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MANAGEMENT

Good Practice Guide
GPG-FM-003

Engineering Tradeoff Studies

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1. INTRODUCTION

Engineering tradeoff studies should be performed to select from two or more options any time during the program or project life cycle. Simple projects may need only simple tradeoff studies, which can be conducted at low cost; however, complex projects may require complex tradeoff studies, which can consume a large portion of the engineering development time and budget. Such complex tradeoff studies require careful planning and implementation. Tradeoff study planning should use a graded approach to ensure cost-effective implementation. (See section 3.) Tradeoff studies are a systematic approach to support management. Such a systematic management approach should be based on the assimilation, correlation, and/or distillation, of available information in a timely manner, so that responsible staff, including program and project management, can integrate information to make effective decisions.

Tradeoff studies are part of the larger systems engineering process, which consists of seven steps: mission analysis, functions definition, requirements identification, architecture development, alternative identification, engineering tradeoff studies based on prepared decision criteria, and test and evaluation.[1]

The primary users of this Guide are Department of Energy (DOE) Headquarters and Field Element managers and their staffs and contractors performing project activities for DOE. DOE project managers should either assume or assign the responsibilities and authorities for implementing the tradeoff study process. When DOE prime contractor(s) will complete the project or project activities, DOE project managers and contracting officers should consider incorporating the principles and processes in this Guide into contract statements of work. If multiple contractors provide direct support on the project, the DOE project manager should coordinate their tradeoff study efforts. This arrangement may require DOE to evaluate end product(s) from the contractors and verify them against end product(s) requirements to determine if the principles in this Guide have been integrated into the project satisfactorily.

This Guide is one of several guides for implementing DOE O 430.1, LIFE-CYCLE ASSET MANAGEMENT. (See *Guide to the Guides*, GPG-FM-000, for a synopsis of the information in each Guide.) DOE O 430.1 provides requirements for the DOE, in partnership with its contractors, to plan, acquire, operate, maintain, and dispose of

[1] In addition, note that Value Engineering (VE) is by nature a tradeoff methodology and may be used in many cases to make selections. See the *Value Engineering Guide*, GPG-FM-011.

physical assets. Requirements within the Order focus on "what must be done" and not on "how it must be done."

The next section of this Guide, Principles and Processes, consists of five major parts, which together form a practical Guide to the use of tradeoff studies.

- Section 2.1, Review of Alternative Development Process, summarizes information from the *Project Execution and Engineering Management Planning (PEAEMP) Guide*, GPG-FM-010, dealing with steps in the systems engineering process. This section explains how tradeoff studies fit into this larger process.

- Section 2.2, Overview of the Engineering Tradeoff Method, outlines the various steps in the complex tradeoff method process, using selection of a project architecture as an example of its application.

- Section 2.3, Planning and the Project Life-Cycle, explains how tradeoff studies evolve throughout the project. (See Table 1.) Engineering tradeoff studies may be useful throughout the project life cycle and can be essential in supporting engineering management's decision process. Several years can separate the various project phases; tradeoff studies should therefore use a configuration management process to ensure change control and to archive decisions and the rationale for those decisions, including risk management considerations. (See *Risk Analysis and Management Guide*, GPG-FM-007.)

- Section 2.4, Change Control, explains how tradeoff studies and the changes they effect are controlled and integrated into the project.

- Section 2.5, Analysis and Modeling Considerations, explains some techniques used to develop decision criteria, which are the cornerstone of the tradeoff study.

2. PRINCIPLES AND PROCESSES

For the purposes of this Guide, three general categories of tradeoff study are identified.

- A mental tradeoff study is a simple process of selection among options where one option is clearly better based on sound engineering judgment; a mental tradeoff study requires no formal analysis. Mental tradeoff studies should be reserved for selections that management has determined will have little or no risk to cost and schedule of the end product(s).[2]

- An informal tradeoff study follows the methodology of a formal tradeoff study but is not documented as formally. This type of tradeoff study is reserved for options that pose medium to little risk to cost and schedule.

- A formal tradeoff study follows a structured and systematic approach for comparison of options/alternatives via formal analysis. Formal tradeoff studies should be based on a focused set of critical parameters that pose medium to high risk to cost and schedule.

Although tradeoff studies should be performed whenever the project manager must select from two or more options, most tradeoff studies fall in the mental or informal category. Whatever category of tradeoff study is employed, all should, at least in principle, follow the formal tradeoff study process described in section 2.2 below. For the mental category, this method provides a disciplined approach in which sound engineering judgment is substituted for detailed modeling and analysis. (Section 3 discusses informal tradeoff studies.)

Formal tradeoff studies are generally conducted only when complex options confront the project manager. It is up to the project manager to identify those tradeoff studies that must be formalized. One of the most complex uses of tradeoff studies is the evaluation of alternative architectures and selection of the preferred architecture. (Architecture as used in this Guide refers to the solutions or end product(s) that satisfy the requirements and meet the functions of the project.) Therefore, selection of the preferred architecture is an excellent example to use to explain the tradeoff study process in a meaningful context and

[2] As defined in the *PEAEMP Guide* (GPG-FM-010), the term "end product(s)" is synonymous with "unique product, facility, system, or environmental condition." It is also synonymous with "structures, systems, and components" as used in contemporary configuration management literature.

in adequate detail. Accordingly, this Guide focuses on formal tradeoff studies used to select a preferred project architecture. Bear in mind that selection of the preferred architecture is but one use of the tradeoff study.

2.1 Review of Alternative Development Process

As stated above, tradeoff studies are part of the larger systems engineering process. This process involves the iteration of a series of steps: mission analysis, functions definition, requirements identification, architecture development, alternative identification, engineering tradeoff studies based on prepared decision criteria, and test and evaluation. See the *PEAEMP Guide*, GPG-FM-010, which discusses this process in section 3.2.2, Systems Engineering Principles. This discussion is supported by a set of key definitions in PEAEMP Table 3.1.1 - 1. Selected parts of the PEAEMP Guide are repeated here as guidance for the use of formal tradeoff studies.

Generally, the starting point of the systems engineering process is development of the high level mission statement, followed by each of the listed steps. This process establishes the level-1 baseline. Another iteration of the same steps follows, performed at the next level of detail, which may be based on logical allocation of the mission statement, functions, requirements, or architecture. The second iteration of the steps establishes the starting point for developing the level-2 baseline. The steps are then repeated at the next level of detail.

At each subsequent level, functions from the previous level are evaluated and subdivided (allocated) to identify all the sub-functions necessary and sufficient to accomplish the parent function (previous level). For example, the parent function, remediate waste, might be allocated to three sub-functions: retrieve waste, process waste, and store waste. After completing the functional analysis to a new level, the project manager evaluates requirements from the previous level, allocates them to sub-functions, and identifies additional requirements. The remaining steps of the systems engineering process are then performed before going to the next level.

Once the requirements and functions have been established, the next step is to search for viable alternatives to perform the functions and meet the requirements. The systems engineering process places great emphasis on verification and quantitative data to show that these alternatives, which may be very creative and innovative, are, in fact, viable means for performing the functions and do, in fact, meet the requirements. Selection from among the viable alternatives should be based on predetermined criteria. The mission analysis should identify goals, objectives, and values that will help determine the selection criteria. In most cases, the criteria are obvious considerations like cost, schedule, and risk. During the selection process, less obvious criteria like organization or stakeholder values should be included.

Preferred alternatives resulting from the selection process become the technical baseline for the project. Iterative refinement of this technical baseline will add details and eventually yield end product(s) that have been verified to ensure they are capable of performing the functions and meeting the requirements.

Where to stop the iteration is a key question. High-level mission statements (e.g., clean up a site) usually stop with the identification of systems (e.g., a preprocessing plant or a high-level waste vitrification plant). Each system may then be handed off to another organization, which repeats the system engineering process to identify the design requirements for each system. The same basic steps are used over again.

Some general guides for stopping the iteration process include the following situations.

- A well bounded end product(s) is identified.
- There are no more practical functional allocations.
- End product(s) can be provided with existing technology.
- End product(s) is affordable.
- For the level of allocation, available information is sufficient to make the required decisions for the next set of activities (i.e., to continue to the next phase or stop project work).
- The complexity and quantity of data has reached a point that one organization cannot manage the information effectively. As a result, discrete systems are identified, which may be worked by different organizations.
- An organization has allocated to a level at which it performs a make-buy analysis. A buy decision is made and the requirements are included in a contract.

Many opportunities exist for the use of tradeoff studies in arriving at the situations listed above. Most of the time, engineering judgment and a mental tradeoff study are all that are necessary. The project manager should consider the following conditions as the minimum in deciding if a formal tradeoff study is required.

- A preferred architecture must be selected from various alternative architectures.
- A technology must be selected.
- Risk is a key factor for cost, schedule, or scope. (See Table 1.)
- Like elements of an allocation process must be combined to allow more effective development.
- Combinations of the above.

2.2 Overview of Engineering Tradeoff Study Method

The engineering tradeoff study method provides a structured, analytical framework for evaluating alternative architectures, designs, component selections, and test approaches. Figure 1 shows one step-by-step method for approaching a tradeoff study. Each step is discussed in the following paragraphs. When performed to select the preferred architecture, this process assumes that functions and requirements are go/no-go constraints. To qualify as an alternative, an architecture must perform all identified functions and meet all identified requirements.

2.2.1 Identify Viable Alternatives

Alternative architectures will be either predetermined (by initial design considerations or by DOE prescription) or developed specifically for the engineering tradeoff studies. Candidate architectures should represent the widest practical range of distinctly different alternatives, screened to include only those that can perform satisfactorily. A second screening may be desirable on the basis of attainability and affordability. (That is, is the candidate alternative achievable within time and budgetary constraints?)

Alternative architectures must be described in enough detail that the relative worth of each can be judged reliably and accurately. If an insufficient number of candidates survive the screening process, the screening criteria can be liberalized or the system engineering process repeated to generate additional, acceptable alternatives. An insufficient number of alternatives may indicate that the lowest level of allocation has been reached and the process should be stopped.

2.2.2 Define Goals, Objectives, and Values

The project's mission analysis should be the primary source for identifying goals, objectives, requirements, and DOE and stakeholder values, which the project manager should use as the basis for establishing decision criteria. At deeper levels of allocation, the engineering process may generate additional goals and objectives to help differentiate among segments, components and parts, and other, lower-level architectures.

Goals, objectives, and values are graded judgments useful in differentiating among alternative architectures. In contrast, requirements are usually go/no-go judgments; if an architecture cannot meet the requirements, it cannot become an alternative. Decision criteria should reflect these graded judgments, and a decision process should formalize the differentiation among alternatives, eventually resulting in the clear identification of a preferred alternative.

2.2.3 Formulate Decision Criteria

Decision criteria are standards for differentiating an alternative's performance relative to project goals, objectives, and values. Good decision criteria may be objective or subjective, but should:

- differentiate meaningfully among alternatives without bias;
- relate directly to project goals, objectives, and values of DOE and stakeholders;
- be measurable or estimable at reasonable cost;
- be independent of each other at all levels of allocation; and
- be universally understood by evaluators.

Objectives commonly deal with risk, cost, and schedule. Most projects will have additional objectives that are mission-specific. For example, a project with an objective to "ensure acceptable technical risk" or "ensure acceptable manufacturing risk" could result in a set of decision criteria consisting of (1) the estimated risk value and (2) any costs, if necessary, to mitigate risk to an acceptable level.

On the other hand, the objective "achieve minimum costs" could result in a set of decision criteria consisting of (1) funding profile, (2) total project cost, and (3) life cycle cost. Subsequent steps would evaluate each alternative for each of these decision criteria, and the decision process would ultimately assign a score for each alternative based on its cost performance. The alternative with the smallest cost profile, lowest project cost, and lowest life cycle cost would receive the most desirable score, or greatest differentiation, and would become the preferred alternative.

A more likely outcome would be that one alternative would have the smallest cost profile, a second would have the lowest project cost, and possibly a third, the lowest life cycle cost. To differentiate among the three alternatives, the decision process must assign a weight factor to each decision criterion.

2.2.4 Assign Weight Factors to Decision Criteria

The project manager should assign numerical weights to the decision criteria according to their importance in determining which alternative to select. This Guide recommends an approach that sums all weight factors to 1.0, a "unity sum."

Weight factors may be determined by conducting either an objective or subjective analysis. Subjective analyses should be rendered more reliable by the use of group consensus or decision support techniques such as Pareto charts, histograms, or cause and effect diagrams.

To help ensure objectivity of subsequent evaluations, management may withhold the weight factors from the analysts who perform the evaluations.

2.2.5 Prepare Utility Functions

Comparisons are difficult for diverse criteria such as cost (dollars), schedule (years), technical performance (widgets per year), and risk (high, medium, or low) unless they can somehow share the same units. Utility functions provide a mediating capability to transform diverse criteria to a common, dimensionless scale. They are not necessary for every tradeoff study application, however.

Utility functions assume that the performance associated with a particular decision criterion can be transformed into a utility score. A recommended approach is for the utility score to range from 0 to 1, with the expected lower bound of the criterion corresponding to a utility score of 0 and the upper bound, to a utility score of 1. The scoring range of 0-1 is arbitrary in this Guide, and an analyst might elect to use a scoring range of 0-10, 0-50, 0-100, or whatever range is appropriate for a project. Whatever the score range, the lower and upper bounds of performance for the entire set of alternatives correspond to the lowest possible utility score (usually 0) and the highest possible score.

For example, if cost analyses determine that the life cycle costs for a set of alternatives range from $2M to $3M, the $2M alternative would have a utility score of 1, and the $3M alternative would have a score of 0. The utility function would thus appear as shown in Figure 2.

The shape of the utility function curve could result from an objective analysis, or it could reflect good engineering judgment. But the utility functions for a given tradeoff study must always use consistent scales (e.g., between 0 and 1) so as not to weight the scores inadvertently. The zero point of each curve indicates the level of performance that no longer provides value. In the above example, alternatives with life cycle costs exceeding $3M are not worth pursuing.

Graphic utility functions of the type shown in Figure 2 are not necessary for every criterion. In some studies, the functions may be in the form of analytic expressions instead. Spreadsheet tables can be used to demonstrate project performance by transforming the analytic expressions to a utility score for each decision criterion.

2.2.6 Evaluate Alternatives

Analysts should evaluate the performance of each alternative for each decision criterion. These performance evaluations may result from vendor test data, parametric analyses, simulations, analogous experiences, or other available and affordable methods.

As described above, analysts use utility functions to convert performance estimates into dimensionless utility scores. A table should then be developed to display and summarize the raw utility scores. The project manager (or decision maker) applies the weighting factors to each raw score, thereby determining the weighted scores and completing the effort. An example is shown in Table 2, which evaluates three alternatives.

This example preserves the utility function range of 0 to 1. For each criterion, the best performer of the three alternatives receives a raw utility score of 1.0, while the poorest receives a 0.00. The intermediate alternative, performing somewhere between the poorest and the best, receives a score between 0 and 1 as determined by the utility function curve.

Alternative 1 has the greatest weighted score, and therefore might be designated the preferred architecture. But alternative 2 has a high score too, nearly as high as alternative 1. Therefore, a sensitivity check should be used to validate these scores before designating a preferred alternative.

2.2.7 Perform Sensitivity Check

The purpose of the sensitivity check is to validate the ranking that results from the decision process by demonstrating that small changes do not alter the ranking. Such small changes could occur for raw scores, weight factors, requirements, or technical capabilities. If the sensitivity check reveals that small changes could reverse a decision, the decision process must be adjusted to make it insensitive.

A minor change in requirements or technical capabilities could permit additional alternatives to pass the go/no-go judgment, qualifying them for inclusion into the selection process. Likewise, a minor change in technical capability can sometimes cause a major change in estimated cost, significantly changing the raw score for a cost criterion. Such sensitivities indicate that the selection process may not reflect the true objectives of the mission.

The sensitivity analysis should evaluate the impacts of relaxing requirements, improving technical capabilities, or reducing uncertainties in cost estimates. The analysis should also identify the changes that will appropriately desensitize the selection process for management's consideration and approval.

In the example shown in Table 2, the weighted scores for two alternatives are so close that an informal examination cannot validate the ranking order. A sensitivity check is therefore warranted.

The first step is to examine how small changes in the raw scores, typically less than 10%, would affect selection of the preferred alternative. The raw scores of 1.00 and 0.00, for alternatives at the extreme high or low end of the performance range, will not incur small changes unless such changes will cause another alternative to replace either the high or low alternative. In the example, no replacement of alternatives will occur at the performance extremes.

Inserting raw score changes of -10% for alternative 1 also does not alter the ranking. The calculated change is shown in Table 3. If a concurrent change of +10% occurs for the second and third-ranked alternatives, the ranking is altered, but the alteration is not considered significant because the change that has occurred is extreme.

At this point, the sensitivity analysis has established confidence in the ranking. A confirmatory check, if desired, would retain the original raw scores, but would introduce small changes in the weight factors while retaining the unity sum of the weight factors.

If the sensitivity analysis does not validate the ranking, several options are available to the project manager or decision maker.

- Delay the decision until research, development, or other additional information is available to improve estimates or reduce uncertainty allowances.
- Acquire better tools to improve estimates and reduce uncertainties.
- Modify the decision criteria or weight factors to desensitize the selection process sufficiently for a valid decision.
- Reduce risk by pursuing a parallel path that develops at least one additional alternative until a valid selection is possible.

2.2.8 Select Preferred Alternative

Once validated, the decision process results should clearly identify the preferred alternative. Note that the preferred alternative (the preferred architecture, for example) may not be selected if cost, schedule, and technical constraints rule it out. In each case, selection of the preferred alternative prompts the project manager or analyst to begin the next level of allocation.

In the example described in section 2.2.6, alternative 1 received the highest weighted score and withstood a sensitivity analysis; it was therefore designated the preferred alternative. Had the decision process been structured differently, however, with different decision criteria, the preferred alternative selected might have received the lowest score, rather than the highest. Other decision structures might, for example, select a preferred alternative based on maximum scores for one set of decision criteria and minimum scores for another set (the max-min process).

2.2.9 Document Results

Tradeoff study reports should be prepared to document the decision process, including the rationale used in the decision process and risk assessment and risk management considerations. At a minimum, each report should describe analysis results and rationale, alternatives considered, decision criteria, weight factors, and results of the sensitivity analysis.

2.2.10 Risk Considerations in Tradeoff Studies

Tradeoff studies should cover a broad spectrum of important parameters during preconceptual activities and each of the project phases. Risk should be one of those parameters for selecting preferred architectures to meet mission needs and also for fine-tuning selected concepts during later project phases.

Achieving acceptable technical, cost, and schedule risks is an obvious and common objective for many projects. Tradeoff studies may use this objective to develop decision criteria, which may include:

- the calculated risk value,
- the confidence level that any necessary risk mitigation programs successfully reduce unacceptable risks to an acceptable value within the required timing, and
- the cost of the risk mitigation programs.

Alternative architectures with acceptable risks should receive better utility scores than projects requiring mitigation programs to achieve acceptable risks. But, if all alternatives require risk mitigation programs, the confidence level and costs for those mitigation programs could be major factors in the selection process. Tradeoff studies should also consider the risks associated with each project phase.

Execution Phase. Tradeoff studies should reduce construction risk by giving preference to designs that:

- are simple,
- use open architectures with commercially available components,
- are compatible with available construction infrastructures,
- are easy to test at factory and field sites, and
- are supportable with existing logistics infrastructure.

Operation and Maintenance Phase. Tradeoff studies should focus on reducing operational risks by giving preference to designs that:

- facilitate in situ testing and maintenance as well as in-service inspections,
- have flexibility to accommodate changes in the operational environment, and
- adapt easily to periodic upgrades to state-of-the-art equipment and modifications for mission changes.

Closeout Phase. Tradeoff studies should focus on reducing close-out risks by giving preference to designs that:

- facilitate post-operations using available technology for remote or in situ monitoring and control of facility status and
- incorporate features that accommodate available technologies or emerging technologies to perform cost-effective decontamination and decommissioning.

2.3 Planning and the Project Life-Cycle

The following subsections present guidance for tradeoff study planning and activities during each phase of the life cycle, as shown in Figure 3. The project manager is responsible for identifying appropriate combinations of tradeoff study methods and levels of tradeoff study to help ensure project performance. One tool that the project manager should consider is a tradeoff study plan, which relates the effort to the project's technical risks, operability, performance criteria, reliability, availability, and maintainability.

2.3.1 Planning Considerations

Tradeoff study planning is an important part of implementing effective and efficient design activities. Important considerations of tradeoff study planning include:

- need for tradeoff studies,
- approach to use,
- methods selected,
- identification of alternatives for consideration,
- goals and objectives for the decision criteria,
- weighting factors if used,
- documented results, and
- resources to accomplish the tradeoff studies.

2.3.1.1 Planning Approaches. A number of approaches can be used to plan the tradeoff study. Common approaches can be by requirement, function, schedule, technology, or cost. To facilitate project planning, management and engineering should establish the approach during the preconceptual activities. A recommended example approach is to organize the tradeoff study activities by requirement; that is, state the requirement, specify the tradeoff study method(s) that will be used to compare and choose the alternatives, and identify the decision criteria that will be used.

Selected requirements (i.e., those management believes will have the greatest impact on project cost, schedule, and risk) should be addressed in the tradeoff study planning and would include requirement types based on performance parameters, codes and standards, and laws and regulations. For projects with complex end products, the requirements could be an extensive data set requiring extensive maintenance. A number of software tools are commercially available to support this effort. Other approaches that can also be used include general data bases or table entries in the planning documentation. The project manager should consider the use of such tools.

2.3.1.2 Procedures to be Included. Responsible organizations usually have standardized procedures for such verification activities as analysis, design reviews, and software development activities (required for verification/validation of simulation models). Where they are used, the most cost-effective approach should be selected.

For simulations, procedures are generally necessary to specify, at a minimum, the simulation objective, the "how to" for completing the simulation, the method for recording the simulation data/results, and the method for evaluating the results. The simulation and tradeoff study procedures, the documentation of the verification activity results, and an assessment of the results are important products from the tradeoff study effort.

2.3.1.3 Planning Documentation. The complexity of the desired end product(s) should be a determining factor in the level of tradeoff study planning and the level of documentation. On projects with limited tradeoff study activities, tradeoff study planning can be documented in the Project Execution Plan. On projects requiring extensive identification and verification activities, a separate tradeoff study plan is recommended.

Any appropriate format for the tradeoff study plan is acceptable. However, the plan should address each requirement for which a tradeoff study will be used, the tradeoff study methods to be used, the decision criteria, the performance period for the tradeoff activities, and the estimated cost of the tradeoff activity if it is estimated separately from other project events. Items that may require separate scheduling would be general design reviews and simulation verification/validation activities. The detailed planning effort should include the preparation of procedures showing how the various tradeoff study activities will be completed.

2.3.2 Preconceptual Activities

During the preconceptual activities, tradeoff studies should be used to select the technology and architecture capable of meeting end product(s) functions and requirements. Evaluations conducted during this phase are typically based on summary level detail and are used with such decision criteria as safety, protection of human health and the environment, cost, schedule, reliability, maintainability, and supportability. Techniques like parametric analysis, modeling, or comparisons to similar DOE projects, either ongoing or completed, should be used to perform tradeoff studies. GPG-FM-028, *Productivity Tools: Automated, Models, and Simulations,* provides additional information. Decisions based on the information generated by tradeoff studies during the preconceptual activities can establish the foundation for all subsequent tradeoff studies and the decisions upon which they are based.

2.3.3 Conceptual Phase

During the conceptual phase of the project, the project manager should develop the tradeoff study plan, if needed, to identify and coordinate specific tradeoff study activities that may be necessary to select a preferred architecture for the project.

At the start of this phase, as shown in Figure 3, many of the decision criteria should have been developed, reviewed, and approved. The conceptual phase may, however, introduce additional decision criteria and possibly discard some criteria developed during the preconceptual activities. Some initial portions of the engineering tradeoff study plan activities, which are based on approved portions of the plan, may be executed during the conceptual phase even while other portions of the plan are still being developed, reviewed, or approved.

During the conceptual phase, tradeoff studies should focus on defining alternative architectures at the conceptual levels of allocation, developing a list of decision criteria for the conceptual architectures, and selecting the preferred architecture. The conceptual phase level of allocation, and its corresponding tradeoff studies, must have sufficient depth to permit definition of end product(s) with enough detail to support cost estimates and evaluations of budget quality.

Tradeoff study activities that should occur during the conceptual phase include the initiation of tradeoff study planning and establishment of a tradeoff study tree, establishment of alternatives at deeper levels of allocation, establishment of decision criteria for each level (which may differ from the criteria used during preconceptual activities), development of tradeoff analyses, and preparation of tradeoff study reviews. Tradeoff study products created during the conceptual phase include the tradeoff study tree and tradeoff study reports, which should be documented and preserved for potential use during later phases of the project. An example of a tradeoff study tree is shown in Figure 4.

2.3.4 Execution Phase

At the initiation of the execution phase, the remaining portions of the tradeoff study plan should be finalized, reviewed, and approved. Tradeoff study activities generally peak during the execution phase as alternative designs are screened and a detailed design selected.

During the execution phase, tradeoff studies should focus on defining alternative architectures down to the component and part level, developing a list of decision criteria for these architectures, and selecting the final architecture. Tradeoff studies will also be used to assess design changes and help ensure risks are acceptable during construction, operations and maintenance, and closeout.

Tradeoff study and evaluation activities that should occur during the execution phase include the finalization of tradeoff studies and tradeoff study reviews, including peer reviews, analysis, and a final assessment of the tradeoff study evaluation results. The tradeoff study and evaluation products would include tradeoff study simulations and a final assessment report. As in earlier phases, results of tradeoff study activities should be recorded for use during the next phase.

Tradeoff study activities generally decline toward the end of the execution phase as functional and operational performance tests are completed. Generally, tradeoff studies will: (1) help establish test, evaluation, and verification methods and (2) assess end product(s) changes that might be necessary to correct deficiencies revealed in the tests and evaluations.

2.4 Change Control

Tradeoff study activities must be integrated into the change control process for the project. Change control requests may occur for a variety of reasons, including changes in project requirements or changes based on the results of tradeoff study activities. The project manager should clearly define the process for proposing changes due to tradeoff study activities, ensuring those changes are integrated into the project and communicated effectively to project participants. (See the *Configuration and Data Management Guide* (GPG-FM-012.)

Project changes should be evaluated to determine their effect on tradeoff study activities. Changes to performance requirements, variance limits, system configuration, etc. should be evaluated for potential impacts, including the impact on cost. Normally, a Change Control Board is established to decide if a change should be made once the potential impact of the change is well defined and documented. Changes that are accepted should be incorporated into the tradeoff study plan and should be performed.

Each tradeoff study should be documented in an engineering report, which should be integrated into the configuration management system. The engineering report includes the tradeoff study tree; describes the alternative candidates, evaluation criteria, and model used, if applicable; provides justification for the decision; and describes changes in weights, scoring, or requirements that would affect the selection. Engineering reports should be numbered sequentially so they can be traced (through a traceability tool) to the requirement from which they originated and to the new requirements that they impose upon the system.

2.5 Analysis and Modeling Considerations

To help the user begin the tradeoff study process, some considerations for developing decision criteria based on analysis and modeling approaches are presented in the following subsections. This is by no means a complete list, and not all of these techniques should be used on every project. The selected techniques should be graded to the project requirements.

2.5.1 Life-Cycle Cost Analyses

Life-cycle cost tradeoff studies are used to evaluate the cost of each alternative and to provide input in evaluating the alternatives' effectiveness. Life-cycle cost studies provide the following cost information to support tradeoff study decisions.

- Cost information for system effectiveness assessments.
- Cost of development, manufacturing, test, operations, support, training, and disposal.

- Design-to-cost goals, current estimate of these costs, any projected change in the estimate of these costs, and known uncertainties in these costs.

- Impacts on the life-cycle cost of proposed changes.

2.5.2 End Product(s) Effectiveness and Cost Effectiveness Analyses

End product(s) effectiveness and cost effectiveness analyses are conducted on life-cycle processes of test, distribution, operations, support, training, and disposal. These analyses are conducted to support (1) inclusion of life-cycle quality factors into the end product(s) designs and (2) the definition of functional and performance requirements for life cycle processes. The results of these analyses are used in evaluating tradeoff studies and assessing end product(s) effectiveness.

2.5.3 Environmental Analyses

Environmental analyses identify and ensure compliance of the alternative selected with all Federal, State, municipal, and international environmental statutes and hazardous material lists that apply to the project. Environmental analyses include environmental impact studies performed to determine the impact of the architecture selected during the entire life cycle of the system on the infrastructure, land and ocean, atmosphere, water sources, and human, animal, and plant life. Use of material or generation of by-products that present known hazards to the environment are to be avoided to the extent possible; otherwise, provisions must be established for properly handling, storing, and disposing of hazardous materials or by-products. The results of these analyses are used to evaluate tradeoff study alternatives and assess system effectiveness.

Analyses performed while evaluating and selecting project alternatives must be integrated and synchronized with activities that support NEPA documentation; specifically, Environmental Assessments (EAs) and Environmental Impact Statements (EISs), which are generated to comply with the NEPA requirements specified under 10 CFR 1021 for the evaluation of major Federal actions. This is accomplished through the sharing of alternative evaluations and EIS analysis results. The *Environmental Interfaces Guide* (GPG-FM-021) describes how environmental considerations and processes are integrated with project planning and execution.

2.5.4 Risk Analysis

A risk analysis is performed to quantify the impact of an undesirable consequence. Risk is quantified based on the likelihood of occurrence (probability) and consequences of an occurrence. For system effectiveness assessments, each element of the system architecture developed to date is assessed to determine what can go wrong and what impact it will have on the system if it does go wrong. For tradeoff studies, risk levels assessed during the estimate of life-cycle costs, evaluation of system cost effectiveness, and development of environmental impact analyses are prioritized and reported as part of tradeoff study recommendations.

2.5.5 Types of Analysis and Modeling Techniques

During systems development, the following analyses and models may be employed: economic analysis, mathematical modeling and optimization, probability and statistical models, queuing theory and analysis, control concepts and techniques, and the heuristic method.

2.5.5.1 Economic Analysis. The purpose of performing an economic analysis is to compare each identified alternative by eliminating as many cost biases as possible. For example, the system that is the least expensive to create and design may be the most expensive to dispose of in the future. During economic analysis, models of the alternatives are constructed to evaluate all known costs of a system from the preconceptual activities through the operational and closeout phases. A brief discussion of the various economic analyses available to the user follows.

2.5.5.1.1 Equivalence Evaluations. If two or more alternatives are to be compared, their characteristics must be placed on an equivalent basis. Two things are said to be equivalent when they have the same effect. Two monetary amounts are equivalent when they have the same value in exchange. Three factors are involved in the equivalence of sums of money: (1) the amount of the sums, (2) the time of occurrence of the sums, and (3) the interest rates. Two useful techniques for calculating equivalence are the following.

Three types of equivalence evaluations may be conducted.

- Equivalent function diagrams. The present value is plotted as a function of the interest rate.

- Determining the equivalent "should" cost of an asset. The cost of any asset is made up of the cost of depreciation plus the cost of interest on the undepreciated balance. Therefore, the "should" cost of an asset is the annual equivalent first cost less the annual equivalent salvage value. This annual equivalent cost is the amount an asset must earn each year if the invested capital is to be recovered along with a return on the investment.

Present-Worth Evaluation - In a system evaluation, the anticipated positive gain or benefit of the system must be compared with a feeling or opinion regarding nonspecified opportunities that may present themselves. A present-worth evaluation is conducted to find the present worth of future savings and disbursements and is one technique for evaluating the positive gain or benefit of a system.

Rate of Return Evaluations - Because the rate of return is a universal measure of economic success, this technique is one of the best methods for comparing a specific proposal with other, less well-defined alternatives. Rate of return is determined by equating either present worth or equivalent annual receipts with disbursements at a given interest rate. The results are plotted. The point at which the disbursement values intersect the receipts values is the rate of return on the system.

Payout Evaluations - Payout evaluations are used to determine the time required for the system to pay for itself. The payout period is the time required for the difference in the present value of receipts to equal the present value of disbursements (or the annual equivalent receipts and disbursements) for given increments of time. The results of the calculations are plotted. The point at which the present worth of the savings and disbursements intersect is the time required for the system to pay for itself.

2.5.5.1.2 Break-Even Evaluations. Break-even evaluations are useful in relating fixed and variable costs to the measures of operational activity (i.e., hours of operation or number of units produced). The break-even point identifies the range of the decision variable within which the most desirable economic outcome may occur. Two types of break-even evaluations may be conducted.

Make-Buy Evaluations - In designing a system, a project manager (or contractor) must decide if it is more cost effective to make a subsystem or component or buy the subsystem or component. It is the responsibility of the program manager to include in the evaluation the availability of assets at other DOE operations.

The first step of such an evaluation is to determine the total annual cost as a function of the number of units for the make alternative. The total annual cost of the make alternative is the fixed costs plus the variable costs incurred in the manufacturing of each unit. The second step is to calculate the total annual cost as a function of the number of units for the buy alternative. The break-even point occurs when the total annual cost of the make alternative equals the buy alternative. The answer is usually in the number of units required to reach the break even point. If the number of units required is greater than the number of units required to complete the project, the choice would be to buy the number of required units.

Lease-Buy Evaluations - In designing a system, a project manager must decide if it is more cost effective to lease a piece of support equipment or to buy the support equipment. The first step of a lease-buy evaluation is to determine the total annual cost as a function of the number of days that the support equipment is to be used. The total annual cost of the lease alternative is the cost of leasing the equipment plus the cost of operating the equipment. The second step is to calculate the total of the buy option. The total cost of the buy option is the initial cost minus the salvage rate times the capital recovery factor (a factor based on the interest rate and the expected life time of the equipment) plus the salvage value times the interest rate plus the maintenance cost plus the operating cost. The break-even point occurs when the total annual cost of the lease alternative equals the buy alternative. The answer is usually in the number of days required to reach the break even point. If the number of days required is greater than the number of days that the support equipment is to be used, the choice would be to lease the equipment.

2.5.5.2 Mathematical Modeling and Optimization. Tradeoff studies are facilitated through the use of various types of mathematical models or a series of models to describe a system. The output of one model may be the input of another, depending on the complexity and depth of the modeling effort. A model is a simplified representation of the real world that abstracts the features of the situation relative to the problem being analyzed. Models allow the analyst to combine the parameters under study to determine the relative merits and effects of the various combinations of parameters on the entire system. Such simulations do not make decisions but are a useful tool to assist in the decision process.

The four types of models are physical, analog, schematic, and mathematical. Physical models look like what they represent, analog models behave like what they represent, schematic models graphically describe a situation or process, and mathematical models symbolically represent the principles of a situation being studied. Mathematical models used to study operational systems must often incorporate probabilistic elements to explain the random behavior of systems.

Mathematical modeling and optimization involves the formulation of effectiveness functions embracing two classes of variables. (An effectiveness function is a mathematical statement formally linking a measure of effectiveness with variables under the direct control of the decision maker and variables not directly under the control of the decision maker.) Mathematical modeling and optimization provide a means whereby various values for controllable variables, designated **xi**, can be tested in the light of uncontrollable values, designated **yi**. For a tradeoff study, different values of **xi** are substituted while the **yi** value remains constant. The functional relationship is expressed as

$$E = f(xi, yi)$$

where E = the measure of effectiveness.

In an ideal situation, all variables of the system or subsystem for which the model is being developed would be included in the effectiveness function. In reality, only the variables assumed to be drivers in system effectiveness measures are used as variables.

If the effectiveness function can be differentiated, basic calculus may be used to find the maximum or minimum values. If the first derivative of a stationary value is equal to zero, it cannot be stated that the function is at an optimum point because the stationary value may be an inflection point of the function. To determine if the stationary point is a maximum or minimum, the second derivative is taken. If the value of the second derivative at the stationary point is positive, the stationary point is a minimum. If it is negative, the stationary point is a maximum.

For non-steady state functions, the mathematical models are constructed to represent a steady state function. Control variables are introduced to change the environment for comparison. This is a simplification technique.

Various types of mathematical techniques are available for the decision maker to use. These techniques include but are not limited to Lagrange multipliers, graphical methods, and various linear and dynamic programming methods.

2.5.5.3 Probability and Statistical Models. Most systems are not static but change under different and random conditions. The rate of change and the conditions that make systems change can be described using a probability distribution. Probability distributions are generally expressed mathematically as functions of the mean (an indication of central tendency) and the variance (a measure of dispersion). In conducting tradeoff studies, the mean and variance of the alternative options are compared and used as a decision criterion.

2.5.5.4 Monte Carlo Analysis. A commonly used model for tradeoff studies is the Monte Carlo analysis, which entails comparison of multiple random variables. This method is used to determine the sensitivity of the system to random processes and to characterize alternatives under differing operational conditions.

2.5.5.5 Queuing Theory and Analysis. Queuing theory is beneficial in performing tradeoff studies when the alternatives under consideration are facilities designed to service a population in which the population forms a waiting line (queue) and receives service in accordance with a predetermined waiting-line discipline. After receiving service, the population may enter yet another queue or leave the system. The objective of queuing analysis is to determine the capacity of the service facility to minimize the total cost of the queuing system, taking into consideration the relevant costs and characteristics of the arrival population. Queuing models frequently are evaluated using the Monte Carlo techniques as described above.

2.5.5.6 Control Concepts and Techniques. Most systems are deployed and must operate in an environment that changes over time. Control of portions or all of a system can help maintain system performance within specified tolerances or increase the worth of the system output. Control variables must be related in some way to the system characteristic or condition being controlled.

Every control system has four basic elements.

- A controlled characteristic or condition.
- A sensory device or method for measuring the characteristic or condition.
- A control device that compares measured performance with planned performance.
- An activating device that alters the system to bring about a change in the output characteristic or condition being controlled.

In tradeoff studies, alternatives are evaluated to determine the extent of the control system required for the system. Alternatives are studied in different combinations to determine the most cost-effective system for producing the system effectiveness desired. The effectiveness of the controls may be evaluated using Monte Carlo Methods from which the statistical history of the controls can be derived.

2.5.5.7 Heuristic Method. The main purpose of some projects is to define requirements and decision criteria for the customer. In these cases, the customer may not be able to set firm requirements for one or more of the following reasons.

- The customer is not a monolith and cannot agree on a common set of requirements.
- Requirements are set by an exterior force that is ambiguous or fluid.
- The objectives of the customer are general and not specific enough to measure.

In such cases, alternative approaches are required to assist the customer in establishing a set of requirements clear enough to serve as the basis for project development. One such approach is called the heuristic method in which tradeoff studies begin with models, which are used and adjusted until the customer and the project manager can agree on the desired performance. Once agreement is reached, the model defines the requirements and a production version of the model becomes the main purpose of the project.

3. GRADED APPROACH

Management should carefully consider the type of tradeoff study required when initiating a project. Not every selection performed during the project life cycle will require a formal tradeoff study. In fact, most tradeoff studies fall in the mental or informal category. Therefore, a graded (i.e., tailored) approach should be used to ensure tradeoff study principles and practices are incorporated in each project commensurate with project factors such as complexity, visibility, and uncertainties. These factors provide the basis for identifying the category of tradeoff study necessary to ensure successful project completion. Some minimum level of tradeoff study activity is necessary to demonstrate that the alternative chosen is the best alternative based on the decision criteria. Without this minimum set of activities, the project manager has no basis to defend the alternative choice.

Mental tradeoff studies, described at the beginning of section 2, are simple and are therefore the type used for most projects. The following example for selecting a general purpose pump illustrates this type of tradeoff study. The project designer should have the following information, based on a top down requirements and architecture allocation process:

- An established basis for the pump being the preferred solution.

- Requirements for the pump functions, including the following:

  - flow, volume, pressure, lift, particle suspension, etc.;
  - safety criteria (i.e., radiation, hazardous material, etc.);
  - operating environment including maintenance support; and
  - reliability.

The construction engineer would ask the procurement department for all the manufacturers' specification sheets for pumps that meet this application. He/she would then review the pump data sheets and select the pump based on cost and delivery schedule information. The selected pump would be entered into the as built documentation and maintenance requirements identified for operations.

In applying this Guide to the preparation of the tradeoff study portions of contract solicitation documents, the DOE project manager should grade the principles and practices to the specific characteristics of a particular project. Tradeoff study tasks should be deleted, altered, or expanded as necessary. The project manager should define the depth of detail and level of effort required and the intermediate and final engineering data expected. The contractor and the Government may tailor the tradeoff study approach further during contract negotiations. The agreed-upon tradeoff study approach should be reflected in the resulting contract. Guidance is provided throughout this Guide on the appropriate level of the tradeoff study effort.

4. MEASURING RESULTS

The ability of tradeoff studies to demonstrate that the alternative architecture performs the mission functions and meets the requirements should be measured throughout the project. Tradeoff study plans and procedures should be thoroughly evaluated for completeness, currency, and accuracy. Tradeoff study reports should be reviewed to determine if the tradeoff study results adequately substantiate the determination that performance requirements are met by the alternative chosen.

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5. SUGGESTED READING

For further information on the topics covered in this Guide, see Attachment A.

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6. ASSISTANCE

Questions concerning this Guide may be referred to the Office of Field Management in Washington, D.C. at (202) 586-4041.

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Table 1. Tradeoff Study Roles in the Project Life Cycle.

Project Life Cycle	Tradeoff Study Role
Preconceptual activities	Help establish the preferred technology and top-level architecture for end product(s).
Conceptual phase	Help develop and select the preferred architecture for end product(s) that meets technical, cost and schedule requirements with acceptable risks.
Execution (Design and Construction Subphases)	● Help select component/part designs. ● Support make/buy decisions. ● Support construction process decisions. ● Assess design changes.
Execution (Turnover Subphase)	● Help establish test, evaluation, and verification methods. ● Assess facility hardware and software changes necessary to correct deficiencies.

Table 2. Example Weighted Summary.

Decision Criteria*	Weight	Alternative 1		Alternative 2		Alternative 3	
		Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Cost	0.20	1.00	0.20	0.50	0.10	0.00	0.00
Schedule	0.15	0.15	0.0225	0.00	1.00	1.00	0.15
Tech. Risk	0.25	1.00	0.25	0.00	0.00	0.55	0.0138
Occup. Safety	0.35	0.05	0.0175	1.00	0.35	0.00	0.00
Environ. Impact	0.05	0.00	0.00	0.50	0.025	1.00	0.05
Totals	1.00		0.490		0.475		0.338

* The decision criteria of cost, schedule, technical risk, safety, and environmental impact are for illustration only. Each project should develop its own specific decision criteria.

Table 3. Extreme Case Changes in Raw Scores*.

Decision Criteria*	Weight	Alternative 1		Alternative 2		Alternative 3	
		Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Cost	0.20	1.00	0.20	0.50	0.11	0.00	0.00
Schedule	0.15	0.135	0.0203	0.00	0.00	1.00	0.15
Tech. Risk	0.25	1.00	0.25	0.00	0.00	0.605	0.0151
Occup. Safety	0.35	0.45	0.0158	1.00	0.35	0.00	0.00
Environ. Impact	0.05	0.00	0.00	0.55	0.0275	1.00	0.05
Totals	1.00		0.486		0.488		0.351

* Alternative 1 raw score decreased 10% and alternatives 2 and 3 raw scores increased 10%. No changes resulted for any raw scores of 0 to 1 at the performance extremes because the 10% changes caused no changes in the performance alignment of alternatives for any decision criterion.

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Figure 3.1-1: Trade Study

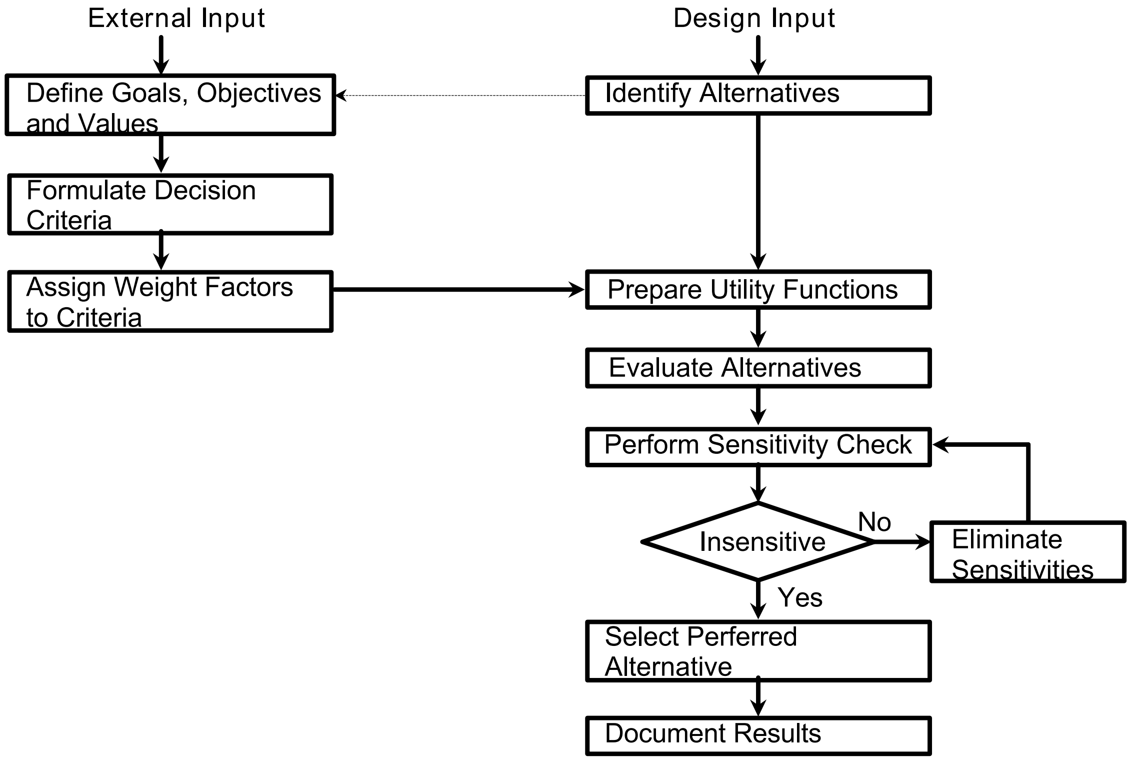

Figure 3.1.5-1: Example Utility Function for Life Cycle

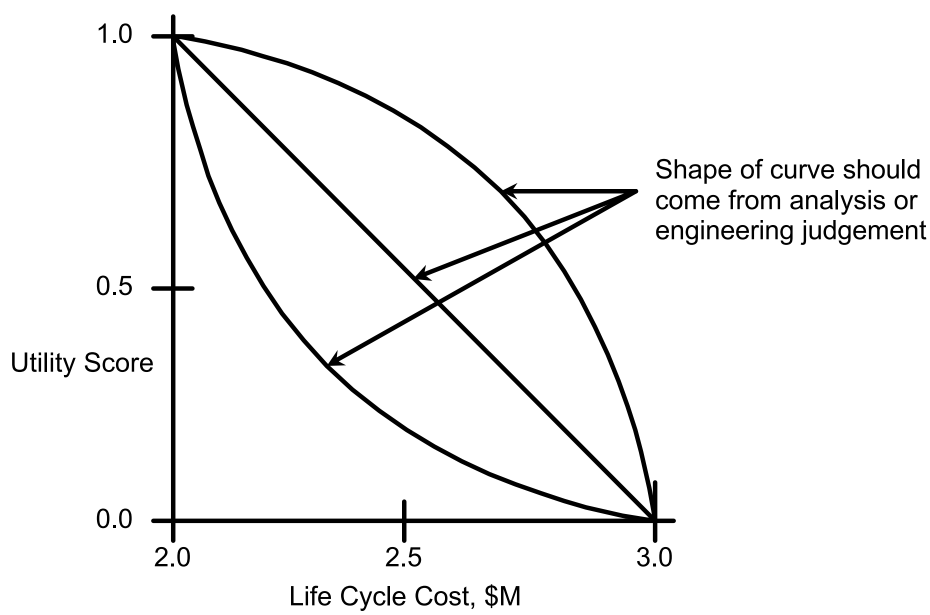

Figure 3-3: Trade Studies

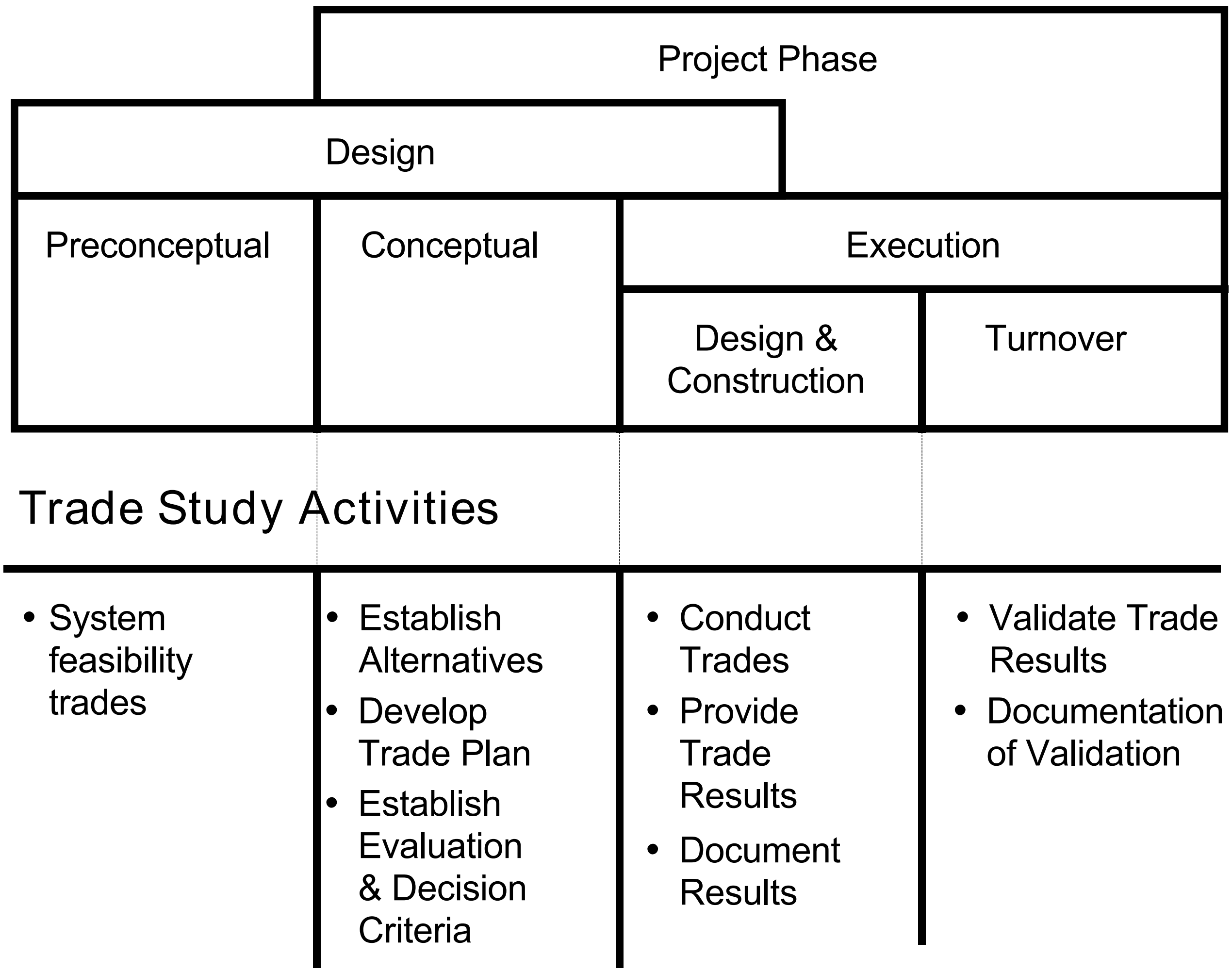

Figure 4
Thermal Control Trade Tree

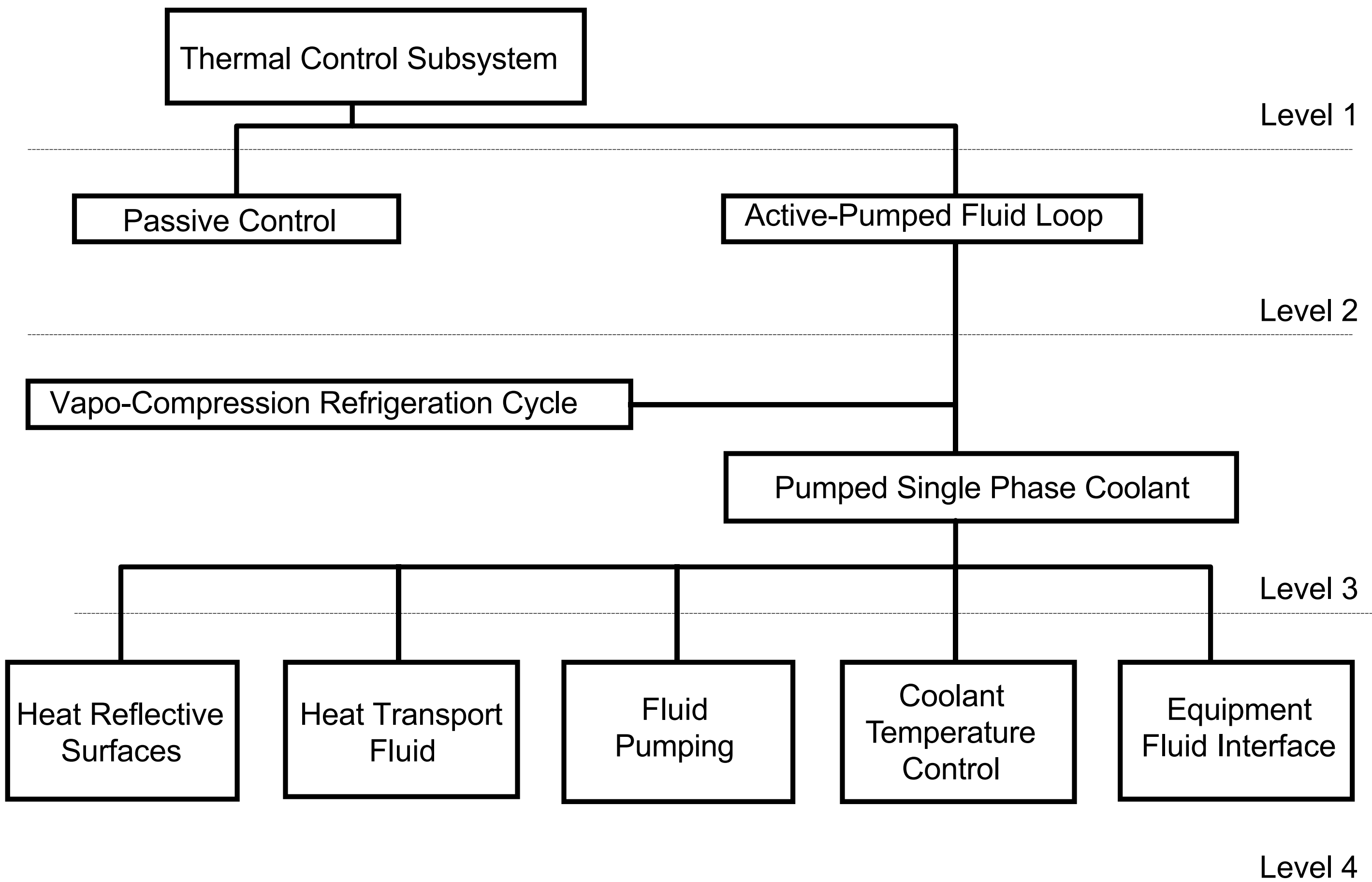

Figure 4. Tradeoff Study Tree Example.

FURTHER READING

The following selected DOE Orders, Guides, and Standards and national and international standards should be referenced for additional information.

- DOE O 430.1, LIFE-CYCLE ASSET MANAGEMENT.
- *Project Management Overview*, GPG-FM-001.
- *Project Execution and Engineering Management Planning Guide*, GPG-FM-010.
- MIL-STD-499A, "Engineering Management," Department of Defense, May 1, 1974.
- IEEE P1220-Final Draft, “Standard for Application and Management of the Systems Engineering Process,” IEEE, September 26, 1994.
- CODE 66-“Systems Engineering Manual,” Lockheed Martin Missiles and Space Company, August 30, 1994.
- “Engineering Economy,” Thuesen, H. G.; Frabrycky, W.J.; Thuesen, G. J.; Prentis-Hall International, Englewood Cliffs, New Jersey, 1977. (Economic Analysis)
- “Systems Engineering and Analysis,” Blanchard, B. S.; Frabrycky, W. J.; Mize, J. H.; Prentis-Hall International, Englewood Cliffs, New Jersey, 1981. (Economic Analysis)
- “Probability and Statistics in Engineering and Management Science,” Hines, W. W.; Montgomery, D. C.; John Wiley and Sons, New York, New York, 1980 (Probability and Statistics).
- “Discrete Event System Simulation,” Banks, J.; Carson, J. S.; Frabrycky, W. J.; Mize, J. H.; Prentis-Hall International, Englewood Cliffs, New Jersey, 1984 (Simulation and Analysis).
- “System Simulation and Analysis,” Law, A. M.; Kelton, W. D.; McGraw-Hill, Inc., New York, New York, 1991 (Simulation and Analysis).
- “Introduction to Operations Research,” Hillier, F. S.; Lieberman, G. J.; Holden-Day, Inc. Oakland California, 1986 (Simulation and Analysis).