to the rate of growth of technology and the life expectancy of COTS products. To allow the system to live its required life with COTS and grow with technology, it is essential that it be easy to substitute products. To that end, the seller should demonstrate that this is not difficult. The buyer should define scenarios to test the seller's product's robustness:

- Hardware components are standard computers wherever possible and support a standard operating environment.
- Software products easily port among platforms including operating environment and hardware.
- Hardware and software elements are not tightly coupled; that is, avoid systems where the hardware and software components cannot be substituted independently.
- There is minimal specialized (without a commercial substitute) hardware content. For anything that is not specialized, show that there is at least one commercial alternative that can be substituted at a cost not to exceed some value acceptable to the customer.
- The software architecture easily accommodates the substitutes of major elements (e.g. databases, telemetry, control). Key criteria are:

  1. a software message passing interface architecture with defined message formats
  2. wrappers around all servers
  3. encapsulation
  4. a system level standard database that can be translated to the specifics of the instances of server implementations.

Product Support - How will the supplier relieve the buyer of the impacts of incompatible upgrades? Incompatible upgrades are not uncommon and are sometimes necessary to make major extensions to the product, particularly in software. While it may not be possible to totally mitigate the impacts of such upgrades, a responsible supplier will provide appropriate tools to aid in the conversion process. They should be an integral part of the product plan and tested as well as the product itself.

Version Currency - Will the supplier agree and demonstrate the ability to maintain an agreed to level of currency? COTS products can have a version/change cycle as short as six months. Support for COTS products declines by cycle and may be as short as two cycles or one year. In addition, COTS products diverge and may suffer degraded interoperability. Sustainment of a system necessitates that its contained COTS elements be reasonably current and that interoperability among multiple COTS elements be assured.

- The supplier should agree to maintain a given currency within the maintenance fee and assure interoperability among contained COTS products.
- The risk of incompatibilities among COTS products in a system increases rapidly as the number of COTS elements increases. The number should therefore be relativity low and/or the seller should demonstrate that it can handle, possibly via the architecture, any problems without impacting the buyer's operation or support costs.

Configuration Management/Change Management - Does the supplier have a robust CM process that can manage multiple and back-leveled versions of the product simultaneously? At any point in time there are often multiple versions of a product in use and requiring support. The seller should agree to provide CM for the current as well as back-leveled versions of the product for a time period acceptable to the buyer. If the product is integrated COTS with developed elements that may become "account" unique, then the seller should show that multiple versions can be adequately configuration managed.

Does the supplier provide a user-friendly mechanism for the CM of operational products across all COTS components? The reliability and integrity of operational products such as databases, scripts, and displays are as important to the success of operations as that of the components of the system. Configuration management is therefore essential. However, it may be difficult across diverse COTS products without special or additional tools. The buyer should look to the supplier to either provide those tools or at least adequate information for the buyer to assess the impact of developing them independently.

Industry Standards - Does the supplier's product conform to dominant published and defacto commercial standards? The seller's product should conform to a reasonable set of dominant commercial standards that are not a risk of becoming extinct at an early age. This provides a critical foundation for buyers who want to extend the system or add other products around it. Standards with a small following or externally imposed have a risk of extinction or simply being ignored in the commercial world because they are inconsistent with a profit motivated business.

Tailorability - Is the documentation adequate to tailor the product/system to the buyer's needs? Virtually all products require tailoring through facilities provided or extensions developed by the buyer. Examples are operational parameters, databases, interface bridges, and imbedded code of the type found in some GUI builders. It is important to assess the impacts of the tailoring process and the adequacy of the support documentation provided by the supplier. Inadequate documentation will impact cost and schedule and/or necessitate a support contract with the supplier.

Training - Are the training materials/aids adequate, particularly if the product is a collection of integrated components? The buyer needs an integrated package oriented towards the operation of the overall system in the context to which it will be used. While some amount of tailoring will be required of the buyer, it is best if it is limited to application or mission usage of the system. While there will most certainly be training material for embedded COTS products, there may or may not be an integrated system level training package. The more training material provided by the seller, the lower the cost of preparing training material by the buyer.

Documentation - Can the buyer perform the support activities necessary with the support documentation provided by the supplier? If the buyer is going to extend the system, integrate it into a still larger system, or perform some level of maintenance, quality documentation is essential. If the product is integrated COTS, the documentation should address the contained elements, the overall system, and the development elements.

Escrow Agreement - Will the supplier escrow the "product" if deemed necessary by the buyer? Providers of COTS products have been known to go out of business or discontinue a product line. In that event it is essential that a third party have the ability to assume control and support the product. The seller should be willing to enter into an escrow agreement. Equally, if not more important, the seller should have conducted a risk assessment of his suppliers and established second tier escrow agreements where the risk is unacceptable. The seller should share that risk assessment with the buyer.

Operability - Does the product provide a common look and feel to the user and maintainer? A product comprised of COTS may have element unique elements (e.g. database, GUI) each with a different look and feel. This complicates the definition, use, and support of the operational system. For some products there is a further operability complication in that they do not use a standard support product in order to reduce product cost. This, of course is at the expense of operability, CM, and interoperability. The buyer should assess operability. To exemplify:

- Is there one common database/GUI/etc. look and feel across the system or is there a collection of independent interfaces that would be more difficult to learn and use.
- Has the seller analyzed the database to identify the occurrences of redundant instances and made an effort to contain the operation impacts thereof?
- To what extent has the seller gone to contain the impact substitution of the database? Not only must the execution interfaces be bridged, but also the operational database must be ported. The best situation would be a standard, system wide database that can be automatically translated into product specific database.
- Are applications tightly coupled to a specific GUI that could lead to operator confusion or simply make product substitution more difficult for the maintainer?

Schedule Risk – The dependency of a specific candidate on the delivery schedules of required material or equipment.

Cost – Includes all cost related to utilizing a specific candidate (i.e. integration, software, hardware, shipping, installation, maintenance, etc.).

Facilities Impacts – Floor space, cabinet space, power and environmental conditions.

Quality - Total performance in the complete product, architecture or system.

Operator Impacts – Distance of equipment or controls, more/fewer commands required, more/fewer displays (i.e. the addition of Candidate A increases the number of displays/windows).

Single Point Failure – The amount of capability lost for the specific option. For each option, identify the worst case single point failure and determine how much of the capability is lost with that failure. Determine the number of functions lost.

Fault Diagnosis – Percent of connection status logged, failure logging accessibility or if additional tools are required to ensure that such logging is available for the specific architecture option.

Reliability - Reliability is a measure of the probability that an item or system will continue to function for a specific duration and under prescribed conditions. Whether discussing hardware or software reliability, it is measured in terms of the probability of success. For hardware, reliability is typically specified as the mean time between failures in hours. The engineer allocates the system reliability figure to lower tier items forming a reliability model. The design team fashions a design that satisfies this allocated figure that is verified by assessing the reliability of the components and computing the resultant reliability figure for the item as a function of the way the components are connected and used. Part and component reliability figures are commonly extracted from reference documents listing proven reliability figures for specific kinds of components. Reliability engineering should be involved early in the procurement cycle to ensure the parts purchased will meet reliability specifications.

Availability - Availability is a measure of the probability that the system will be available for use at any point in time. It is measured in terms of a particular combination of the system reliability and maintainability. The MTTR estimates and availability requirements are major factors in the determination of spares and other factors such as Life Cycle Cost and Built-In-Test (BIT). Availability analysis models should include cost of redundant hardware, cost of spares, and cost of various maintenance levels such that competitive life cycle cost are realized.

Product Regulatory Compliance – Most products must comply with Federal Regulations for safety and Electromagnetic Compatibility (EMC). The Occupational Safety and Health Administration (OSHA) determines the federally regulated safety requirements. Product safety standards are intended to prevent injury by electric shock, and hazards due to energy, chemicals, mechanical injury, heat, radiation, or fire. The Federal Communications Commission (FCC) administered EMC standards regulate the ability of a device to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to other devices in that environment.

System Safety and Human Hazards - safety requirements based on customer needs and design is analyzed to identify safety hazards to life, health, and property value. The principal approach is to build a model of operation in cooperation with the maintainability and logistics of the system operations and support process and to examine this process for conditions that can cause hazards to develop. The product is evaluated for ways to prevent these conditions from ever developing or ways to control the risks when they do occur. A hazard list is prepared and ways are found to eliminate or control each hazard.

Electrostatic Discharge - Systems operating in the atmosphere are susceptible to a build up of electrostatic charge that, if allowed to reach a high potential relative to the surrounding charge, can have a detrimental effect on sensitive on-board electrical equipment. This effect is known as Electrostatic Discharge (ESD).

Environmental Analysis - Environmental analysis is accomplished to determine to what environments the product system will be exposed, to characterize those environments with precision, and to identify product characteristics needed to survive in those environments. Environmental aspects involved always include the natural environment, but may also include a hostile element activated by persons or groups intent on reducing the effectiveness of system capabilities and a non-cooperative element entailing other systems that may unintentionally interfere with system operation. This may include nuclear, biological, and chemical analyses as a function of the threats posed by a hostile force. The effects of these agents are defined for the benefit of design teams and design alternatives reviewed for compliance with recognized effective solutions to the problems posed by the agents. In the larger sense the environment includes everything that is not in the system; so even cooperative systems that purposefully interface with the system are technically part of the environment.

Environmental Impact Analysis - The system must operate within a prescribed environmental definition. The system and the environment will interact in certain ways and the goal is to minimize the adverse impact of the system on its environment. This is accomplished by understanding the interface between the system and the environment in terms of all materials and energy that are exchanged across this interface. Each of these interfaces is studied for ways to reduce environmental impact. Environmental laws and regulations are studied for compliance issues.

Mass Properties - ensuring that the design falls within weight and center of gravity (CG) constraints established for the product. The principal method involves allocation of available weight to system elements and monitoring the design process to see that responsible teams and designers remain true to their allocations. A weights table is established that lists all of the system elements and their weights with subtotals and grand total. Weight margins may be established to protect the project from weight growth problems and provide for management of difficult weight issues as the design matures.

Also computing the CG of elements where this is a critical parameter. In maintenance situations this data may be required not only for a whole end item (hoisting and lifting, for example) but for various conditions where the item is incomplete as in assembly and disassembly operations.

Structural Dynamics and Stress Analysis - This discipline determines the needed strength of structures under static and dynamic conditions under all system conditions. Computer tools are used to model the structure and support structural design personnel in selection of materials and design concepts. There is a division environmental laboratory available to test and verify design concepts.

Thermal Analysis - Heat sources and sinks are identified and the resultant temperature of items in time is determined. This discipline is involved in positioning and mounting of items for thermal control and elements involved in altering the environment within which items are located. Support for this specialty is found within Product Engineering of the HPD matrix.

Disposal Analysis - During the development of a system, the eventual disposal of the system will be considered in accordance with tasks defined in the SOW. Features that encourage safe and low cost disposal will be included in system characteristics.

Site Facility Analysis - system-to-facility integration analysis by generating facility requirements specifications for the system itself and all support systems needed. Product specification and network interconnections that relate to the facility interface are compiled and refined. New facility code requirements and technologies are investigated. This specialty also provides Interface Control Documentation for system-to-facility interfaces, conducts testing of facility interfaces in preparation of shipment, and provides installation teams for installation at customer facilities.

Components Analysis - The role of components engineering is to ensure the use of components qualified for the application and to standardize on the fewest possible number of different parts. This is accomplished by development of a standard parts list from which designers may select parts. Any suggestions for additions to the list by designers are reviewed to determine if a suitable part has already been identified or an existing listing can be applied to the new application. Some parts may require a company parts specification written by components engineering.

Deployment Planning Analysis - If the program involves products that must be moved into use within a customer environment, this process of creating the initial operating capability will be subjected to analysis to determine optimum methods and techniques. Results of this analysis will be applied to requirements and designs as appropriate.

Maintainability - Maintainability is a probabilistic statement of the time it will require to repair a failure. This can be stated in terms of the Remove and Replace (R&R) time, total repair time (MTTR: Mean Time to Restore or Mean Time to Repair), or other parameters. The maintainability engineer allocates system level repair time to items in the system and tracks design team performance in responding to these allocations. As design alternatives are evaluated, the maintainability engineer looks for features that will encourage or deter maintenance actions.

Life Cycle Cost - Life Cycle Cost (LCC) is defined as the total cost of a system over its life cycle from development through disposal. LCC is a technique to determine and track during development the total cost over the complete life of a system. This includes the non-recurring cost of development and deployment, the recurring cost of manufacturing, testing, and training, the operations, maintenance, logistics support cost during its useful life, and the disposal cost of the system at life's end. This total cost may be allocated to system elements and used as a target for development. Design to cost is a component of LCC.

Design to Cost - Design to Cost (DTC) is an organized way to allocate non-recurring development cost (an element of LCC) to system elements to control the total system cost. DTC promotes the philosophy that unit cost of a product is a parameter of design which is equal in importance to performance. DTC is a technique to encourage cost-conscious behavior in the development team, and toward that end, the product development cost targets are met. DTC is applied like any other allocable quantitative requirement such as reliability or weight. A system development cost number is first identified and this cost is then allocated down through the hierarchy based on anticipated development difficulty. The design team identifies a target figure that includes a margin to protect against exceeding the required value and tracks estimated cost as a function of the design choices made. DTC is used as a selection parameter for alternative design solutions. The program Lead Systems Engineer makes the original DTC allocations, integrates the current team estimates, and tracks this parameter in time.

System Cost/Effectiveness Analysis - System cost/effectiveness analyses will be employed to support the development of life cycle-balanced products and processes and to support risk management activities. It is both a very important specialty engineering analysis discipline and an integral part of the program decision-making and control apparatus. A system level Measures of Effectiveness (MOE) hierarchy will be defined for the system as a basis for computing cost and effectiveness parameters for alternative solutions that must be traded one against the other.

APPENDIX B

FORMULAS

Utility Formulas: Use the appropriate formula below as defined in section 3.5.2.4.1.

$0 \le U \le 10$

Less Than $\longrightarrow U = 10\left(1 - \frac{P}{L_{Max}}\right)$

Greater Than $\longrightarrow U = 10\frac{(P - L_{Max})}{(P_{Max} - L_{Min})}$

Nearest To $\longrightarrow U = 10\frac{P}{L_{Max}}$

Range Max $\longrightarrow U = 10\frac{(P - L_{Min})}{(L_{Max} - L_{Min})}$

Range Min $\longrightarrow U = 10\frac{(L_{Max} - P)}{(L_{Max} - L_{Min})}$

$$\text{Range Mid} \longrightarrow \begin{cases} \text{If } P < \text{Mid Point} = \frac{(L_{Max} + L_{Min})}{2} \text{ then, } U = 10\frac{(P - L_{Min})}{(L_{Max} - P)}; \\ \quad \text{where } 0 \le U \le 10 \\ \text{If } P = \text{Mid Point} = \frac{(L_{Max} + L_{Min})}{2} \text{ then, } U = 10; \\ \quad \text{where } 0 \le U \le 10 \\ \text{If } P > \text{Mid Point} = \frac{(L_{Max} + L_{Min})}{2} \text{ then, } U = 10\frac{(L_{Max} - P)}{(P - L_{Min})}; \\ \quad \text{where } 0 \le U \le 10 \end{cases}$$

APPENDIX C

Trade-Off Analysis Checklist

All Trade-Off Analyses seem to share certain desirable characteristics. These characteristics are summarized in as a checklist for evaluation of trade study planning and execution.

Table 11 - Trade-Off Analysis Checklist

1. Objectives • Is the fundamental objective clearly understood? • Is the problem defined & bounded?
2. Viable Alternatives? • Is each alternative clearly defined? • Have the alternatives been prescreened? How? • Are affordability limits established? Sources? • Can all of the screened-out alternatives be defended? • Do alternatives meet requirements?
3. Selection Criteria? • Are all significant criteria identified? • Do the criteria discriminate between alternatives? • Are the criteria measurable? • Do the criteria relate to the study problem and objective? • Is a defensible rationale established for each criterion? • Are criteria developed from operational measures of effectiveness where possible? • Does this study use the same numerical scale as predecessors? • Is the location of the "zero point" explained?
4. Weighting? • Are rationales for criteria weights explained? • Are criteria weights consistent with guidance? • Are criteria weights consistently distributed?
5. Evaluation Methods? • Are test data confidence levels incorporated? • Are models validated? When? By whom?
6. Sensitivity? • Are error ranges carried through with worst case analysis? • Have the effects of changes in the utility curve shapes been examined? • Have rationales for the limits been developed?
7.Adverse Consequences? • Have the alternatives been evaluated for adverse consequences? • Have the alternatives with adverse consequences been appropriately judged for inclusion/exclusion, and the rationale documented?