AN APPROACH FOR ESTIMATING SYSTEM ENGINEERING COSTS

by

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Industrial and Systems Engineering

(ABSTRACT)

A critical part of a proposal for the development of a complex system is its cost. One important element of this cost is the effort to perform the systems engineering function. The prevalent method for estimating these costs is a "bottom-up" engineering estimate based on the experience and judgment of the estimator. In some cases, analogy to actual costs of previous, similar programs is employed. Neither of these methods provide the accuracy, consistency, or defensibility needed.

Various methods and models are used to assist in estimating costs in other disciplines across differing applications. These methods were evaluated for suitability in estimating systems engineering costs for a computer based electronic defense system. The requirements and conditions, both technical and organizational, for developing a cost model are delineated. Considerations for automating the model are discussed.

Major findings are:

- Models used in conjunction with traditional estimation methods can improve the overall systems engineering cost estimation process,
- Activity based parametric and analogy models show the most promise in the near term due to the reasonable accuracies achievable, the high speed and low cost with which estimates are generated, and their adaptability to automation, and
- Before a model can be developed and be a useful tool within an organization a number of conditions must exist, primary among which are the adoption of a standard cost structure for bidding and managing systems engineering efforts, the creation and maintenance of a cost/parameter database to allow entry and analysis of actual program cost data, and management acceptance and commitment of adequate resources.

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1.0 Introduction and Background

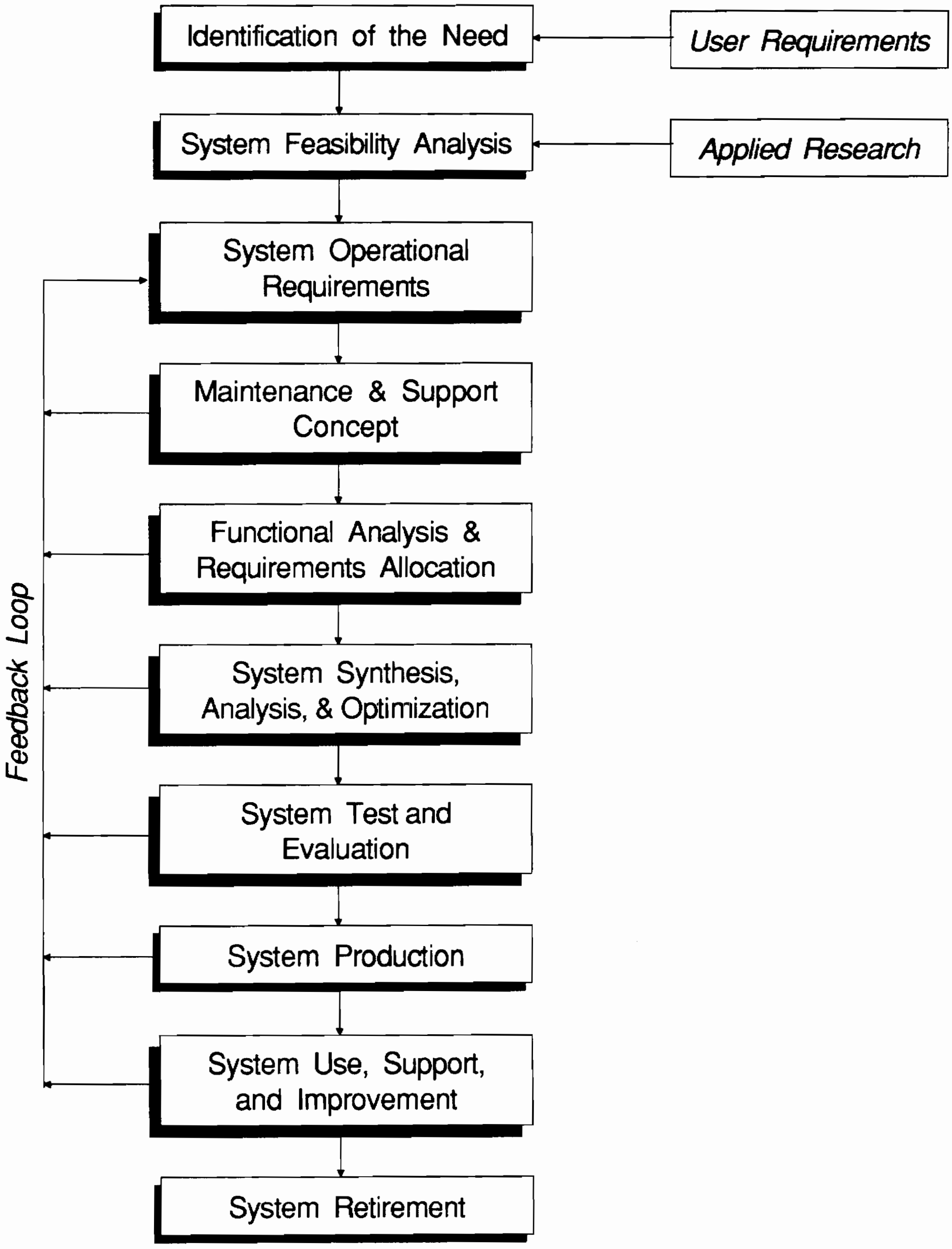
1.1 Introduction

As the size and complexity of systems has increased to the large, high-tech, highly interactive systems of today, a need for an orderly, systematic process for bringing these systems into being was recognized. Nowhere is this more true than in the development of military/defense systems. "The complexity of modern day weapon systems requires conscious application of systems engineering concepts to ensure producible, operable, and supportable systems that satisfy mission requirements." [43]

Although a wide variance exists in the understanding of what constitutes systems engineering, the definition to be used herein is:

> "The effective application of scientific and engineering efforts to transform an operational need into a defined system configuration through the top-down, iterative process of requirements definition, functional analysis, synthesis, optimization, design, test, and evaluation." [5]

Figure 1 is a simplified depiction of the systems engineering process.



Source: Blanchard [5]

Figure 1. Simplified Systems Engineering Process

Not only is the performance of systems engineering advisable in these circumstances, it is typically a contractual requirement imposed by the government, frequently through the prescription of standards such as MIL-STD-499 [29] and/or DOD-STD-2167 [13].

To be awarded a contract to develop a system, a corporation must submit a proposal to the government, a major constituent of which is the costing data. Here, the contractor provides the customer with his estimate of how much it will cost to perform the requested efforts and deliver the requested products to the stated requirements. One significant element of this cost is the cost of performing the systems engineering function.

Experience, observation, and research have shown that in estimating the cost of systems development, a wide range of methods are used. These range from "seat of the pants" guesses to the application of elaborate parametric models, with more tending towards the former. The various disciplines or functional areas involved in the system development typically possess their own techniques for generating their contributions to the total project cost. For example, software development cost estimates are frequently based on the COnstructive COst MOdel (COCOMO) [7], which has been incorporated into a number of automated support tools.

One area where cost estimating methods are weakest is systems engineering. Why is this? Of any discipline, systems engineers should appreciate the use of a systematic means of analyzing a problem and coming up with a logical and repeatable solution.

It is the purpose of this research to investigate possible cost models that may be applied to the systems engineering effort, to evaluate the utility of the most likely candidates, and to describe the requirements for implementing the recommended approach.

1.1.1 Research Objectives

The goal of this project is to develop an approach for estimating systems engineering costs associated with the development of a computer based electronic defense system. The costs to be so estimated have been limited to those connected with the systems engineering tasks typically performed by a government contractor during the advanced/full scale development phase of a moderately large system development.

Other supporting objectives are to:

- Determine the "state-of-the-art" in engineering cost estimation,

- Identify possible, and evaluate the most likely, cost estimating techniques for application to the estimation of systems engineering costs,
- Provide a concise, but complete, delineation of the tasks which together compose the total systems engineering effort with a brief description of each,
- Identify the parameters which affect the costs associated with each of these tasks,
- Recommend an approach, and
- Describe the organizational and technical prerequisites for implementing the approach.

The intent is to provide a framework that may be of assistance to an organization interested in developing a cost model for improving their performance of systems engineering cost estimates. The information and guidance provided constitutes a starting point for further development in the future.

The cost estimation has been focused on manhours by labor category (level) as opposed to dollars, as this measure provides more utility and flexibility, avoiding the necessity for, and complication of, indexing. The calculation of total cost by applying current/average salary figures, time value of money, and inclusion other cost factors such as materials and burdening is already a well understood and documented process.

1.1.2 Challenges

One dilemma associated with the estimation of up-front costs is a "chicken or the egg" situation in which to develop a "bottom-up" approximation for system engineering tasks for the various stages of system development presupposes that the information generated in the early stages (such as requirements analysis) is already available. In fact, during the pre-proposal stage, a preliminary systems engineering effort must be undertaken in order to generate enough insight into what the system will ultimately be, to support the proposal and costing process. Typically, this will begin with mission/requirements analysis and progress until a preliminary system architecture is selected and hardware and software configuration items have been identified.

1.2 Description of the Approach

The approach chosen to accomplish the objectives of this project consists of three echelons - information gathering, analysis, and synthesis. A diagram of this approach is presented in Figure 2.

To evaluate candidates for a systems engineering cost model first requires a review of the available literature to develop a comprehensive listing of the lower level systems engineering tasks that may need to be performed, along with a description of each. Note that for any given project, a

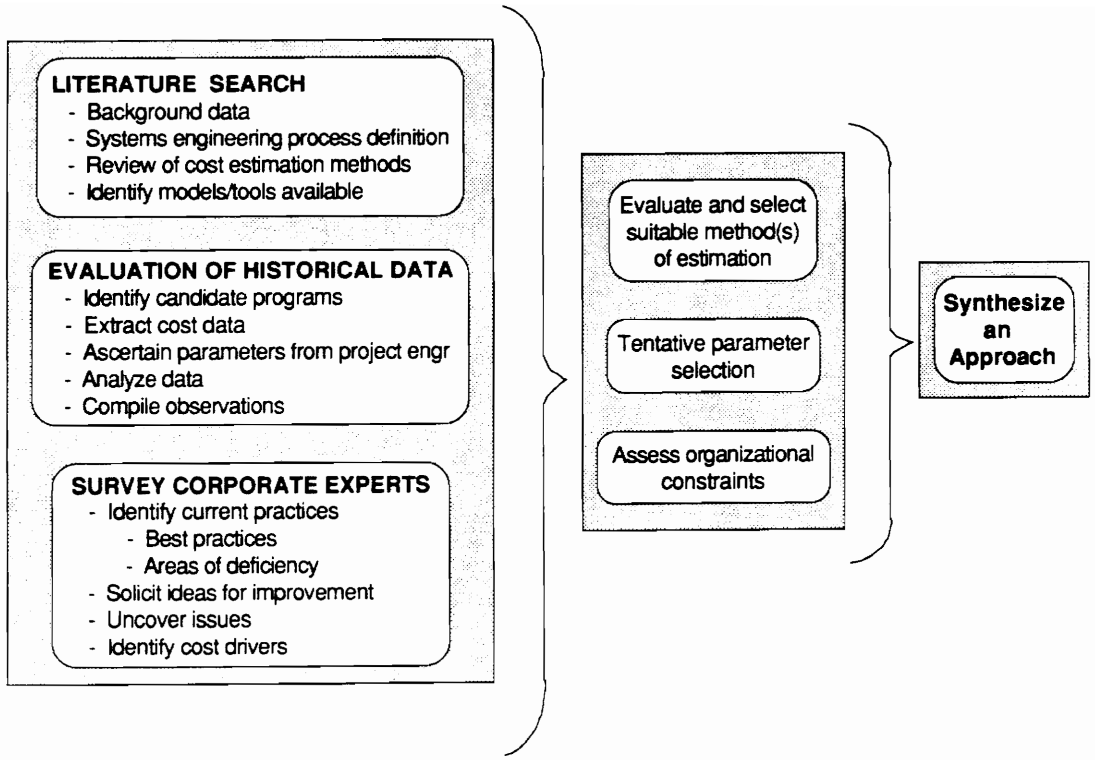


Figure 2. Research Approach

subset of these tasks may actually be required. These tasks were then analyzed and logically grouped.

Another area of research involved the examination of existing methods and techniques for performing cost estimation, particularly as applied to engineering in general and systems engineering specifically. Available cost models have been identified and an initial assessment of their applicability made. A survey of existing tools (i.e., automated models) was conducted to determine if any suitable products already exist or could be modified to perform the desired function.

Historical cost data, along with available data describing system and development characteristics, for ten actual, completed programs was compiled and analyzed. The data was then restructured into a common cost structure.

A questionnaire was developed to ascertain from the field what cost estimation methods/models are in use, what their input parameters are, and what their effectiveness has been. Where possible, personal or telephonic interviews with systems and cost engineering "experts" were conducted.

From the questionnaires and cost data analyses, a preliminary identification of variables influencing cost for each major task was attempted. The available cost models were then screened for applicability. Those determined to be the most likely candidates have been evaluated in further detail.

Throughout this process, a list of assumptions and simplifications was maintained, and issues documented for further study.

Based on the above research, requirements for the development and implementation of a model were deduced. In addition to the technical requirements, the organizational environment necessary to produce and maintain it are considered. An approach is suggested.

1.3 Problem Analysis

In order to constrain this research to manageable proportions, the application which the system engineering cost model will address has been scoped to a well-defined, yet easily expanded, problem. Bounding conditions are:

a. Computer based electronic defense type system

b. System scale - moderate

c. Advanced/full scale development phase

d. Limited strictly to systems engineering tasks (no related specialty engineering efforts will be addressed; however, the SE interface to these tasks/groups and the SE products provided to them are covered)

e. Systems engineering tasks typically performed by the Government or its consultants are not included.

f. Emphasis will be on the evaluation of front-end costs (requirements analysis through hardware/software development) and testing. System production through disposal are omitted.

As previously stated, diversity exists in the definition and implementation of the systems engineering process. Since the cost of performing this process is closely tied to its composition, a baseline description is used for purposes of this research (see Section 2.2 and Appendix A).

Research has been limited to the identification and evaluation of alternative models and methods. No attempt is made to actually develop a new model; however, the information provided is intended to assist in the preparation for doing so.

Empirical research is limited primarily to a single corporate entity. This is because within the highly competitive defense contracting environment, there is an inherent inhibition of corporations to release any information providing insight into the costing practices of their organizations. Although not ideal conditions for a study of this type, the company chosen is considered to be typical within the defense business.

1.4 Redirection of Research

In naivety, the original intent of this research was to actually develop an automated model for estimating systems engineering costs. After a thorough review of the literature and, more importantly, attempting to compile and use existing historical cost data, the enormity of the task and inherent difficulties involved became apparent. At this point, the course of the project was altered to the analysis and delineation of the requisites for developing such a model. From this perspective, the preceding exercise provided an excellent platform for the further conduct of this investigation as well as for future research.

Chapter 2

2.0 Review of the Literature

2.1 Introduction

The escalating complexity of systems has resulted in an associated increase in the complexity of the processes used to develop them and in the difficulty of estimating their costs. This difficulty is underscored by the many well publicized cases of substantial cost overruns on government contracts. Most of these overruns can be traced to either poor development processes or inadequate cost estimating practices, or both. In actuality, a link exists between these functions since cost is (or should be) a critical design parameter. Past failures, in many cases, are due to inattention given to future cost issues during early program development. [14]

The systems engineering discipline evolved as a response to improve the development process. Standards such as MIL-STD-499 and DOD-STD-2167, along with many others, have helped to systematically guide both customers and developers through the steps necessary to achieve a successful program.

Likewise, the sophistication of cost estimation, accounting, and control systems has expanded. The government now typically requires that a standard Cost/Schedule Control System (C/SCS) be used and prescribes the use of a standard cost structure. The Work Breakdown Structure (WBS) is a hierarchial organization of hardware, services, and data cost elements which together define the total effort and products comprising the program. Although originally arranged along functional lines (i.e., design, fabrication, test, etc.), a product-oriented structure is now used.

In the late 1960's, the government found that a complete cost data bank for one program could be usefully employed in estimating the costs of other similar items. [40] However, to do so requires that similar cost structures and reporting methods be used.

MIL-STD-881, originally issued in 1968, establishes the criteria governing the preparation and employment of work breakdown structures for use in defense acquisitions. This standard provides a summary of the upper 3 WBS levels. Figure 3 depicts these levels for an electronic system. In 73, the Secretary of Defense introduced the Contractor Cost Data Reporting (CCDR) system to improve consistency among programs. However, no systematic procedure exists for applying these policies. At the lower levels of the WBS, structures diverge and many different approaches can be found in costing the work element. [8]

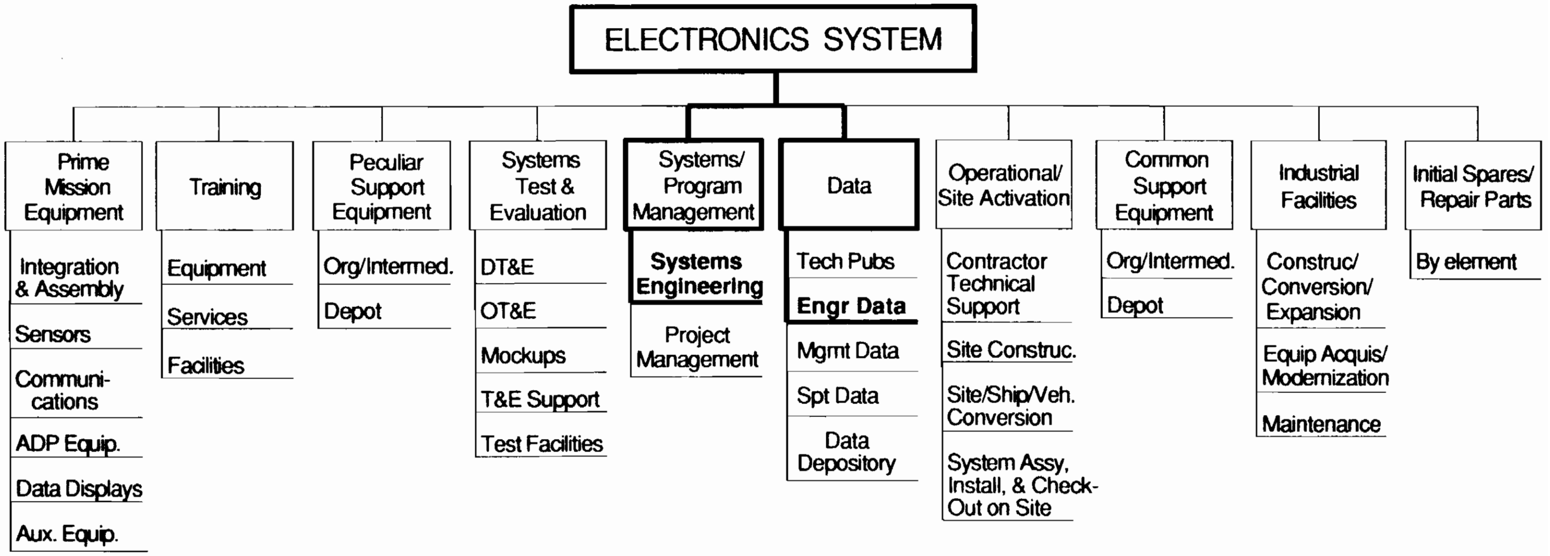


Figure 3. Standard Work Breakdown Structure for Electronic Systems

2.2 Systems Engineering

Systems engineering emerged as a discipline in the late 1950s and early 1960s primarily as a result of the space program. As alluded to earlier, systems engineering is a top-down, integrated, life-cycle approach to system design and development which when properly applied can serve to mitigate the possibility of programmatic disasters, which invariably manifest themselves in the form of excess costs.

However, the system engineering function itself is a program cost element which can suffer from the same costing afflictions as the program as a whole. It is the estimation of these costs that is the subject of this paper.

To address the costs associated with the systems engineering function, it is essential to understand the activities or tasks which compose this process. It is beneficial to examine these activities in the context of the system/development life cycle. Note, however, that one of the hallmarks of the systems engineering process is its iterative nature. Therefore, although activities may be discussed or depicted as if they occur in a sequential fashion, this is not usually the case.

The system life cycle can be broken down into several distinct phases. Although numerous different characterizations are in use, the divisions used herein are 1) requirements definition and analysis, 2) conceptual design, 3) system design, 4) detailed specification, 5) system development, 6) integration and test, and 7) production, operation, and support. This breakout tends to emphasize the "front-end" systems engineering activities, which are the primary focus of this research.

During the requirements definition and analysis phase, a complete understanding and description of the users' needs is developed. Feasibility analyses are undertaken to assess alternative technologies that may be applied and research that needs to be initiated. The preliminary operational, maintenance, and support concepts are determined. Functional analyses decompose what the system is to do.

The conceptual design phase begins to look at how the system is to perform its functions. Trade studies are conducted to evaluate possibilities. A preliminary system architecture is selected.

In the system design phase requirements are allocated to hardware, software, and the various system components. Simulation, modeling and prototyping support the evaluation and optimization process as the design is refined.

Detailed specification involves the definition of requirements for all configuration items and supporting items. From these specifications, the hardware and software can be designed.

System development is when the system components are created and assembled. Systems engineers monitor this process, assist in integration, and prepare for test.

During integration and test, the complete system is brought together and verified to meet its requirements through a series of inspections, demonstrations, and test procedures.

In the production, operation, and support phase the approved configuration is manufactured then deployed, used, maintained, and supported in its operational environment. At this point, systems engineers are involved in assessing system performance and implementing any upgrades to the system.

Figure 4 illustrates the systems engineering activities that are typically performed in each of the above phases. This is not to imply that no crossover of activities occurs across phases. In fact, a feedback and corrective action loop exists in which the results of one activity may necessitate repetition of a previous activity. However, it is convenient to view the activities as depicted for simplicity.

A description of each of the tasks identified in Figure 4 is located in Appendix A.

2.3 Cost Engineering

Cost engineering is that area of engineering principles where engineering judgment and experience are utilized in the application of scientific principles and techniques to the

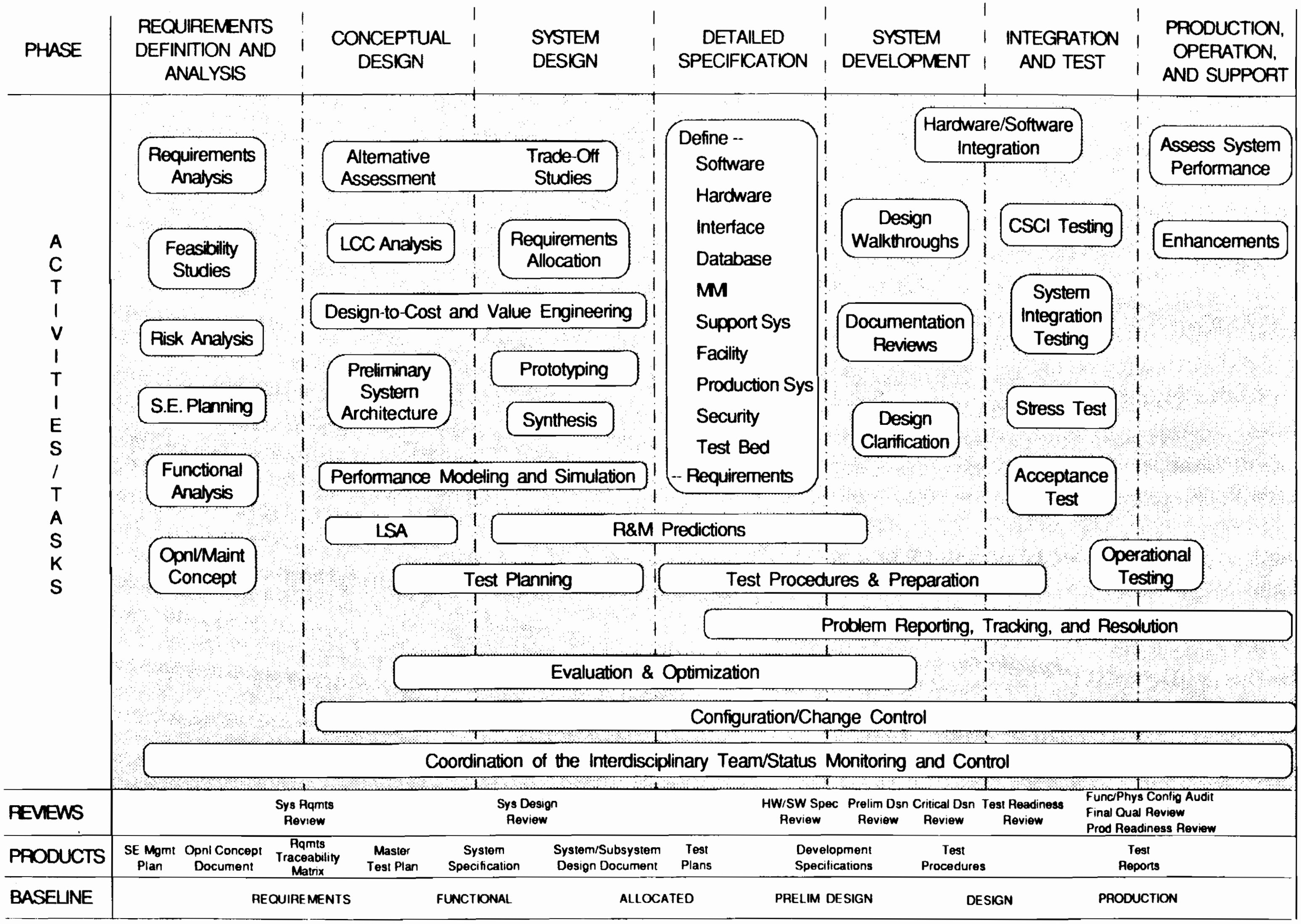


Figure 4. The Systems Engineering Process

problems of cost estimating, cost control, profitability analysis, planning, and scheduling. [4,18] Like systems engineering, cost engineering is not considered as an engineering discipline in the same context as electrical engineering, mechanical engineering, or other design specialty area, but is concerned with the entire development process.

Cost engineering is a field which has been continuously increasing in scope and importance. From humble beginnings in the 1950s, this area of engineering has increased dramatically. [4] Trends towards balanced budgets, competitive contracting, and expanded international business are providing some of the impetus for the explosive interest in this subject. [14] "As technology and society advance, it becomes necessary to estimate more closely to remain competitive. An estimate based on overdesign may be too high to win the award. If based on underdesign, it may well win the award, and end in disaster." [20]

Founded in 1956, the American Association of Cost Engineers (AACE) provides professional recognition through its certified cost engineer (CCE) and certified cost consultant (CCC) programs. In 1983, the AACE had over 6000 members, with over 600 CCE/CCCs designated. At that time, college level courses in cost engineering were being taught and degree programs under consideration.

2.4 Cost Estimation

One (though not the only) area in which systems engineering and cost engineering become interrelated is in the area of system cost estimation. Cost requirements influence the system design. Design information is needed to estimate system costs. "Despite the notion that cost estimating precedes design, cost estimating acts as a shadow and requires some sort of design even before a preliminary estimate is started." [34] "The first part of the concept estimator's job is to develop a reasonable definition of the product." [46]

Cost estimation is a projection into the future from a database compiled from past experience. [8] Concept estimating is the estimating of the cost of a system that has not yet been designed. [46] This implies a degree of prediction or forecasting. Forecasting involves the extrapolation of past data into the future using linear or nonlinear curves and mathematical relationships. [34]

According to the AACE, cost estimates can be classified by type as:

TYPE	ACCURACY
Order of magnitude	-30 to +50%
Budget	-15 to +30%
Definitive	-5 to +15%

The complexity of the cost estimate will depend on the range of accuracy desired which in turn is a function of the amount of information available. There is a cost associated with accuracy. "Research has shown that, irrespective of a projects size, the cost of preparing an estimate increases about fivefold as the allowable error is reduced from +30% (study) to +10% (definitive)" [17] Thus, depending on the purpose of the estimate and the degree to which the design has progressed, different methods of estimation would be appropriate. For example, the accuracy and expenditure to support a bid/no bid decision would generally be much lower than that for the bid package itself.

2.4.1 Cost Estimation Techniques

A major task in cost estimation is to determine the cost behavior of a cost element so that the amount of the cost element may be estimated when the factors driving the cost change. A number of various methods or techniques have been applied to the cost estimation problem. Some of these are introduced below.

Analogy. This technique involves direct comparison with historical data from similar programs/systems to extrapolate the cost of corresponding elements of new programs. It usually involves the application of one or more complexity factors for scaling purposes. The general equation used is:

$$C_{i2} = C_{i1} * \Sigma \beta_j ,$$

where C_{i2} = cost of the i^{th} element for the new program,

C_{i1} = cost of the i^{th} element for the past program,

β_j = the j^{th} scaling factor

The strength of the analogy method is that it can provide sufficient accuracy for the least cost in the shortest time. [8] However, in order to develop a relatively accurate cost estimate for a specific system-related item, records for the cost of that item for several, identical, or at least highly similar, systems is required. [10]

Grass Roots. This is also known as a bottom-up estimate and is an industrial engineering approach that involves breaking down the system into separate segments of work at various levels. The elements at the lowest levels are then examined in detail and estimates are made for each. The detailed estimates are then consolidated at each level into a total estimate for the overall system.

Typically, labor estimates at the lowest levels are based on the engineer/estimator's experience and judgment, although other methods may be used. A 'subjective estimate' is a euphemism for what has historically been better known as an educated guess. [10]

The system must be relatively well-defined before this method can be used. It is generally more expensive than analogy. [8]

Delphi Method. This is a decision support technique in which the estimates of multiple experts are combined to form a single collective estimate, or expected value, for the various cost elements. Considered a behavioral model, this method reduces the uncertainty associated with a single estimator, but at a corresponding increase in cost.

Parametric. This is a statistical approach in which cost estimating relationships (CERs) that make use of product characteristics (such as hardware weight or software language) are employed to predict costs and schedules. These relationships are derived through the use of regression analysis on several cost records for the item of interest and the value of one or more system characteristics known to have an impact on the cost of that item. [10]

The general form of the parametric equations is:

$C_i = ax^b$, where C_i = cost of i^{th} task/element

x = value of parameter

a = coefficient

b = exponent

for a single parameter relationship. The value of a and b are derived as a result of the regression, bayesian, or other curve fitting technique.

Worthwhile use of this method requires that sufficient data exist and that historical costs are fairly consistent for statistical analysis. In an area where there are constant changes in technology, the CERs may be invalidated faster than new ones can be developed. [8] This technique has been used for decision prescription diagnostics, risk analysis, variance analysis, and interval estimates. [33]

Linear Programming. This is a mathematical, operations research tool which can be used to allocate resources in an optimum manner to minimize cost or maximize profit. All relationships are expressed in terms of single variables raised to the first power. The general form of the objective function and constraint equations used are (respectively):

$$Z = C_1X_1 + C_2X_2 + \ldots + C_nX_n = \Sigma\, C_jX_j$$

$$A_{11}X_1 + A_{12}X_2 + \ldots + A_{1n}X_n = \Sigma\, A_{ij}X_j = B_i\ , \quad i = 1,2,\ldots,m$$

where: Z is the total cost (to be optimized)

X_j is the amount of resource j

C_j is the cost per unit of resource j

B_i is the boundary value of the ith limitation

A_{ij} are the coefficients of the constraint relationships

Use of this method requires setting up the objective function and restraint equations to realistically represent the situation. A by-product of the final solution is a sensitivity analysis. [20] It also provides short range planning aids, goal matching strategies, and project time management aids. This method is perhaps more useful in cost control or cost effectiveness analysis than in initial estimation of specific costs. Other techniques in this category include dynamic and geometric programming.

Simulation. Simulation involves the manipulation and observation of a synthetic model representative of the entity for which the cost is being estimated. These models can be either deterministic or probabilistic. The Monte Carlo method is a simulation technique in which random number generation is applied to a probability distribution in order to characterize the uncertainty element. The collection of field data and determining of Monte Carlo numbers is one approach, or theoretical distributions fitted with empirical coefficients can be used.

As an example, consider a cost element expressed as $C = X + Y$, where X and Y are each probability distributions with X characterized by a Poisson distribution with a mean value of μ:

$$P(X) = \frac{e^{-\mu}\mu^{x}}{X!}$$

To perform Monte Carlo simulation, the distribution is converted to a cumulative probability, then the values of X (and Y) are repetitively assigned through random generation, and the average value of C determined. Simulation is most useful when solution by direct analytical means is exceedingly difficult or impossible to perform and may be used in conjunction with other cost estimation methods, especially for risk analysis purposes.

Heuristic. This includes rule based or knowledge based systems (KBS). KBS, also known as artificial intelligence (AI) or expert systems (ES), consist of a set of computer problem solving techniques developed to imitate human thought decision-making processes which capture the problem solving behaviors of the human expert (cost estimator/engineer) and make it useable by non-experts. "These computer systems have the ability to apply domain-specific problem-solving knowledge and achieve a high level of performance similar to that of a human expert". [33] The domains of interest in this case would comprise cost estimation, systems engineering, and computer based electronic defense systems.

In order to build a successful expert system for cost estimating, first, a domain must be created. This alone requires copious amount of data collection and analysis. The design and implementation of the expert system model will be a major project.

Percentage. This involves estimating one cost element (or set of elements) from the estimated value of other loosely related cost elements. A cost is estimated by multiplying one cost by a ratio cost factor to arrive at another cost. The simple equation used by this method is:

$$C_i = a * C_j$$

where: Ci and Cj are the i^{th} and j^{th} cost elements, and

a is the coefficient of proportionality

A classic example of this method is to estimate the finished building cost by multiplying the cost of the shell by a ratio of a = 1.6. In this case, accuracies of ± 20% can be expected. [17]

Level of Effort (LOE). This is a subjective estimating of cost by determining manning requirements over the program schedule, then summing. Allocation of values to lower level cost elements sometimes follows.

Back-calculation from Goal. This involves starting from a cost "bogey", usually provided by marketing, and backfitting costs into the structure until the estimate matches the bogey. This is a budget allocation process more closely aligned with pricing than with cost estimation and is not considered good management practice.

Published cost data. Some industries publish standard cost figures for various cost elements. For example, the construction industry publishes values of building costs based on square footage, labor rates by location, etc. However, when using published cost data, it is not always clear what is included in the cost, and cost indices must usually be applied. Even if the index was good when started, changes in labor productivity may make the index less useful. [17] Such data is generally not available for the types of systems or efforts of concern.

Combinational. Any of the above methods may be used together in a number of ways to complement each other. They could be combined to yield a single result or used independently as a cross-check on each other. When combined, the quality of the results is presumably enhanced; however, the cost of preparing the estimate is also likely to be higher.

The above methods can be grossly classified as shown in Table 1.

One other estimating method, though less scientific, deserves to be mentioned. A "guesstimate" is based on the estimator's observational or rough experience. "Despite all statements to the contrary, guesstimating has not disappeared

Table 1. Cost Estimation Categories

CATEGORY	METHODS	APPLICATIONS
Experience Based	Heuristic AI	Prediction Decision making
Simulation	Monte Carlo Deterministic	Uncertainty analysis Contingency planning "What-if" scenarios
Parametric	Regression Bayesian	Prediction Risk analysis Variance analysis
Discrete State Optimization	Linear/Goal Programming Network/Graph Theory	Resource allocation Scheduling Sensitivity analysis
Elementary	Analogy Grass Roots	Estimation

from the cost-estimating scene. Nor has its substitute, estimation by formula and mathematical models, been universally nominated as a replacement. Somewhere between these extremes is a preferred course of action. " [34]

2.4.2 Considerations

In the selection of a cost estimation technique or development of a cost model, a number of considerations exist. The most significant of these are described below:

Accuracy/Uncertainty. The accuracy needed will greatly influence the method or model selected. For any method, the accuracy will be directly dependent on the uncertainty of the information input to it. In the early stage of a project, when sound decisions are vital yet difficult to make, it may be more important to know the probable error in a cost estimate than to know the estimated value of the cost. [17]

Sensitivity. The degree to which the results are affected by changes in the various inputs is also important. "A comprehensive sensitivity analysis should be performed in support of any system planning effort where cost is an important trade-off criterion." [15]

Calibration. Whenever a model is used outside of its original home environment (i.e., that within which it was created), adjustments must be made. Even then, adjustments will be continuously required to offset such factors as the changes in productivity over time. Simply using a model without adapting it to the environment in which it is used will not lead to accurate results. [24]

User requirements. A model should be based on the needs of the user. It should provide the information he needs in the form in which he needs it, should be easy to use, and require minimal, meaningful input data in an available form. It should be acceptable to intuition and experience, should be simple and transparent with traceable logic and ground rules, and have an applicable database. [28]

Cost analysts should find out what problems general management have and, by anticipating the questions they are likely to raise, be prepared with the answers when they are asked. [14]

Acceptance. Whenever a new method is introduced, there are organizational and cultural barriers that must be overcome. "There exists an inherent reluctance to change from tradition, regardless of the evidence that our present method is beset with deficiencies. Fear of the unknown will favor rejection." [14]

"The responsible person, or groups, accepting the output of models must feel comfortable with the information being provided. This can only come from a moderate understanding of the model being used, information pertaining to the technical validity, confidence in the people using it, and the track record of both." [14]

Engineers do not like to estimate cost. To them, success is measured by technical achievement. However, programmatic success or failure is usually measured in financial terms. Therefore, one challenge is to instill an appreciation for the relevance of cost as a design parameter.

To be most effective, model estimates should precede traditional estimates by months. A major cultural impediment to early cost analysis is the theory that what is not known (the baseline design) cannot yet be estimated. Actually, the estimating, by injecting cost into the development process, will actually help shape the design concepts that lead to the baseline. Another reason to begin cost analysis early is that at this point system architects have not yet locked themselves into a specific design and so do not feel as compelled to defend an approach as they might in later phases.

Pitfalls. Some of the things to remember about cost estimating are:

1) Estimates turn into operating budgets, that if overrun, tend to label a program as a failure, regardless of technical achievements.

2) Management may view parametrics as any estimating method other than bottom-up. The characteristics of different models are likely to be misunderstood and confused with one another.

3) A difference exists between pricing (which includes issues such as budget reserve, competitive position, and anticipated follow-on activities) and cost estimating. The support structure for a model can be damaged if the modeling function is seen as doing more than just inputting to the price-setting exercise.

4) Some of the most common errors made in cost estimates arise from the following [27]:

- Failure to consider all the elements of cost
- Failure to evaluate capabilities and limitations of resources
- Guesstimating direct labor hours

- Forgetting set-up/preparation time
- Failure to consider changing conditions
- Failure to consider responsibility for and effects of design change
- Misjudging coordination time requirements

2.4.3 Applications

Much has been written on the subject of costing. The motivation for professional cost estimating is a result of the necessity for profits, stewardship of resources, and competition. [34] In short, the financial performance (and thus survival) of a business depends in large part on competent cost management. The evident interest is therefore not surprising.

An extensive review of academic, business, and engineering literature, as well as commercial product documentation, yielded much information concerning how cost estimation techniques and models have been applied in the recent past. Research and implementations have been documented in the areas of construction costs, capital/plant costs, software development costs, and hardware unit costs. Overall development costs have been investigated for many narrow/specific applications, such as satellites, missiles, nuclear waste disposal, etc. Also, much of the literature pertained more to cost accounting/control vice the estimating effort. This was especially true for labor costs.

2.4.3.1 Systems Engineering Cost Estimation

Little was found related to the estimation of front-end, systems engineering analysis/design costs. This is consistent with the work of Boger and Liao [8] in their research into non-recurring costs. Of course, information about work done in other areas is still of great utility in that the approach and many of the methods and techniques used may be suitable for application to the systems engineering task. Also, many of the conditions necessary for creating the model are the same, with similar pitfalls to be avoided.

The primary reason for the paucity of prior research in this area is most likely due to the lack of data, both on which to base the research and on which to base the estimate.

The lack of acceptable nonrecurring cost models can be partially attributed to the lack of adequate historical data existing in an analyzable (i.e., consistent and comparable) form. [8] Another contributing factor is that frequently a major portion of the system analysis and design work are accomplished during the proposal or pre-proposal stage when minimal cost accounting is performed.

Estimating during early program stages is difficult at best, since the data on which estimates are generally based is not yet available. If available, it is far from firm. The point in time at which this data is needed, it should be remembered, is during what is known as the "feasibility study" stage [10] or while the system requirements and preliminary system designs are still evolving [15]. "The information available on which to base a preliminary cost estimate can vary from very little on the one hand to virtually none at all on the other." [17]

One exception to this lack of information is in the area of logistic support analysis (LSA), for which the government publishes a guide for estimating costs [32]. This guide provides standard manhour estimates for each task, along with scaling factors for:

- Program type (development, product improvement, non-developmental item)
- Support concept (organic, commercial, interim)
- System type (electrical, mechanical)
- Number of LSA candidates
- Complexity (low, average, high)
- Life cycle phase (pre-concept, concept, demonstration/validation, full scale development, production)

Although organizationally, LSA is frequently considered an integrated logistic support (ILS) responsibility, and thus not strictly a topic of this report, a large number of these tasks overlap or are obviously systems engineering activities.

One approach which may be adaptable for aggregating systems engineering costs, that is largely independent of model or technique used, is a matrix model which organizes costs by phase, subsystem, and function [39]. This is illustrated in Figure 5.

2.4.3.2 Design to Cost

Although the focus of this paper is estimation of systems engineering costs for purposes of proposal input and budgeting, another related issue for which systems engineering cost modeling may apply is that of design to cost (DTC). This refers to the incorporation of an economic figure of merit as a system design parameter, to be considered in conjunction with performance, and included as a factor in trade-off analyses. DTC treats cost and technical objectives together.

Technical enthusiasm, especially when accompanied by technical success, often mask a major project objective -- to produce an end product that is affordable by its intended consumer. To do this, cost estimations are performed throughout the development process. This is accomplished most effectively by providing online access to cost models and databases, which allows engineers to rapidly make economic evaluations of their designs in a concurrent engineering

END ITEM	PHASE	TASK	FUNCTION							
			Mgmt/Supv	Lead Engr	Engr	Spec Engr	Tech/Lab Spt	Pubs/Admin	• • •	Total
System	Analysis	Rqmts Anal Feas. Study Opn/Maint Cpt ⋮								
		Total	∑	∑	∑	∑	∑	∑		∑∑
	Concept Design	Altern. Assess DTC LSA ⋮								
		Total	∑	∑	∑	∑	∑	∑		∑∑
	⋮									
	Total		∑∑	∑∑	∑∑	∑∑	∑∑	∑∑		∑∑∑
Subsys #1	Analysis	Rqmts Anal Feas. Study ⋮								
		Total	∑	∑	∑	∑	∑	∑		∑∑
	Concept Design	Altern. Assess DTC ⋮								
		Total	∑	∑	∑	∑	∑	∑		∑∑
	⋮									
	Total		∑∑	∑∑	∑∑	∑∑	∑∑	∑∑		∑∑∑
Subsys #2	Analysis ⋮	Rqmts Anal ⋮								
	Total		∑∑	∑∑	∑∑	∑∑	∑∑	∑∑		∑∑∑
⋮										
Total			∑∑∑	∑∑∑	∑∑∑	∑∑∑	∑∑∑	∑∑∑		∑∑∑∑

Figure 5. Cost Aggregation Matrix

environment. A designer commits 75-85% of the eventual product costs during design; therefore, significant cost savings could be realized if designers were able to evaluate their designs on a cost basis. [12]

2.4.3.3 Other Uses of Cost Estimation and Modeling

In addition to use in quotations and DTC, other purposes served by cost estimation models include:

Bid/no bid decisions. Despite the lack of precision, the initial estimate is a useful management tool for judging whether a product can be priced competitively. [46] This can be done before a great deal of funds have been expended.

Evaluation of design alternatives. "The greatest utility of the computerized cost model is that many tradeoff studies between competing designs can be made quickly, accurately, and continuously while the system requirements and preliminary system designs are in a constant state of flux." [15] Models can be used to determine the relative costs of each of several competing design alternatives, before the details of the designs are completed.

Cost monitoring and control. Models can be used as a tool for comparing estimated versus actual cost as the design progresses. Estimates to complete (ETC)/estimates at completion (EAC) become an iteration of cost risk analysis, not an iteration of the bottom-up estimate. [14] This can aid in early detection of potential cost problems later on in the development.

Evaluate design changes and contract modifications. As changes in the contract or changes in design intent occur, the cost model may be used to determine the magnitude of any impact to the basic contract. [15]

Establish cost targets. Sometimes, cost models are used to establish targets or bogies for bottom-up estimating. This is not necessarily recommended.

Reasonableness checks. Model results can be used as a cross check for estimates derived from other methods, such as a bottom-up estimate. In one study, project leaders felt that the greatest advantage attainable with such models at present was the possibility of using them as a means of communication or as a kind of check-list. "The models draw your attention to a number of aspects which you would otherwise have overlooked". [24]

Negotiations. It can prove beneficial during contract price negotiations to have model estimates available as back-up to the quoted value. In fact, mutually supportive results from several sources are unlikely to be disputed. This places the user in a good negotiating position and lessens the chances of the price being cut back due to undefensible estimates.

'Should-cost' calculations. When evaluating a proposal from a contractor, sub-contractor, or vendor, models can be employed to determine what range of costs are reasonable for the item being offered.

Sensitivity analyses. Another advantage is the possibility of ascertaining the sensitivity of cost-determining factors. [24]

2.5 Tools Available

A review of the automated (computer based) cost estimating products currently commercially available identified a number of software, hardware, and logistics models, but none directed towards the front-end systems engineering costs. In fact, these models generally assume that this effort has already been completed and often require inputs that would result from such an effort.

Leading parametric models for estimating software development costs include PRICE-S, SLIM, SEER, COCOMO, Estimacs, Before You Leap (BYL), SPQR/20, BIS/Estimator, FAST-E, System-3, and SOFTCOST-R. Some of these use software lines of code (SLOC) as their primary input, while other are based on the more recent function point theory. There are models whose purpose is to perform the size estimation itself. Others additionally estimate schedule, reliability, and/or software maintenance costs. Many include outputs for systems engineering costs; however, these costs do not include the entire systems engineering effort, but only the portion directly associated with the software such as software requirements analysis or computer software configuration item (CSCI) testing.

Hardware estimation tools have been around longer than those for software. PRICE-H and SEER-H, PRICE-HL, and PRICE-M estimate costs for hardware products/systems, maintenance, and microcircuit chips/boards respectively. Also, a number of CAD/CAM tools include some cost estimation capabilities and the government possesses many of their own models for specific applications. Again, some hardware related systems engineering costs are generated by some of the tools.

In the ILS area, tools such as CASA, LCCC, EDCAS, LogToolSet, OSAMM, ORLA, and others are available. These models provide estimates for the various elements of life cycle cost, spare/repair costs, LSA tasks, and for optimizing support costs. As mentioned previously, a large degree of overlap exists between the ILS and systems engineering functions.

2.6 An Early Parametric Method

In 1971, Silver [40] described a technique for estimating cost for one system based on actual costs for a similar but different previous system using an empirical product-oriented cost data bank. The steps he followed are summarized below.

1) Prepare WBS for new program. As far as possible, pattern it after the existing/standard WBS.

2) Document system/program differences. An engineer documented the hardware differences, while a management specialist documented scope changes in LOE tasks.

3) Identify/select parameters for each task.

4) Create factors for each parameter, with associated weights.

5) Score each factor for each task (relative to the baseline, in which = 100 points) and multiply by weight.

6) Assess impact of the varied parameter on the known cost base for each work package (based on combined judgments of experts).

7) Apply universal parameters (i.e., normalize for index, quantity, technology, etc).

Although this technique was described over 20 years ago for satellite systems, the general concept is still applicable today.

Chapter 3

3.0 Research

An empirical investigation was conducted within the confines of a single corporate organization. This study focused on the characterization of current practices and identification of problems encountered when attempting to utilize existing data to support estimation of future efforts. The ultimate goal is to enable the use of historical information in the creation of a model for estimating systems engineering costs.

3.1 Cost Estimating Practices

To discover the state of current systems engineering cost estimation practices, an expert questionnaire consisting of 27 questions was developed. This questionnaire was distributed to the chief systems engineers at seven independent operating units of a major defense contracting corporation. These units are located in the eastern, middle, and western parts of the United States and one in Canada. A total of fifteen questionnaires were returned, most of which came from east coast facilities. The questionnaire can be found in Appendix B and a summary of the responses is located in Appendix C.

The average respondent is now serving as an engineering section manager with 21 years of experience, having worked on

16 different programs and having prepared 63 quotation estimates during that time. All had experience with the types of system of interest.

With one exception, engineers reported that no systematic, documented procedure was in place for developing systems engineering cost estimates. (One unit reported that some procedures existed, but were not used.) This has led to each engineer developing his own personal method for arriving at an estimated value. The methods of preference were analogy (with 93% of the respondents citing this method) and level of effort (with 87% usage). Most (55%) found their estimates to be difficult to justify to auditors and to their own management. The exception was the single operating unit which had instituted standard guidelines for preparing systems engineering estimates. In the five years since these guidelines were established, no auditor had challenged an estimate.

Although the analogy method was near universally indicated, a large majority of participants complained that the historical data, when available, lacked adequate detail, was inconsistent across programs, and was deficient of descriptive information about the previous system/program. This appears to be a "Catch-22" situation. The lack of costing data and standards leads to the use of various individual costing methods and structures. Thus each systems engineering effort is structured and managed in a different way, beyond those differences expected due to the unique characteristics of the individual programs. This results in an inadequate, inconsistent, and sometimes inaccessible information base from which to support future costing efforts. This lack of sufficient support in turn encourages the use of personalized techniques.

Most respondents indicated that their units tended to overrun or break even on their systems engineering budgets. A majority (79%) reported that they had experienced situations in which certain systems engineering activities had been downscaled or omitted due to inadequate funds or because they had not been included in the original bid. This underscores the need for improvements in the cost estimation process; however, several respondents insightfully noted a deeper problem - lack of an institutionalized systems engineering process itself! The point being made was that without a defined process with documented tasks, the estimator has little basis for his quotes. In other words, he must know what activities he should be doing before he can estimate them.

One question was designed to ascertain the primary factors driving systems engineering costs; however, most respondents interpreted the question to mean "what factors lead to cost problems". Although this was not the intent of the question, some meaningful information was obtained from the responses. The chief culprit cited as adversely impacting systems engineering cost performance was insufficient requirements management. Requirements related reasons were mentioned ten times, to include inadequate requirements analysis, allocation, and tracing, and failure to control changing requirements. Other problem areas addressed were poor planning, lack of training/experience, inadequate status monitoring, faulty pricing strategies, poor communication across disciplines, and failure of the customer to provide promised information, equipment, and review of specifications in a complete or timely manner.

A very important observation was that a widespread perception exists that the systems engineering function is completed prior to award; therefore, little funds need be allocated to systems engineering efforts under the contract. This also leads to design reviews and deliverables being scheduled early in the contract, leaving insufficient time for analysis and design. This may lead to some of the requirements and other problems mentioned above. Additionally, it was noted that when project budgets become troubled, the systems engineering budget is frequently the first to be cut.

No automated tool or cost model is in use at any of the operating units to support systems engineering cost estimation, although several reported such tools in use for software costing. All respondents signified that they would use such a model if available and felt that it would be useful when used in conjunction with other estimating methods. Although most indicated a relatively low level of faith in a model, many added remarks evidencing a "wait and see" attitude, indicating that their trust would increase with their familiarity with the model and as its track record was established.

A number of ways in which a model could be used in a supporting role were suggested. These included reasonableness checks, early ROM estimates, feasibility assessments, determination of confidence factors, to enhance the credibility of an estimate, or to force the reevaluation of an estimate.

Mixed reactions were received concerning the use of a standard WBS for quoting systems engineering costs. Although all participants agreed that a standard cost structure would enhance the usefulness of historical data to support future estimates, disagreement existed as to the level of detail that the structure should possess. Some felt that the sample WBS provided was too detailed while others felt that it was not detailed enough. The principal concern of those who felt it to be too detailed was the tendency for estimates to increase as the number of pieces it is broken into increases. Those favoring increased detail did so primarily for reasons of supporting work package identification for planning and management purposes.

Other criticisms involved the need for the structure to be more product oriented and the flexibility to accommodate customer specified structures. Advantages noted included improved consistency, better metrics collection, and support for historical database development; help in understanding the systems engineering effort; provision of accountability by cost element and ability to sum costs by phase, unit, and function; the requirement for less manpower to develop and to review quotes; and the ability to better scrutinize estimates.

Learning curves were not found to be in widespread use in estimating systems engineering tasks, and when used tended to be done in an intuitive rather than prescribed manner. Applications identified were in the integration and testing of additional systems after the first and in the lowering of effort required when prior or similar development work had preceded a program.

Few respondents were familiar with the estimating practices of other corporations; however, those that were indicated that similar difficulties in estimating systems engineering costs were common in other companies throughout the industry. Informal verbal interviews with representatives of three other companies tended to confirm this generalization.

3.2 Evaluation of Historical Data

Historical data for ten completed system development programs performed by one unit of the same defense contractor between 1980 and 1990 were collected and analyzed. Programs evaluated ranged in size from $1.9M to $29.7M, consisting of a single equipment item up to 208 racks of equipment, and from 0 to 165K lines of new software code. All were computer based electronic defense systems, with applications including electronic warfare, command and control, and training systems. The operational environments for these systems included ground fixed, vehicular, surface ship, and airborne. Most systems were characterized as more software intensive; however, some were predominantly hardware.

Data collected included cost figures in the form of actual manhours maintained by the cost accounting system, the work breakdown structure (WBS) for the program, the WBS dictionary (when available) which describes the effort or product associated with each element of the WBS, and descriptive information about the system, program, and development. Descriptive data was obtained primarily through interview of the lead project engineer, although review of program documents were also a source of data. Examples of cost and WBS data for one of the ten programs is included in Appendix D.

During the process of compiling and analyzing the above data, several problems became apparent. These are described below:

1. **Lack of consistency in cost structures used between programs.** Some consistency existed among programs within a single department/business area, probably because one person developed the WBS for many of these programs, but generally the cost elements were non-comparable.
2. **Cost accounting performed at too high a level.** In general, too little detail/resolution was provided. Typically, the jobs were quoted to a much lower level, but "managed" at a higher level (elements were "rolled up" into a single account). This has allowed program managers to "hide" problem areas. One extreme example of this was a program in which all systems engineering and testing were covered by a single account. Although this was a recent program and would otherwise have been a prime candidate for inclusion in this study, the single account rendered the data useless for analysis purposes.

3. **No documentation of program parameters.** This was especially a problem for programs which had been completed more than 2 years in the past. Parameters of interest included, for example, the number of source requirements, software lines of code (SLOC), hardware configuration items (HWCIs), etc.
4. **Availability of data on classified programs.** In some cases, the parameters themselves were classified and thus presented difficulties in use. In the case of completed programs, classified documents (such as specifications) in which many of the parameters were identified (though themselves unclassified) had to be returned to the customer or destroyed, leaving no way to resurrect these values.
5. **Many key personnel assigned to past programs are no longer with the company.** This left either no one or those with only marginal familiarity with the program available for interviews to ascertain program/system parameters.
6. **Use of generic style WBS element descriptions.** This resulted in an inability to discern from the brief entry in the WBS dictionary what specific

efforts were/were not included in an individual cost element.

7. **Differences in how subsystem system engineering was handled.** In some cases, systems engineering for individual subsystems were broken out separately, and in other cases it was included with the system level engineering effort.

8. **Long term programs incurred too many changes over time.** The amount of modifications, upgrades, new task orders, etc. made the cost accounts look like a tangle of spaghetti. In some cases, smaller programs were "buried" within larger programs simply due to the convenience of using an existing contractual vehicle.

9. **Data for closed out programs no longer maintained on the system.** Only an incomplete paper trail existed in archives, and this was located in an offsite warehouse. This was also the case for deliverable documents (such as specifications) associated with these programs.

10. **No master cross-reference of jobs to account numbers is maintained.** To obtain cost data from the cost accounting system for a program, its Accounting Order (AO) number was needed. To obtain parametric data from project engineers, the program

title was needed. It was difficult to link AO numbers with titles, especially for older programs.

11. **Labor classification changes affected the labor mix values.** At one point, a Senior Engineer who had been classified as a level 3 was changed to a level 2. After this point, the ratio of level 2 to level 3 labor values was different, the degree varying on each program depending on their original mix and at what point in the program the change occurred.
12. **No clear division was made between effort expended on a task or activity vice a deliverable document.** For example, in some cases interface engineering/definition and preparation of an interface requirements specification were accounted for separately, while in others they were combined. (Note that per MIL-STD-881, engineering data is separate from systems engineering.)
13. **Accuracy of time reporting.** In some cases, there was an apparent lack of regard about how time was logged among subaccounts of the same program. Newer company directives have addressed this, however, effects may have been incurred on the older programs.
14. **Complexity of cost account summaries.** It was not always apparent which elements summed into which

others - when cost "roll ups"/summaries were provided. However, special "pyramid" reports could be obtained for current programs.

These findings are consistent with those of Boger and Liao [8], who performed a similar study concerning non-recurring costs for missile systems in a dual source environment which cited such problems as inconsistent treatment of nonrecurring cost elements, use of different methods to aggregate costs into elements, loss of information to corporate memory, lack of documentation of explanatory variables, and WBSs which do not distinguish between recurring and non-recurring costs. Inaccuracies in time reporting had also previously been recognized. [37] A number of programs considered for inclusion in this study had to be disregarded due to some of the problems delineated.

Note that no attempt was made to compare original quotes (from proposals) to actual costs. This would be a logical next step in the future evolution of this investigation in that past discrepancy trends could be used to focus attention on areas that have exhibited a tendency to be underbid (or overbid). It is expected, however, that data availability could again impede such an effort.

Once cost (manhour) data was obtained, an attempt was made to restructure it into a common form to allow comparison of data among programs. Because of the problems identified above, with one exception, it was not possible to compile sufficient data to look at individual tasks comprising the first four phases of development. The notable exception was for software requirements definition, where data was separately accounted for on four programs. On four others this effort was entwined with the generation of the software requirements specification.

A matrix was developed showing tasks/cost elements against programs. To enable comparison, summary lines combining system analysis + design and analysis + design + specification was listed. In addition to systems engineering tasks, overall costs for software engineering, hardware engineering, ILS, and program management were included to facilitate any correlation with these areas and systems engineering costs. This matrix is shown as Table 2. In this matrix, systems engineering specifically associated with subsystems was summed together to yield a total for the entire system. For programs with multiple subsystems, an additional matrix was developed showing the breakout of these costs. One example of these is provided in Appendix D.

Based on these figures, the systems engineering effort was found to comprise approximately 21% of the total labor expended on the average, with a standard deviation of 6.4. Additionally, some of the "miscellaneous" effort, which is a

Table 2. Historical Cost Matrix

TASK NAME	PROG	A	B	C	D	E	F	G	H	I	J
SE MANAGEMENT		1246	0	1944	2332	440	634	0	0	495	0
ENGINEERING MGMT PLANS					136						
MONITOR/CONTROL						262	275				
SPECIALTY ENGINEERING					579						
TECHICAL REVIEWS		1246		1944		100					
SYS RQMTS REVIEW					340						
SYS DESIGN REVIEW											
SW SPECIFICATION REVIEW											
PRELIM DESIGN REVIEW					851		159				
CRITICAL DESIGN REVIEW					426		200				
TEST READINESS REVIEW										495	
FUNCTIONAL CONFIG AUDIT											
PHYSICAL CONFIG AUDIT						78					
FINAL QUALIFICATION REVIEW											
SYSTEM ANALYSIS		262	451	0	0	2890	0	0	0	0	2934
REQUIREMENTS ANALYSIS											
FEASIBILITY STUDY											
OPNL/MAINTENANCE CONCEPT											2934
FUNCTIONAL ANALYSIS						1162					
TRADE-OFF STUDIES											
CONCEPTUAL DESIGN											
LOGISTIC SPT ANALYSIS *						4743					
LIFE CYCLE COST ANALYSIS *											
DESIGN TO COST			451								
VALUE ENGINEERING											
TASK AND SKILLS ANALYSIS						1728					
SYSTEM DESIGN		0	0	0	0	0	0	0	0	0	0
ALTERNATIVE ASSESSMENT											
REQUIREMENTS ALLOCATION											
PROTOTYPING											
EVALUATION/OPTIMIZATION											
PRELIMINARY DESIGN											
ANALYSIS + DESIGN		262	3102	2749	599	4855	974	0	5604	0	7728

Table 2. Historical Cost Matrix (Cont.)

TASK NAME	PROG	A	B	C	D	E	F	G	H	I	J
DETAILED SPECIFICATION		0	6556	5983	1421	4628	0	0	0	0	1452
SOFTWARE RQMTS DEFINITION			5769	5703	1421	4628					1149
INTERFACE RQMTS DEFINITION			641								
HARDWARE RQMTS DEFINITION											
DATABASE DEFINITION			146	280							118
MMI DEFINITION											
SUPPORT SYSTEM DEFINITION											
FACILITY RQMTS DEFINITION											
PRODUCTION SYS DEFINITION											
SECURITY REQUIREMENTS											185
ANALYSIS + DESIGN + SPECIF		262	9658	8732	2020	9483	974	11045	5604	12681	9180
SUBSYSTEM DESIGN				8402	513		1160	9338			
TOTAL A + D + S		262	9658	17134	2533	9483	2134	20383	5604	12681	9180
SYSTEM INTEGRATION & TEST		3152	325	4939	5761	8169	856	6347	9607	9132	3110
TEST PLANNING					677		384			4713	
VERIFICATION ANALYSES		102									
TEST BED DESIGN/DEVELOPMENT		39			73	730					
HW/SW INTEGRATION		1589	325		926			5474	3964		1661
CSCI/PERFORMANCE TEST		1054		2718	2190	6680	70				
SYSTEM INTEGRATION TEST											673
SYSTEM ACCEPTANCE TEST/FAT		259		2185	420	456	63	520	4196	4379	651
STRESS TEST										40	
R&M DEMONSTRATIONS		109						250			
OPERATIONAL TEST/SUPPORT				36	1475	303	339	103	1447		125
SUBSYSTEM INTEGRATION				8810	323		1998	9304			
SUBSYSTEM TEST				6129	1741		74	1219			
TOTAL INTEG & TEST		3152	325	19878	7825	8169	2928	16870	9607	9132	3110

Table 2. Historical Cost Matrix (Cont.)

TASK NAME	PROG	A	B	C	D	E	F	G	H	I	J
SYS ENGR DATA/DOCUMENTATION		3135	1107	12728	2569	6605	659	0	3664	8134	1543
SE MANAGEMENT PLAN						101					
OPERATIONAL CONCEPT DOC											
SYSTEM SPECIFICATION		195	341							582	28
PRIME ITEM DEVMT SPEC											
MASTER TEST PLAN		206			714	497	165				
SOFTWARE REQUIREMENTS SPEC		958	689	2881	369	142	265			3434	514
INTERFACE RQMTS SPEC		401	77	27		70					141
HARDWARE SPECIFICATIONS		66			124	524					
TEST PLANS		132		129		11					20
SOFTWARE TEST PROCEDURES		735		5620		4627				1433	840
ACCEPTANCE TEST PROCEDURES		289		4040	670	512				2685	
TEST REPORTS		153		31	324	84	7				
ENGR/SPEC CHANGE NOTICES											
CMPTR SYS OPERATORS MANUAL											
SOFTWARE USERS MANUAL											
REVIEW AGENDA/MINUTES											
TECHNICAL REPORTS					368	37	222				
TOTAL SYSTEMS ENGINEERING		7795	11090	51684	15259	24697	6355	37253	18875	30442	13833
SOFTWARE ENGINEERING		9230	3761	104491	27377	20690	5763	0	10228	17081	12299
HARDWARE ENGINEERING **		2217	2280	53201	4899	30742	785	10402	16231	36692	16637
INTEG LOGISTIC SUPPORT ***		1984	2010	3357	757	8661	0	5578	3684	8438	0
PROGRAM MANAGEMENT ****		2434	7216	11384	3479	6622	1462	12915	7075	13833	16810
ALL OTHER		4886	12210	110204	11289	51456	6435	92126	51967	78265	79697
TOTAL PROGRAM		28546	38567	334321	63060	142868	20800	158274	108060	184751	139276
SE % OF TOTAL		27.31	28.76	15.46	24.20	17.29	30.55	23.54	17.47	16.48	9.93

21.10 AVE

6.38 STD

NOTES:
* Included in ILS totals (not SE totals)
** Includes engineering drawings, does not include lab opns
*** Does not include training or technical manuals
**** Does not include Cost/Schedule Control, Congiguration Management, or Quality Assurance

significant value in some cases, may contain hidden systems engineering content. Note also that LSA and LCCA values are summed into the ILS line rather than the systems engineering line since they are typically performed by this specialty engineering group.

At this point, total labor hours were used. No attempt was made to analyze the data by labor level, although reports were available with this information broken out. A future analysis objective, however, would be to evaluate what the typical labor mix has been for each task. In this way, modeling could perhaps be performed to either estimate a total manhour figure which could be apportioned among the levels or to estimate a single manhour figure for a given level (for example, level 3 engineer) and to calculate the other levels based on a ratio.

Parameters associated with each of the ten programs were ascertained through interview of the lead project engineer or other key project member when the lead engineer was not available. The personal interview method was chosen over data collection forms based on the work of Fad [14] which indicated that forms can intimidate the information source and stifle progress. Additional advantages discovered by using the personal method were that 1) it conveyed a sense of the importance of the information, 2) the interviewer was available to clarify the intent or constraints of the questions, and 3) it ensured that the data was provided when requested, whereas a form might easily be put aside and forgotten. Even so, the answers to some questions were not always immediately available, and had to be provided at a later time.

The form used by the interviewer is provided in Appendix E. Parameters were selected for inclusion on the form based on results of the expert survey, on information contained in the literature, and on previous experience. Boger and Liao propose that non-recurring costs are predominantly influenced by the complexity of the system. "The most important explanatory variable that needs to be operationalized is the complexity of the weapon system. Defining and standardizing the measure of system complexity holds the key to developing viable parametric CER models for nonrecurring costs." [8]

Table 3 presents the major parameters for each of the ten programs examined. Remaining to be done is the correlation of these parameters to the resulting costs of the individual systems engineering tasks and/or to the overall systems engineering cost. In this case, due to the small number of observations and the large number of variables, statistical methods would yield unreliable results, even if possible to apply. It would be possible to perform regression analysis of each task against each parameter, or to perform multiple regression against small sets of (2-3) parameters; however, a

Table 3. Program Parameter Matrix

QUES	PARAMETER	VALUES									
1	PROGRAM	A	B	C	D	E	F	G	H	I	J
101	YEAR AWARDED	1990	1985	1985	1986	1988	( )	1982	1980	1987	1986
2	TYPE PROGRAM	CD	AE	BE	A?	CE	D	AE	ACE	CE	ACD
3	CUSTOMER	A	A	B	B	B	B	A	A	A	A
4	EXPER W/CUSTOMER	N	Y	N	?	N	Y	Y	N	YN	Y
5	RELAT W/CUSTOMER	A	B	A	A	A	G	A	A	D	B
6	SPEC QUALITY	B	C	C	C	C	( )	BC	C	D	B
7	TYPE SYSTEM	D	FAC	HC	KC	HC	C	CI	CH	A	C
8	OPNL ENVIRONMENT	C	A	E	E	E	DE	D	E	A	A
9	DEG OF RUGGED	B	A	D	D	D	B	B	D	AB	AB
10	SPECIAL RQMTS	CD	ABCD	N	N	C	N	BC	N	AC	N
11	RELI/MAINT	N	Y	N	N	Y	N	Y	N	N	Y
12	MISSION AREA	AH	AH	L	L	L	L	DG	L	A	AH
13	# OF STDS	27	67	19	28	20	?	?	16	41	?
14	PROCESS STDS	ADEF	A	B	ADE	A	?	EF	BF	B	B
15	# CDRLS	42	102	170	( )	136	10	70	31	?	18
16	EXPER W/SIM PROGS	A	B	B	B	B	A	B	B	B	A
17	EXPER W/MISSION	B	A	B	A	A	A	B	A	B	A
18	PREVIOUS IR&D	N	N	Y	Y	N	N	N	N	N	N
19	PROGRAM PHASE	AB	A	B	B	B	D	AB	ABC	B	BC
20	PREV PROTOTYPE	N	N	N	N	N	Y	N	YN	Y	Y
21	% SE DONE @ PROP	30	30	30	15	0	30	10	20	10	20
22	NEW/UPGRADE	A	A	A	A	A	A	A	A	B	B
23	DES TO COST	N	Y	Y	N	Y	N	Y	N	N	N
24	DEP ON NEW TECH	N	N	Y	Y	N	N	Y	Y	N	N
25	TECHNOLOGY LEVEL	5	7	8	7	4	5	8	8	4	4
26	SCHED CONSTRAINTS	C	A	C	B	C	A	C	B	BC	BC
27	DEVMT PERIOD	14	-	30	30	24	( )	18	24	24	18
28	DOLLAR VALUE	3.1M	5M	24.7M	8.1M	9.2M	2M	7M	12M	29M	10M
29	AMT OF SE BID	?	?	?	534K	11002	?	?	?	?	?
30	MORE HW/SW	C	B	C	C	A	B	A	C	C	B
31	COMPLEXITY LEVEL	4	7	8	8	6	5	8	8	7	5
32	# SOURCE RQMTS	22/240	145	51	62	202	( )	1.5"	64	113	?
33	# CRITICAL TPMs	1	10	0	6	?	?	many	17	15	-
34	SIZE	A	B	C	B	B	A	C	C	B	A
35	DESCRIPTION	A	C	C	C	C	C	C	C	B	B
36	# SUBSYSTEMS	1	2	7	6	3	6	9	2	1	1
37	# RACKS	0	6	288	20	?	3	21	43	21	3
38	# UNIQUE HWCIs	4	10	?	24	?	12	125+	50	19	?
39	# UNIQUE CMPTR	2	3	3	4	2	2	0	5	3	2
40	# FUNC AREAS	13	9	60	15	?	5	9	18	55	?
401	# FUNCTIONS	?	?	?	?	?	?	-	123	169	?
41	# UNIQUE CSCIs	3	3	35	4	6	2	0	3	4	?
42	# SLOCS	15	165	104	66/145	55	30	0	203	110	?
421	LANGUAGE	E	?	E	CE	A	G	-	CE	BCE	?
43	# EXT INTERFACES	7	14	0	3	0	4	7	0	15	?
44	# INT INTERFACES	3	9	84	10	18	12	many	31	24	?
45	# ALGORITHMS	?	-	-	2	-	0	0	12	-	-
46	TIME DOMAIN	A	A	A	A	A	A	A	A	A	B
47	DEG OF MMI	B	C	C	C	C	C	C	C	C	B
48	# DISP SCREENS	20	?	?	( )	?	( )	-	31	54	10
481	# MENUS	-	?	?	( )	?	( )	-	24	34	?
49	UNIQ PERF CHALLENGES	2	4	1	3	3	1	2	1	1	1
50	AVE EXPER LEVEL	A	B	B	B	B	B	C	B	B	B
51	AVE PERF RATING	3	4	4	3	4	3.5	4	4	4	3.5
52	OVERTIME	10	10	10	5	15	5	5	5	13	5
53	STAFFING	C	C	A	C	A	C	A	C	C	C
54	DEG OF AUTOMATION	BC	BC	C	B	BC	B	B	A	B	B
55	PLANNING/PROCESS	6	7	5	2	5	2	8	6	4	4

Note: Letters refer to choice(s) from form, read from top to bottom, then left to right.

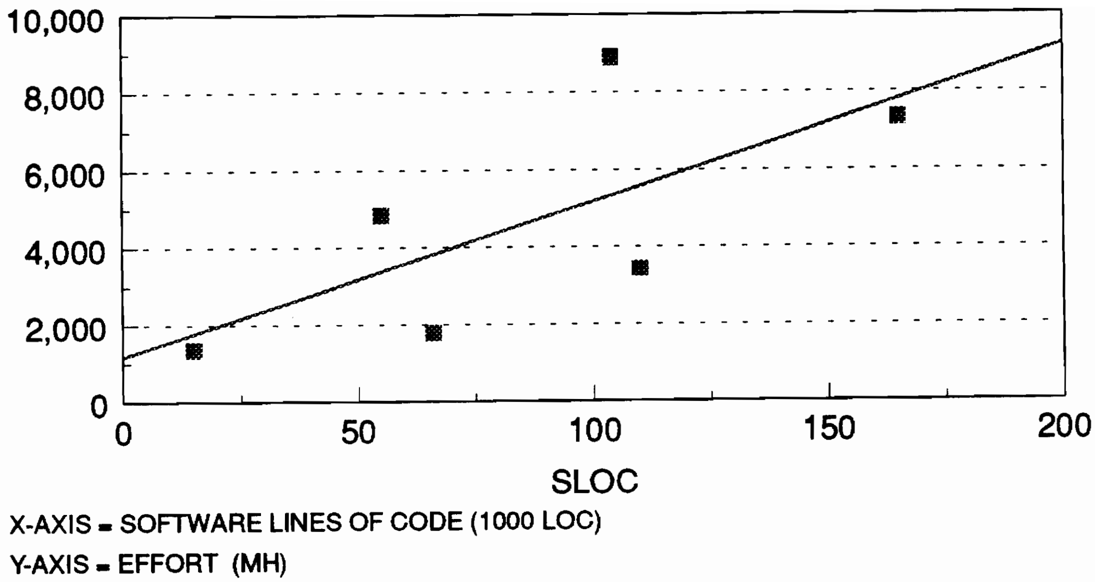


Figure 6. Correlation of Cost to Lines of Code

large variance is anticipated. Also, this would require an analysis to determine the degree of interdependence among the variables. Correlation could be accomplished on agross level for a single parameter by the construction of graphs of cost/effort versus parameter. Figure 6 is an example of such a graph which plots software requirements analysis and specification costs versus new SLOC for applicable programs from among the subject ten using a least squares approximation.

In addition to analyses performed at the system level, similar analyses could be performed for each subsystem of a multiple subsystem effort. In this case, each subsystem would be handled as small independent system.

Once this type of analysis has been performed for each variable, top candidates for potential cost drivers can be identified and relationships determined. This type of effort is premature at this time.

3.3 Identification of Potential Cost Drivers

As stated earlier, the primary cost driver for systems engineering costs, as well as for many other development costs, is the complexity of the system. The components of complexity, though, are what remains to be discovered. "Picking those particular variables which can precisely measure the complexity of a () system is a difficult task." [8] Some parameters proposed in the literature include the following:

- Degree of uncertainty in the design requirements [8]
- Level of risk due to technical advancement [8]
- Whether the program is joint or single service [8]
- Whether the system is single or multi purpose [8]
- Number of data items required, number of drawings, production rate/productivity [8]

- Number of components, technology assumptions, and environmental influences (physical requirements and packaging [46]
- Level of use, degree of inheritance, amount of R&D, schedule, performance factors, and geographical location [39]
- State of development/maturity level [15]
- Process flow [17]
- Weight, size, reliability, integration characteristics, environment, performance requirements, function/mission, technology [40]

When asked to define complexity, the experts interviewed exhibited some difficulty. Most alluded to the degree of interdependence among system components and timing considerations associated with these interactions. Size in terms of numbers of components was also mentioned. The chief factor affecting complexity was identified as the number and type of internal and external interfaces within the system.

This was confirmed by the results of inputs received on the parameter matrix in which the number of interfaces and the number of functions were selected an equal number of times in terms of the number of systems engineering activities whose cost was significantly affected by these factors. These were followed closely by the number of subsystems. Other parameters affecting the cost of a large number of tasks included number of algorithms, source requirements, CSCIs, and HWCIs; similarity with previous jobs and experience level of the team; and the quality of the SOW/specification received from the customer. Note that these results are not definitive due to the low number of inputs evaluated.

From this same matrix can be ascertained which activities appear to be affected by the most factors. These ranked (in descending order) as system acceptance testing; system integration test and monitoring software development; and change control and evaluation/optimization. Again, these results are far from conclusive and may reflect more the activities with which the respondents were most familiar. Also, fewer responses received for the later task phases seemed to result in a higher average factor selection rate for these items.

When asked to identify the tasks/activities which cost the most to perform, the cumulative results indicated the following:

- Test plan and procedure development
- Specification development/documentation
- Test performance
- Design (including trade studies, simulation, and prototyping)
- Requirements analysis

- Software requirements definition
- Integration
- Reviews and audits
- Planning, monitoring, and control

Of course, the choice of grouping of these activities affects their relative positions in the rank ordering.

Using the historical data from the ten programs evaluated and grouping the tasks into four gross categories led to the following ranking by average percentage of systems engineering costs:

- Analysis, design, and specification
- Integration and test
- Documentation
- Management (including reviews and audits)

Note that eliminating Program B (which was an analysis and design phase only program) caused a reversal in the ranking of the first two task areas. This then directly correlates with the results of the survey when the tasks are similarly grouped.

Chapter 4

4.0 Model Evaluation

A number of types of cost estimation methods exist which may be applied to the front-end systems engineering cost estimation problem, although no comprehensive model or tool is currently available for this purpose. The objective, then, is to identify the most suitable method from which a model or tool may be generated.

4.1 Applicability Comparison

The first phase of evaluation involves the identification of the most likely candidates from among the many possible. A qualitative comparison of the six major methods described in Chapter 2 is presented in Table 4. The current grass roots approach is included among these for baseline comparison purposes and because one alternative that should always be considered is the 'no change' or status quo option.

Strengths and weaknesses of each method are assessed with respect to performance, features, development, maintenance, and organizational issues. Although this is a subjective assessment, it is noted that the only two methods listing more advantages than disadvantages are the analogy and parametric methods.

Table 4. Qualitative Comparison of Methods

METHOD	ADVANTAGES	DISADVANTAGES
Analogy	o Reasonable accuracy o Low cost o Quick	o Large, detailed database required o Requires subjective assessment of relative complexity for scaling
Grass Roots	o Can be accurate o Fits well within WBS and with most cost accounting systems o Standard method for government contracting	o System must be relatively well defined o Possible for cost elements to be overlooked during the breakdown o Lowest level estimates still subjective/difficult to defend o Initial estimates tend to be high o Expensive to perform
Parametric	o Quick o Low cost o Successfully used in software cost estimation and in conjunction with other methods o Accepted practice by government o Allows for frequent iteration	o Initial model development requires investment plus availability of large, consistent cost/variable database o Must be continually calibrated to update CERs o Requires some operator knowledge to avoid misuse
Goal Programming	o Good for resource scheduling, optimization, and sensitivity analysis o Standard linear programming packages are available	o Initial model development requires research and investment to define objective function and equations o Handles limited types of cost relationships o Constraint equations vary by program and over time o Requires knowledgeable operator
Simulation	o Allows for "what if" analysis o Provides uncertainty information	o Requires determination of probability distributions o Initial investment required o Requires availability of consistent empirical data
Heuristic	o Can capture the knowledge of many experts o Can be customized to domain o Easily used by non-expert	o Large investment required to create domain o Development time is lengthy o Availability of experts

A more quantitative evaluation is given in the decision matrix of Table 5. In this assessment, similar types of factors are considered as previously; however, criteria are more specific, are assigned relative weights (from one to three, higher being better), and are addressed with relation to each candidate method. Scoring of each technique was performed by a single evaluator, using values of one to five (higher being better). This yielded the following rank ordering:

- Analogy
- Parametric
- Grass Roots/Simulation
- Heuristic
- Goal Programming

Further comparison will focus on the top two ranked candidate methods.

A number of similarities exist between the parametric and analogy methods. Both are based on historical costs and both require the application of factors linked to system complexity. Both can be applied at either the gross level (i.e., to predict total systems engineering cost alone), at the task level, or at some intermediate grouping such as by process phase.

The difference is that the analogy method extrapolates cost directly from the historical costs of a single similar

Table 5. Ranking of Methods

		GRASS ROOTS		ANALOGY		PARAMETRIC		GOAL PROG		SIMULATION		HEURISTIC	
CRITERIA	WEIGHT	SCORE	VALUE	SCORE	VALUE	SCORE	VALUE	SCORE	VALUE	SCORE	VALUE	SCORE	VALUE
COST													
Development	3	5	15	4	12	3	9	2	6	2	6	1	3
Maintenance	2	5	10	4	8	2	4	2	4	3	6	3	6
Per use	3	1	3	4	12	5	15	3	9	4	12	4	12
SPEED	2	1	2	4	8	5	10	3	6	4	8	3	6
ACCURACY	3	3	9	4	12	4	12	3	9	3	9	4	12
UNCERTAINTY	2	1	2	1	2	4	8	3	6	5	10	3	6
DEVELOPMENT													
Database Rqmts	2	5	10	2	4	2	4	3	6	3	6	5	10
Schedule	2	5	10	5	10	3	6	3	6	2	4	1	2
SIMPLICITY	1	3	3	5	5	4	4	1	1	3	3	1	1
USEABILITY													
Knowledge Level	1	2	2	4	4	4	4	2	2	3	3	5	5
Data Inputs Reqd	2	1	2	4	8	3	6	2	4	2	4	3	6
Flexibility	1	1	1	1	1	2	2	5	5	4	4	3	3
ACCEPTANCE	2	5	10	5	10	3	6	2	4	2	4	2	4
TOTAL			79		96		90		68		79		76

system or program based on one or more scaling factors, whereas the parameter method indirectly applies the historical data by using the actual costs and characteristics of multiplesystems/programs to derive relationships which are applied to the new project.

An important consideration is how the scaling factors used in analogy are generated. In current practice, they are sometimes based on a subjective assessment of the relative size or complexity difference between the past and proposed system/program. "Based on my experience, I'd say that this job is about 1 1/2 times as complex as our last one." The complexity factor, ß, is thus ascertained to be 1.5 across the board.

In other cases, ß is determined on a more objective basis by comparing program/system characteristics such as number of stated source requirements, number of hardware configuration items, or number of top level system functions - the ratio becoming the complexity factor.

In the best situation, ß is mathematically calculated based on multiple characteristics and validated by comparison of several past programs with each other. Care must be taken when using multiple characteristics that:

- The characteristics are independent, and
- The same cost effect is not attributed to more than one characteristic.

Any characteristic used must be one that can be reasonably well estimated early in the development. It will not be helpful to create a super estimating method or model based on an input value which is itself speculative in nature.

The high ranking of the analogy method in the decision matrix stems primarily from its relative simplicity. This causes model development time and investment to be minimal and also makes it easier to use and to understand. It also has a high "acceptance factor" in that estimation based on actuals intuitively makes sense.

McNeill [27], however, points out some potential errors in budgeting by actuals. First, he contends that the changes which are continually taking place in modern industry invalidate all such comparisons. These include advancements in state of the art, newly available tools, methods, and schedule requirements. Second, actual costs themselves are subject to random variables and thus do not constitute an error-free standard. Third, use of actuals is a "reflection of past performance eloquently defended", implying that personal and departmental incentives may override other more pertinent factors.

A prototype system for estimating software development costs called the Estimation Decision Support System (EDSS) developed at Imperial College, UK, incorporates an analogy meta-model which combines statistical methods and logical inference, having found the typically practiced method of making estimates by comparison with previous projects to be too casual to provide quality estimates. [11] This system provides the capability to automatically recognize similar records and ranks them in order of applicability. Several estimates can be generated based on different methods or foundation, and from which one can be chosen or which can be averaged to produce the final choice. To support this, an extensive database is needed. The design of the EDSS system recognizes the imperative to support the program manager, to be flexible, and easy to use. This model shows much promise and utilizes many techniques and features that could be directly applied to the systems engineering function.

A second difference between the analogy and parametric methods is that the analogy method typically uses a linear scaling factor whereas the parametric relationships are typically exponential in nature. This is a more realistic representation since "in general, costs do not rise in strict proportion to size." [17] Of course, these more complicated relationships are inherently less simple to understand and thus to accept or to defend.

In the parametric method/model, it is the generation of these relationships which is of interest. "The measurement of the cost of a system in terms of the system's performance parameters is usually based on a statistical regression technique. The general procedure is first to determine which parameters have a significant effect on the system cost. This is done by means of sensitivity analyses, using statistical correlation measures [such as the R^2 significance test of independent variables]. Next, combinations of parameters are tested to determine whether improvements in the coefficient of correlation can be effected over that obtainable with any single parameter. Then, that combination of parameters with the highest coefficient of correlation (or, if no combination excels, that single parameter with the highest coefficient of correlation) is used to construct a regression equation. The net result is an expression of the functional relationship between a system's parameters and its cost. A popular expression for this method is known as the CER (cost estimating relationship)." [39]

Parametric models have been successfully used for space systems [15], nuclear waste management systems [30], elevator design [23], and for various assembled components or products [12]. In recent years, their application in the area of software development has been tremendous. Additionally, the government auditing agencies have now made provisions in their procedures to accept parametric cost estimates as viable alternatives to the conventional proposal quotes. [14]

In an experiment conducted by Kusters, in which experienced project leaders estimated software costs from bottom-up, then with two parametric models, the results then being compared to the actual costs, it was concluded that "no proof is given that the models can be used for estimating projects at an early stage of system development" based on the differences found between the estimates and reality. "Therefore, only limited confidence should be placed in estimates that are obtainable with a model only." [24] He also warns against using lines of code as an input parameter (as shown in Figure 6) since this value cannot be accurately estimated at an early stage of development.

Two difficulties associated with the development of a parametric model are 1) the need for a large, consistent, and appropriately detailed database of historical cost and parametric data and 2) the need to handle a large number of parameters.

"Since nonrecurring costs consist of several categories of cost items, a parametric cost estimating model with a small number of available observations and a large number of potential explanatory variables would be unreliable, even if possible." [8]

"A feasible solution is to disaggregate the nonrecurring costs into relatively homogeneous groups of cost items for data accumulation purposes. With a consistent database and relatively homogeneous cost items, a parametric model for each group may be constructed with a relatively small number of observations, a typical constraint in major weapon systems cost estimation." [8]

To reduce the number of parameters several actions can be taken. First, analyses can be performed to determine the root(s) of each parameter so that only those with independent roots (i.e., those that are non-collinear) are retained. For example, in the elevator problem, elevator travel height, number of floors, and elevator speed are all functions of building height and may be represented in the cost equation by this variable. [23] A second procedure involves the performance of a sensitivity analysis to determine which parameters most significantly affect cost, eliminating those that do not. This, however, is not a trivial exercise.

The third operation is more practical than theoretical - to omit those parameters that cannot be easily or accurately measured. As in the case of analogy, the most precise model is for naught if reliable inputs cannot be had.

4.2 Conditions for Model Development

Whether an analogous or parametric model are to be developed, a number of technical and organizational prerequisites exist. These are described below.

Historical Cost Database: Most, if not all, organizations maintain records of expenditures for each project. Government contractors are required to do so.

However, unless a concerted effort had previously been initiated, the likelihood of sufficient data existing in a useable form is low. "The key element in such a system will be the provision of consistent and comparable databases." [8] The necessary characteristics of the database are:

- It must contain enough programs to allow for statistically valid analyses to be performed. The programs should be of similar type for comparison purposes.
- It must be consistent in content across all programs. This implies the use of a standard cost structure to the degree possible. It is recognized that all programs are unique and that customer imposed constraints may deter from this goal; however, the standard structure can be tailored to accommodate these situations.
- Cost data must be maintained to a sufficient level of detail. "The level of cost data (must be) sufficiently low (level 7) to permit full visibility of detailed particles by the cost analysts." [40] Costs for Task-A cannot be estimated from data maintained only at the task group or function level. This again suggests the use of a standard cost structure.

- Detailed descriptions of what is and is not included in each cost element must exist.

Program Parameter Database: Along with the cost data, information characterizing the complexity of the system and the program must be collected and maintained. To do this assumes that these parameters have been identified. Initially, it may be expeditious to hypothesize a reasonable superset of possible parameters (perhaps in a brainstorming session and/or using the delphi method). Later, after a sufficient amount of associated cost data is available, sensitivity and other analyses can permit this list to be trimmed. Characteristics of the parameter data are:

- Explanatory variables should be well documented and complete.
- Parameters should be maintained in a database. This may or may not be the same database in which the cost data is located.
- Parameters should be collected for all programs for which cost data is to be used. Although similar types of programs are needed, a good cross section of parameters is useful. This will permit identification of significant changes in CERs across the range of a given parameter.

Management Acceptance and Support: This element may be the most critical prerequisite of all. First of all, management must recognize that a deficiency exists in the current estimation method or at least that room exists for improvement. They must also be convinced that it is cost effective for an improvement to be undertaken (note that where adequate methods are in place, this may not be the case), and that the resulting model or method will address their needs.

Once this occurs, a sincere commitment is needed to accomplish the objective. This commitment should be expressed not only in the form of a supportive attitude, but backed by an adequate commitment of resources and a willingness to adapt from "the way we have always done things".

The implementation of the cost and parameter databases described above will require participation across the organization. First, program managers must be willing to incorporate the standard cost structure on new programs to the extent possible and to assist in the collection of parametric data during the progress of those programs. Coordination with the cost accounting department will be needed for access to and manipulation of actual cost data. Responsibility for the creation and maintenance of the parametric data will need to be assigned and computer resources allocated for this purpose. Refinement of both the systems engineering and overall quotation estimation processes may also be advisable depending on the current state of those functions.

As analysis and model development efforts progress, feedback should be provided and assistance rendered when new cost estimates are developed. In other words, an atmosphere of mutual cooperation and exchange of data across the organization is key. This interaction among the affected parties is essential to acceptance of the initiative and will facilitate the integration of the model into the process later on. Even then, a close working relationship will be needed to establish a track record and enhance credibility of the methodology and model.

4.3 Tool Requirements

What set of characteristics describe the ideal automated cost model? It should:

- Enhance the accuracy of estimates.
- Provide visibility into the uncertainty of the estimate.
- Be intuitively understandable to the project manager, supporting his natural experience and inclinations.
- Reduce the cost of preparing an estimate, either by decreasing the amount of data needed or by simplifying the procedure. [17]

- Be adaptive in that as new historical cost data becomes available, it can be immediately incorporated into the model. [15]
- Should not be made too detailed lest it become unmanageable, yet it should not be made too general lest it become insensitive to significant parameters. [39]
- Be easy and quick to use for both beginners and experienced users.
- Handle varying degrees of estimation accuracy as needed for different purposes. [11]
- Support multiple estimates based on different methods, assumptions, or goals and allow for selection or averaging of the results.
- Execute on a personal computer (PC) using either a local database or via local area network (LAN) access to a central database.
- Enable resulting estimates to be directly fed into the cost accounting system for inclusion with the total program estimate.

4.4 Approach

After reviewing current methods and practices and evaluating candidate techniques, an approach has been formulated for the development and employment of a systems engineering cost estimating model. Although described in terms of an organization currently performing ad hoc systems engineering and using grass roots estimating methods, the approach is not limited to such an organization.

A five phased approach is proposed, preceded by a planning period. This is depicted in Figure 7, with each stage described below. In essence, this approach entails the application of the systems engineering process to the development/improvement of the cost estimation "system".

Planning stage. Before a commitment is made to initiate a change in current costing methods, some preparation is required. The first action should be an assessment of the state of the current systems engineering process and cost estimating practices. This will lead to the identification of the deficiency to be addressed or improvement to be sought.

If no well defined systems engineering process is followed, it is advisable to institute one. This does not imply that a rigid, formal procedure be enforced on every program without deviation, but that a standard process be documented that will serve as a basis for tailoring to fit the unique characteristics of each program. This process also forms the basis for cost estimation. It may be that good systems engineering is customarily practiced, but has never been explicitly defined. In this case, it merely needs to be documented in some form. However, it may be because no

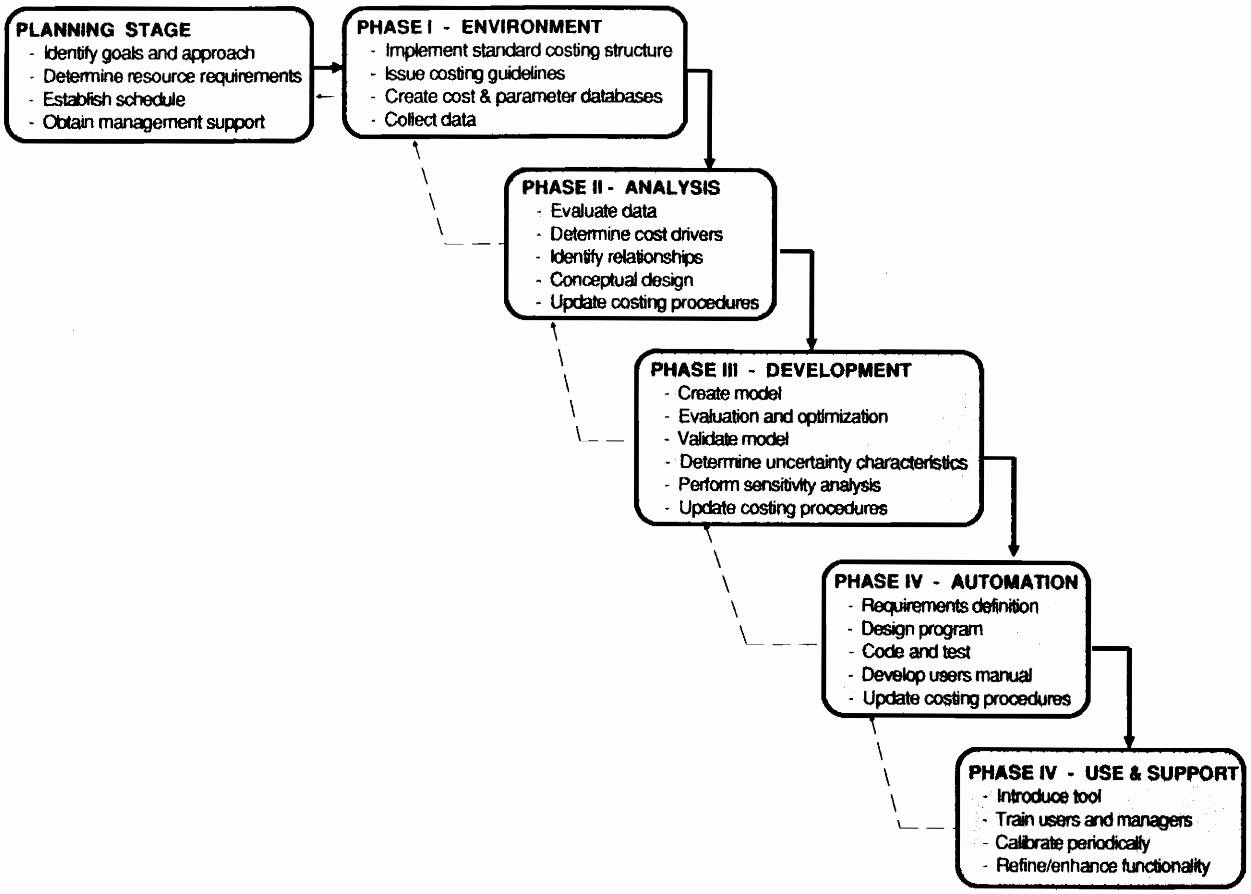


Figure 7. Five Phased Approach to Model Development

standard systems engineering process is followed that budget problems occur rather than because of poor estimating practices. In this case, attention should first be focusedon improving the basic systems engineering process, then on evaluating the cost estimating function. Remember that whatever cost estimation method or model is ultimately developed, the cost elements will be closely associated with the process activities. Therefore, it is important that these activities be defined and understood.

Based on this self-assessment, the need for action should be determined, and goals and objectives for the initiative should be identified. A plan of action or proposal should then be devised for accomplishing these goals. This plan should address the activities described in the five phases below and include a schedule and an estimation of resources required. The cost estimation improvement program should be treated as exactly that - a program - and managed accordingly.

The next step is to obtain management support for the initiative. To do this, the emphasis should be placed on the expected benefits to be derived from such an endeavor. The objective here is to receive approval and commitment of resources to proceed through completion of conceptual design. (At this point, a review will be required to determine the cost effectiveness of continuing the project.)

Phase I - Preparing the Environment. The objective of this phase is to put into place the mechanisms and infrastructure necessary to provide the required input data and to otherwise support the new cost estimation methodology.

If not already in place and found to be adequate, a standard costing structure should be developed and adopted for use on all proposals and new start programs. A candidate for this purpose is the WBS shown in Figure 8, which can be adapted and/or expanded as needed to best fit both the systems engineering process in use and the characteristics of the typical program. Once a standard is adopted, however, tailoring for use on individual programs should be performed sparingly. In general, tailoring should consist of the elimination of cost elements associated with activities which will not be performed on the particular program and of aligning the cost elements in such a way as to fit within any customer specified costing structure. It should not consist of rolling up cost elements into a single higher level account. The program budgets should then be managed within the same structure used for estimating.

If necessary, effect modifications to the current cost accounting system or methods to support the data collection, access, and manipulation that will be required to perform future analysis. Care must be taken, of course, to minimize changes and disruption to ongoing business. Examples of

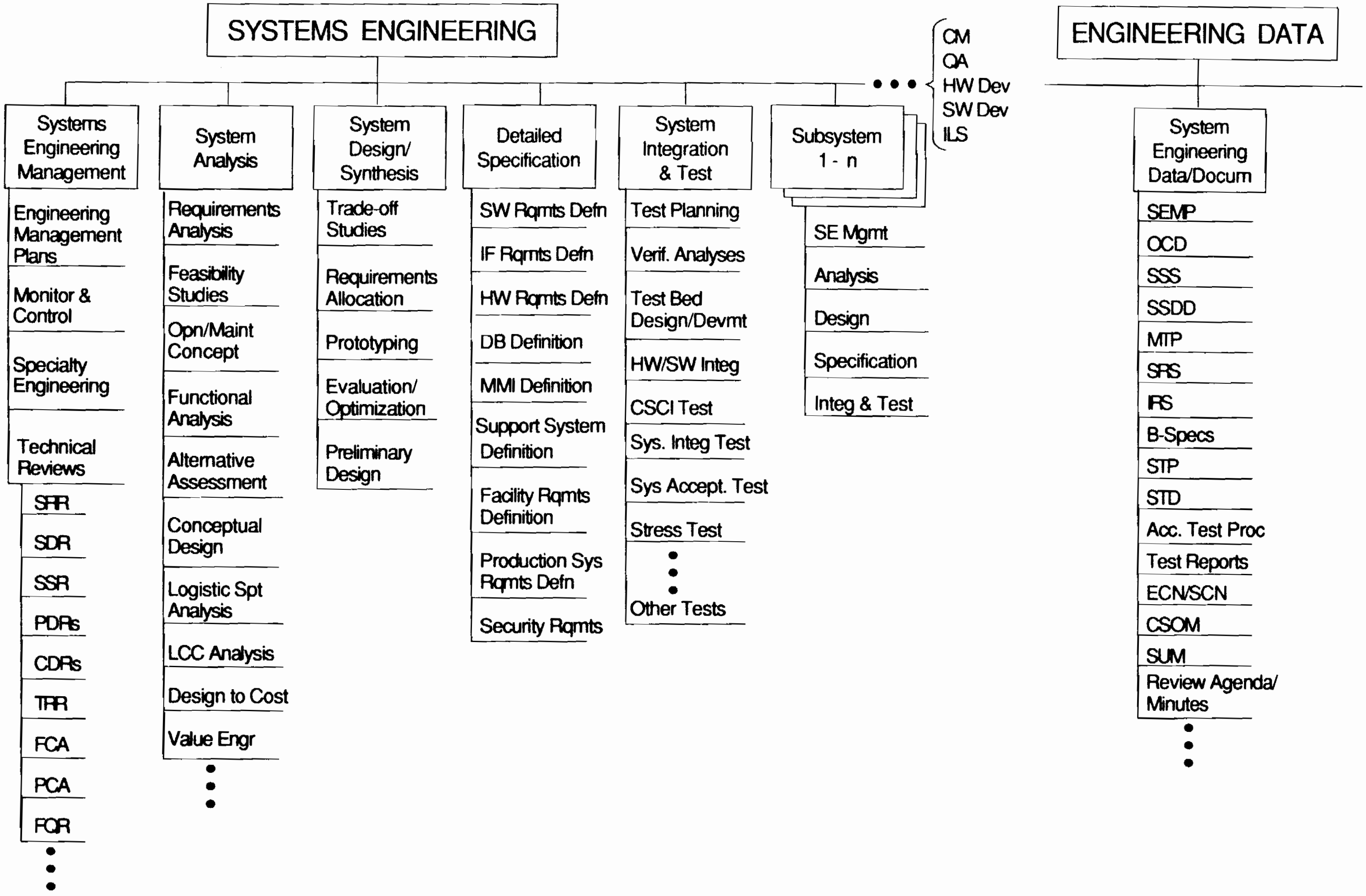


Figure 8. Candidate Systems Engineering Cost Structure

desired changes might be the addition of new summary accounts across functional as well as product lines or the ability to download certain cost files into another system for further analysis. Because these types of changes may be costprohibitive, it may be necessary to defer them to a later phase and institute work-around solutions in the interim. As a minimum, a way to maintain the data for closed out programs must be implemented.

The historical cost and parameter databases described in 4.2 above should be established and maintained. In particular, adequate descriptions of work performed under each WBS element should be compiled, parametric data collected throughout the development, and a file of basic program information organized. This file might contain such things as the names of key personnel assigned to the program, original cost estimates, system block diagrams, software architecture, data flow diagrams, a list of CDRLs, etc. This information will assist the analyst when attempting to make complexity assessments.

To facilitate collection of parametric data, at the beginning of each new program, the project engineer should be provided with a data sheet or information indicating what parameters are of interest and should be tracked. This information may then be compiled at 6 - 12 month intervals, or during an "exit interview" at the close of the program. The periodic method is preferred because some parameters are more closely associated with efforts at the early or mid stages of development and if not collected then, may not be as available later. Also, periodic checks provide insight into the variation of each parameter over time.

Another important step is the development and promulgation of a set of costing guidelines. At this point, the guidelines should be kept as close as possible to current practices while including those changes necessary to ensure that adequate data is obtained. This may reduce to merely documenting methods currently in use or may entail more extensive effort. The objective is to establish consistency and repeatability. Costing guidelines should include:

- A general description of what and how to estimate
- Assignment of responsibilities
- The standard WBS with element descriptions and tailoring guidelines
- Checklists
- Metrics collection procedures
- Information about where to obtain historical information and guidance on how it should be applied
- Rules of thumb
- Where to go for assistance

If it does not already exist, consider the establishment of a cost engineering group. The importance of reliable cost estimating and the sophistication of the task warrants a dedicated function rather than relegation to "other duties as assigned." "An estimator is found in organizations whose development has matured, especially those organizations where engineering and design are important." [34] "Clearly, estimating the [parameters] requires the services of a professional who is familiar with the current state-of-the-art technology and has some knowledge of the functional attributes of the system concept." [46] Members of such a metrics group are specialists in measurement and estimating and acquire their skills over many projects. [22] The charter for such a group would include such functions as cost and parameter database maintenance, trend analysis, model development/evaluation, metrics collection, productivity determinations, quote reviews and cross checks, calculation of relative costs of design alternatives, etc. "Organizational placement and support are critical to achieving the benefits available through parametrics. Attachment of the responsibility to traditional functions like finance and systems engineering introduces conflicts. An independent department, available to the new business development manager, is an ideal place for the parametric function." [14] The size of the group would be proportional to the size of the organization. One organization interviewed had established a cost engineering section staffed with a couple of permanent cost engineers along with other members selected from among the best program engineers to serve for terms of one to two years on a rotational basis. In this way, the cost engineering group was kept abreast of current engineering and program practices and the engineers took valuable cost estimation knowledge and experience back to the program areas with them.

Phase II - Analysis. Once sufficient data has been compiled, it can begin to be analyzed using statistical and mathematical techniques to determine the major cost drivers, their general patterns of variation, the elements and form of the complexity factor(s), cost and parameter statistics, and productivity factors. Examples of productivity factors for systems engineering documentation development might be the average number of pages for each type document, average number of manhours per page, average number of comments received per document, average number of submittals, ratios of labor levels used, etc. The identification of cost estimating relationships is a key outcome of this phase. Additionally, insight into which tasks tend to be overbid or underbid can be gained and adjustments made accordingly.

It is important to know how much analysis is enough. Too little analysis is likely to result in a poor representation of reality while too much analysis may result in low marginal benefits. "A truly complete analysis would entail isolating all the variables in the system on a global basis, determining their limits, their functions, their relative weights, their interdependence, their time rates of change -- in short, an impractical if not completely impossible undertaking that would be in itself the poorest of cost-effectiveness practice, since the cost and time required for such futile attempts in all likelihood would be prohibitive compared with the reduction in the error of the estimates. Most cost-effectiveness models therefore are suboptimizations at best and usually will not be found to contain any second- or higher order terms.

"Since the optimum solution is not attainable in the limit, the results must always be a relatively imperfect solution at best. It is in the attainment of an appropriate degree of suboptimization that there will always be found a considerable exercise of judgment. Like it or not, judgment is needed to arrive at what may be considered too much analysis versus what may be considered too little analysis. ... In the final analysis, the best that can be hoped for in a world full of uncertainty is a good compromise with the unattainable." [39]

The results of this analysis can be used to refine the cost structure and database content as needed. Cost estimating guidelines and procedures should be updated at this time also.

During this phase, the conceptual design of the model should be developed. This entails the performance of a requirements analysis, a feasibility evaluation, and alternative assessments. The end product of this effort will be a functional specification for the model and a recommendation as to whether or not to proceed with its development. At this point, a review should be held to evaluate the design and to make this decision.

Phase III - Model Development. The results of the analyses, the compiled data, and the functional specification can now be used to create a theoretical cost model. An iterative cycle of synthesis and experimentation should occur as the model is evaluated against actuals; its accuracy, uncertainty, and sensitivity assessed; and its features and performance optimized with respect to its specified requirements. The model should then be empirically validated in two ways. First, by comparing estimated to actual costs using historical information, and second by using the model in parallel with current methods and comparing results.

When determined to be suitable for use, based on a design review, costing procedures should again be updated. The revision should include "how to" information concerning the use of the model as well as guidelines as to the role it should play in the overall cost estimation process. For example, under what conditions will it be used as the primary source of cost estimation values and under what conditions will it be used as a cross-check on values obtained using other methods?

Phase IV - Automation. During this phase, a computer based version of the model is generated. This is accomplished as for any system development. Alternative hardware architectures are evaluated and a platform selected. Software, interface, MMI, and database requirements are specified. The software design, coding, and test are performed. Integration testing is performed in the operational environment, ensuring interoperability with associated systems. Validation and user testing is conducted. The development of a comprehensive users manual for the system is essential.

Although this phase is shown as following the development phase, in actuality it may be performed in parallel. In fact, depending on the complexity of the model, it may be entirely too calculation intensive to be used manually. In this case, an automated prototype may be developed along with the algorithms and serve as the test bed for model evaluation and optimization. In this way, as changes or additions are incorporated, the effects can be quickly ascertained.

Costing procedures should once again be revised to delineate appropriate usage of the automated model, its preferred role in the estimating process, and responsibility for operation, calibration, and maintenance support. Will it be used only by the cost engineering group or will it be accessible to program engineers? How can results be used during contract negotiations? What are the limitations of the model?

Phase V - Use and Support. As with any new automated tool, the new systems engineering cost model should be gradually introduced into the organization in a manner which minimizes disruption and hostility. The tool should not be introduced until a degree of maturity is realized. It is counterproductive to release the model prematurely, especially in order to meet an arbitrary deadline, when all the bugs are not yet out.

It is recommended that the model, at least initially if not always, be used in conjunction with current grass roots estimation methods. Its introduction should be preceded by education and training, targeted to both users and managers. Managers should be briefed on ways in which the tool can be used to support them (see paragraph 2.4.3.3). Users should know what input data is required and be taught to understand the general effects of that data on the resulting estimate. Assistance should be provided in installing, using, and maintaining the tool; interpreting results; and for general support. An unsupported tool will not be used.

Following introduction, performance of the model should be monitored. Refinements should be made as necessary. A track record should result establishing a level of credibility. Feedback from users should be collected, and improvements and additional features incorporated.

It is imperative that the model be periodically calibrated as the basic relationships will change over time based on changes in technology, productivity, and other factors.

4.5 Limitations

Although the potential for many benefits exist with the use of cost estimation models, limitations also exist. "The engineer using the computer must still possess a thorough understanding of what it is providing him and just as he realizes its benefits, he must also be able to identify and cope with its limitations in handling cost estimates of facilities with unique characteristics." [17]

All models perform best in their "home" environment; that is, under similar conditions to those in which it was developed. When used in a foreign environment, results are more difficult to predict. "A different-configuration situation contains a larger range of uncertainty than does a like-configuration situation ... an unfamiliar configuration poses a substantial challenge to the estimator -- a challenge which is significantly less formidable when a detailed end-item-oriented cost data bank is used" [40] Therefore, it is important to understand the environment (type of system, size of system, etc) to which the model applies as well as the assumptions made during its development.

As previously cautioned, the quality of the output of a model is dependent on the quality of its inputs and upon the skill of the user. The quality of an estimate has less to do with the specific estimating tool than with the soundness of the information used to drive the tool and the consistence of its application. "Models can be no better than the people who operate them and, perhaps more importantly, those who interpret and present the results." [14]

Chapter 5

5.0 Conclusion and Recommendations

A number of possible cost estimation methodologies were evaluated for application to the estimation of systems engineering costs. Attempts were made to utilize historical cost data from actual programs to identify relationships between costs and explanatory variables. Experts were queried to ascertain current practices, judge the merits of different approaches, and subjectively rank contributors to cost. From these investigations, an approach to the development of a systems engineering cost estimation model was formulated.

5.1 Conclusions

There is a need to improve the consistency, accuracy, and defensibility of systems engineering cost estimates. A model can help to do this, particularly when used in conjunction with other methods. Parametric and analogy models appear to be the most suitable in the near term; however, both require the development of a comparable database of costs as well as cost drivers, which takes some time to establish.

Preliminary findings indicate that leading cost drivers, all of which are a measure of system complexity, are:

- Number/types of interfaces,
- Number/diversity of functions,
- Number of hardware and software components,

and that rankings of systems engineering task areas by relative contribution to cost are:

- Integration and test, and
- Design and specification.

A number of conditions must exist before a model can be developed and be a useful tool within an organization. Chief among these are:

- Existence of a defined systems engineering process
- Institution of a standard cost structure for bidding and managing systems engineering efforts
- Establishment and maintenance of a consistent and comparable cost and parameter database
- Management support and resource commitment

5.2 Recommendations

Any organization which performs large system development or integration programs requires a healthy systems engineering function and a means of estimating the cost associated with this function. For those organizations which have experienced difficulties in predicting these costs, the approach outlined in Section 4.4 may provide a practical method for addressing deficiencies in current estimating practices. However, this will not be on overnight process. It will require the commitment of time and resources to reach the end result - a reliable and consistent cost estimation process.

Based on the results of the method evaluation, the model should be based on either the analogy or parametric technique or on a combination of these techniques. For quotation estimates, the model should be used in conjunction with traditional grass roots methods. The model alone, once validated, may be used for other purposes such as early ROM estimates for feasibility assessments or bid/no bid decisions.

"There can be some pressure to have the parametric estimate support the consensus estimate. To yield to that pressure is a mistake. It is the differences pointed out by the parametric estimate that provides the real, long-term benefit." [14]

5.3 Future work

As may be obvious, much work remains to be done in the field of systems engineering cost estimation. Some suggested avenues for future investigations are listed below.

- Continue research into the identification of major cost drivers (i.e., primary contributors to complexity) and cost estimating relationships.

- Refine the proposed cost structure based on feedback during usage.
- Expand the study to encompass a larger number of organizations to incorporate a broader cross section of practices (this may be possible if performed by a full time academian who has no ties to any particular corporate entity).
- Track new WBS initiatives rumored to be in progress within the government.
- Perform an analysis of proposed costs to actual costs to identify trends.
- Analyze labor distributions for each task.
- Determine productivity factors.
- "More research needs to be performed by cost engineers in integrating design and cost estimation." [12]

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Appendix A

Systems Engineering Task Descriptions

Systems Engineering Task Descriptions

Requirements Analysis: Contractor performs analysis of customers stated requirements. Includes extraction, decomposition, organization, interpretation, and assessment. Ambiguities, gaps, conflicts, and testability issues are identified. A dialogue with the customer and users is maintained to ensure that the intent of the requirements has been inferred. Once understood and categorized, implied requirements are specified and lower level requirements are derived. Generally, original and manipulated requirements are maintained in a database of some sort for traceability purposes.

Feasibility Studies: The early investigation, analysis, and determination of possible technical design approaches in response to a defined need for a new system. This includes evaluation and comparison of new technologies, as well as the accomplishment of applied research in areas where additional knowledge is desired. [5]

Risk Analysis: An iterative process which identifies potential problem areas, quantifies the probabilities associated with these problems, assesses the effects of these risks, and generates alternative actions to reduce risks. Risk management further includes contingency planning, implementation of risk mitigating strategies, and continual monitoring of risk levels and sources. [43]

Planning: The effort to determine how the systems engineering tasks will be accomplished and controlled to meet program objectives. These are documented in the Systems Engineering Management Plan (SEMP). The plan should identify the organizational structure, functions, and responsibilities; all activities to be performed, management techniques, analyses, trade studies, and TPM parameters that will be employed; and schedules and resource requirements.

Functional Analysis: A stepwise, top-down technique for analyzing performance/functional requirements by progressively decomposing functions into discrete tasks or activities. All system functions (i.e., WHAT the system is to do) are defined and refined at ever increasing levels of detail to determine the actions/tasks the system must perform to satisfy user needs. This can be accomplished through a series of functional block and/or flow diagrams.

Operational Concept: The identification of operational/mission criteria as input to the design process, to include planned deployment, mission profile/scenario, performance parameters, usage factors, effectiveness requirements, system lifetime (inventory profile), and operating environment.

Maintenance Concept: The identification of support criteria as input to the design process. This includes levels of maintenance (preventive/corrective, organizational, intermediate, depot), repair policies, support responsibilities, logistic support elements, effectiveness requirements (for support capability), and maintenance/support environment.

Coordination of the Interdisciplinary Team: The integration of personnel from the various functional areas (such as hardware, software, production, test, etc.) and from specialty engineering (to include reliability, maintainability, safety, human engineering, EMI/EMC, etc.) to form a team. The coordination of the activities of and interactions between these participants ensures the consideration of all factors in the design process, to result in an optimum, balanced system design. This effort also includes team meetings and peer reviews.

Status Monitoring and Control: Those efforts to assess progress; identify discrepancies which could adversely affect cost, schedule, performance, or efficiency; and make necessary adjustments.

Trade-Off Studies: Examination and evaluation of possible design alternatives which are performed throughout development. Initially used in determination of the system concept/architecture, then later to decide item configurations and design details. Alternatives are evaluated on a multi-attribute basis, "trading-off" various criteria such as performance, effectiveness, cost, and schedule to arrive at the best selection.

Design to Cost: The inclusion of cost as a design parameter early in and throughout the system design process. As such, quantitative cost requirements are allocated down from the system level to the various program elements and configuration items. The DTC figure-of-merit may be specified in terms of life-cycle cost, development cost, unit production cost, or other cost value. Government contracts sometimes contain this requirement, or it may be imposed internally.

Value Engineering: The systematic use of techniques which identify the required functions of a system, establish values for these functions, and provide the functions at the lowest overall cost without a loss of performance. [20]

Life Cycle Cost Analysis: The evaluation of total system costs associated with acquisition and ownership of a system throughout its full life to include research and development, design, production, operation, maintenance, support, and retirement. These analyses are conducted periodically to support cost effectiveness assessments and alternative decisions. [5,29]

Logistic Support Analysis: The process employed on an iterative basis throughout system development that addresses the aspect of supportability in design. It is used in the evaluation of a given or proposed configuration to determine the direct impact of the system/element on total logistic support and the feedback effects of the support system upon the system design. [6] This leads to the definition of system support needs to include manuals, training, spares/repair parts, support equipment, and tools. [43]

Survivability/Vulnerability Assessment: Early assessment of the ability of the system to perform critical functions in man-made hostile/threat environments. Survivability from all threats found in specified levels of conflict should be included in the design process. The analyses includes vulnerability assessment under all operating conditions, identification of test methods to verify survivability requirements, and use of a threat model to determine survivability levels. [29]

Conceptual Design: Includes activities which result in an understanding of the problem and its requirements. Such activities result in top level candidate solutions with attendant assignment of logical and physical requirements to specific elements in each candidate (i.e., a preliminary system architecture). [44]

Performance Modeling and Simulation: The development and/or manipulation of system representations (physical, analog, schematic, or mathematical) in order to economically predict its performance under various input conditions. The primary use of such simulation is to explore the effects of alternative system design characteristics on system performance without actually producing and testing each candidate system. [6]

Test Planning: The identification and documentation of the method by which each system requirement is to be tested, where, by whom, resources required, pass/fail criteria, etc.

Evaluation and Optimization: Efforts performed throughout the development cycle to select, design, and produce the system configuration that best satisfies program requirements such as performance, cost, schedule, reliability, maintainability, readiness, etc. This involves the identification of objectives, establishment of candidates, selection of evaluation criteria, comparison/scoring, and ranking. [5,19]

Configuration/Change Control: The systematic management of all changes to the system design. It is the process by which the functional and physical characteristics of a system/element are identified, changes to these characteristics are monitored and controlled, and information is provided concerning the status of change actions. Once a baseline is established, a current description of any developing item and its traceability to previous configurations should be available. [43,44]

Requirements Allocation: The top-down distribution, or apportionment, of system level requirements to the subsystem, equipment, software, unit, or below, to the depth necessary for providing criteria as an input to design. It includes allocation of performance and effectiveness factors, design criteria, and system support requirements. Initially, requirements are allocated to category (i.e., hardware, software, personnel, facilities, data, procedures, processes), then later to specific elements.

Prototyping: The development of a working, physical representation of the prime equipment, software, and/or associated elements of support from the design for purposes of evaluation prior to production. The intent is to verify design adequacy to the maximum extent appropriate for the stage of development. The prototype may evolve through a series of configurations such as an engineering model or service test model. [6] Frequently, only high risk elements of the system are prototyped. Rapid prototyping involves the early development of representations for system elements as an input to the design process for that element (for example, this is typically used in definition of MMI requirements). The prototyping effort includes the construction of breadboards for custom boards/circuits and the test, analysis, evaluation, corrective action, and reporting associated with the prototype.

Alternative Assessment: Refers to the development and evaluation of alternative concepts to address operational requirements, system requirements, and performance criteria. It includes analysis, concept evaluations, and technological assessments of alternatives under consideration. It also includes the development of threat models and scenarios that demonstrate the potential or lack thereof of each alternative.

Reliability and Maintainability Predictions: Performed as engineering data becomes available, as a check on design in terms of the system requirements and the factors specified through allocation. Values of MTBM, MTBF, and MTTR are predicted using various techniques and compared against the requirement. Prediction is accomplished at different times in the equipment design process and will vary somewhat depending on the type of data available. [6] Predictions are used to identify areas for possible design improvement or to compare design alternatives early in the design process.

Synthesis: The process of design, or defining HOW the system will perform its specified functions. This involves the selection of a configuration which is representative of the form that the system will ultimately take.

Software Requirements Definition: The analysis and specification of the detailed requirements of each software configuration item. These requirements are ultimately documented in a software requirements specification.

<ins>Hardware Requirements Definition</ins>: The analysis and specification of the detailed requirements of each hardware configuration item. These requirements are ultimately documented in a Type B specification.

<ins>Interface Requirements Definition</ins>: The analysis and specification of the detailed requirements of each internal and external system interface, both physical and logical. Software interfaces are ultimately documented in an interface requirements specification. Hardware interfaces are ultimately documented in an interface control drawing.

<ins>Database Definition</ins>: The analysis and specification of the content, format, and access requirements of each system database.

<ins>Man-Machine Interface Definition</ins>: The analysis and description of the various system elements which perform human interaction functions; for example, the layout of display screens and the menu structure for a operators console or the configuration of knobs and indicators on a control panel.

<ins>Support System Definition</ins>: The analysis and determination of the logistic system needed to support the prime mission system during its operation and maintenance. This includes the

requirements for special tools and test equipment, training devices, spare parts, and distribution mechanisms.

Facility Definition: The analysis and determination of requirements for the facility in which the system will be operated or maintained. This may entail the definition of a new facility, upgrade to an existing facility, or layout of equipment within an operating space. Critical considerations include environmental control, power distribution, security, maintenance access, and human factors, among others.

Production System Definition: The analysis and determination of the processes, resources, and facilities required for the production of the prime mission system. This should occur in parallel with system design and have an influence on that design.

Security Requirements Definition: The analysis and specification of system security features and constraints.

Test Bed Requirements Definition: The analysis and determination of resources needed to fully verify system performance. Requirements for such things as the test facility; test equipment; external system/interface simulators; data collection, analysis, and reduction systems;

test data bases and scenarios; and supplies, spares, and pre-faulted module must be defined.

Test Procedure Development: Those activities required to establish and document the specific steps necessary to evaluate the system against design specifications, operating conditions, and physical environments. This includes detailed descriptions of the tests to be conducted, how the system is to be set-up, what test data will be used and how it will be entered, where output data will be recorded, what analyses will be performed, and pass/fail criteria.

Design Walk-Throughs: Informal reviews of the hardware and software designs as they progress. These are held to ensure that the designs adequately satisfy allocated requirements, that one element of the design does not adversely impact another, and to control the addition of features beyond those specified. These reviews are held at frequent intervals and are in addition to the formal PDRs and CDRs.

Documentation Reviews: Inspection of hardware and software design documentation and of analyses and reports generated by the various specialty engineering groups to monitor the technical progress of the system development.

Design Clarification: The resolution of system design issues that arise during system implementation. This entails filling in overlooked gaps in the design, resolving conflicts between two design specifications, and clarifying ambiguous areas. Occasionally, it also involves adjusting the design to overcome unforseen difficulties or performance problems.

Test Preparation: Development of each element of the test bed previously defined, organization of resources, coordination of activities, and validation of capabilities.

Problem Reporting, Tracking, and Corrective Action: The closed loop process by which discrepancies are detected, identified, documented, investigated, resolved, and validated. Such discrepancies may be attributed to faulty design, documentation, or implementation. Control of these actions to include categorization, prioritization, and assignment of responsibility is held by a configuration control board. Status is usually maintained in an automated database and trend analysis may be performed.

Verification Analyses: The confirmation of certain system requirements through analytical methods in lieu of demonstration. This may be preferred in some cases due to testability limitations or for cost effectiveness reasons.

Hardware/Software Integration: The incremental combination and checking of hardware, software, data, and other elements of the system until a complete functioning system is formed and is deemed ready for formal testing.

CSCI Testing: Formal qualification testing of each computer software configuration item in accordance with approved software test procedures. This includes conduct of the "practice" runs of the test, regression testing, and reporting of results in addition to the formal witnessed testing itself.

System Integration Testing: Formal qualification testing of all CSCIs composing the system to verify the operation of the integrated whole.

Stress Test: Conduct of rigorous testing of the system to the maximum limits of its performance capabilities for a specified period of time with the objective of identifying any problems or degradation that may occur under circumstances of prolonged peak loading.

Acceptance Test: Performance of system tests which result in the formal acceptance or "sell-off" of the system to the customer. These tests are usually repeated for each subsequent system produced.

Operational Testing: The test and evaluation conducted by the customer to assess the military utility, operational effectiveness, suitability, logistic supportability, and interoperability of the system. Technical and logistic support to the customer is provided under this task.

Assess System Performance: The activities associated with the collection and analysis of data pertaining to how well the system is performing in its operational environment with its intended user and maintainer. This includes field reliability and maintainability data, user evaluations, and other performance measures. This information may be used to influence the design of future systems or to better support the existing system.

System Enhancements: Once the system has been deployed, enhancements may be implemented based on identified deficiencies, new technology, changing mission or environment, or previously identified growth features (or pre-planned product improvements). This task includes the identification, analysis, design, and test of these modifications to the system.

Technical Reviews: Those activities involved in the scheduling, preparation, performance, and reporting of formal and informal technical reviews held with the customer. The objective of these reviews is the determination of the technical adequacy of the existing design to meet known technical requirements. Formal reviews occur at key points in the development to evaluate whether or not to proceed with the next step. Informal reviews include technical interchange meetings which are called to investigate and resolve specific technical issues. Issues, questions, agreements, and action items must be documented and minutes recorded and disseminated. Formal reviews are defined and governed by MIL-STD-1521 [31].

Systems Engineering Data/Products: The preparation, publication, and delivery of specified engineering documentation to include plans, drawings, specifications, procedures, and reports. Note that this task generally does not include the preceding research and analyses efforts, but only the documentation operation. However, the current state of automation causes these two activities to be difficult to separate.

Baselines: Designated points in the system design and development process where the system characteristics or configuration is defined to progressively more detailed levels. The baseline is defined by a specific set of documents (for example, the functional baseline is defined by the system specification). The management of the baseline configuration and changes thereto is a systems engineering responsibility.

Appendix B

Expert Survey Questionnaire

SYSTEMS ENGINEERING COST ESTIMATION
QUESTIONNAIRE

Respondent Data -

1. What systems engineering positions have you held?

2. How many years of experience do you have? ______

3. How many programs have you been involved in? ______

4. What range of sizes were these programs (in $M)? ______

5. Approximately how many quotation estimates have you prepared? ______

6. What types of systems have you developed? (check all that apply)

______ Electronic
______ Computer based
______ Weapons
______ Communications
______ Command & Control
______ Navigation
______ Military/defense
______ Civilian/commercial
______ Other (specify ____________________)

______ Large (> $100M)
______ Med ($5M - $100M)
______ Small (< $5M)
______ Mostly hardware
______ Mostly software
______ HW/SW mix
______ FFP
______ CPFF

Methodology section -

7. Does your operating unit have a systematic, documented procedure for developing systems engineering cost estimates? (yes) (no)

8. Does each systems engineer have his own personal method for estimating these costs? (yes) (no)

9. What type of cost model(s) do you use to estimate systems engineering costs?

______ a. Parametric/causal

______ b. Application of actual/historical data with complexity factor adjustments (analogy)

______ c. Level of effort based on experience

______ d. Reverse calculation from goal value

______ e. Percentage of hardware and/or software engineering quote

______ f. Guess, then justify

10. Do you have access to historical/actual system engineering costs for previous, completed programs? (yes) (no)

If so, is this data maintained to the level of detail to be useful as a basis for a new program estimate (i.e., WBS level, task level, etc.)? (yes) (no)

11. Are systems engineering costs accounted for on a consistent basis across contracts (i.e., elements are comparable)? (yes) (no)

Is a standard WBS breakout followed to the extent possible for systems engineering on all contracts? (yes) (no)

12. Is adequate descriptive information available about the previous system and contract to compare requirements complexity? (yes) (no)

13. Briefly (1-2 paragraphs) describe your method of estimating systems engineering costs.

14. In general, does your unit overrun, underrun, or break even on its systems engineering budget? (please be direct) ________________

15. Have you ever experienced a situation in which certain systems engineering activities were downscaled or omitted due to inadequate funds or because they hadn't been bid? (yes) (no)

16. Does your unit/facility provide any automated tools to support systems engineering cost estimation? (yes) (no) If so, which one(s)?

17. Have you found it easy or difficult to defend your systems engineering cost estimates during pre-award audits? ____________

To your own upper management? ____________

18. List what you believe are the top 5 factors affecting systems engineering costs (in descending order of impact).

1)
2)
3)
4)
5)

19. List the 5 systems engineering tasks you believe cost the most to perform (in descending order).

1)
2)
3)
4)
5)

20. System complexity appears to be a dominating factor in system engineering costs. How would you define "complexity"?

What do you feel are the primary factors affecting complexity?

21. In the attached matrix (Table 1), indicate the parameters which have a major influence on the cost of each activity. Add any other parameters you believe are significant.

22. Do you apply a 'learning curve'? (yes) (no) If so, describe how.

23. If you use a cost model, is it calibrated periodically or after each job completion? (yes) (no) If so, how?

24. Comment on the proposed systems engineering WBS shown in Figure 1. (Mark-ups are acceptable.)

    What advantages/disadvantages do you see to this WBS or other similar WBS?

    Do you think that use of a standard costing structure that was managed to the appropriate level of detail would enhance the usefulness of historical cost data to the development of new systems engineering quotes?
    (yes) (no)

25. If a parametric (or other) model were available, would you use it? (yes) (no)

    What level of faith would you place in it?

    (high) (med) (low) (none)

    Do you think that a model when used in conjunction with other methods would be useful? (yes) (no)

    If so, suggest some ways.

26. Are you familiar with costing methods used in other companies? (yes) (no)

    If so, how do these compare with those used in your unit?

27. Do you have any other insights or comments about systems engineering costing that you would like to share?

Table 1. Parameter Matrix

TASKS/ACTIVITIES PARAMETERS	PLANNING	COST ESTIMATION	MONITOR/CONTROL	MISSION/OPNL/RQMTS ANAL	FEASIBILITY STUDIES	RISK ANALYSIS	OPNL/MAINT CONCEPT	FUNCTIONAL ANALYSIS	SPECIALTY ENGR COORD	CONCEPTUAL DESIGN	TRADE-OFF STUDIES	LCC ANALYSIS	RQMTS ALLOCATION	PRELIM SYSTEM DESIGN	MASTER TEST PLANNING	PERFORMANCE MODELING	PROTOTYPING	EVALUATION/OPTIMIZATION	DETAILED SYSTEM DESIGN	SW RQMTS DEFINITION	INTERFACE RQMTS DEFINITION	MM I DEFINITION	DATABASE DEFINITION	HW RQMTS DEFINITION	MONITOR HW DEVMT/SUBCONTR	MONITOR SW DEVMT/SUBCONTR	REQUIREMENTS MANAGEMENT	PROBLEM RPT/TRK/RESOL	CHANGE CTRL/BASELINE MGMT	TEST PLANNING/PREPARATION	TEST PROCEDURE DEVMT	TEST PROCEDURE VALIDATION	HW/SW INTEGRATION	PERFORM CSCI TEST	REGRESSION TESTING	SYSTEM INTEGRATION TESTING	SYSTEM ACCEPTANCE TESTING	SYSTEM ENGR AFTER DELIVERY
SIZE/COMPLEXITY																																						
$ value thru 1st system																																						
# of source requirements																																						
# of major functional areas																																						
# of subsystems																																						
# of hardware items																																						
# of software items																																						
Software lines of code																																						
# of interfaces																																						
# of algorithms																																						
Real time behavior																																						
# of TPMs																																						
# of unique processors																																						
# of display screens/windows																																						
Performance challenges																																						
Type/mission of system																																						
CUSTOMER FACTORS																																						
New/old customer																																						
Degree of cooperation																																						
SOW/specification quality																																						
#/type of MIL standards/specs																																						
Level of documentation																																						
Supportability																																						
Ruggedization																																						
Operational environment																																						
EXPERIENCE																																						
Similarity with previous jobs																																						
Experience with mission area																																						
Amount of previous IR&D																																						
Previous prototype																																						
Amount of SE during proposal																																						
RESOURCES																																						
Experience level of team																																						
Performance rating of team members																																						
Level of automation																																						
RISK FACTORS																																						
Dependence on new technology																																						
New system or upgrade																																						
FFP -v- CPFF																																						
Design to cost																																						
Schedule constraints																																						

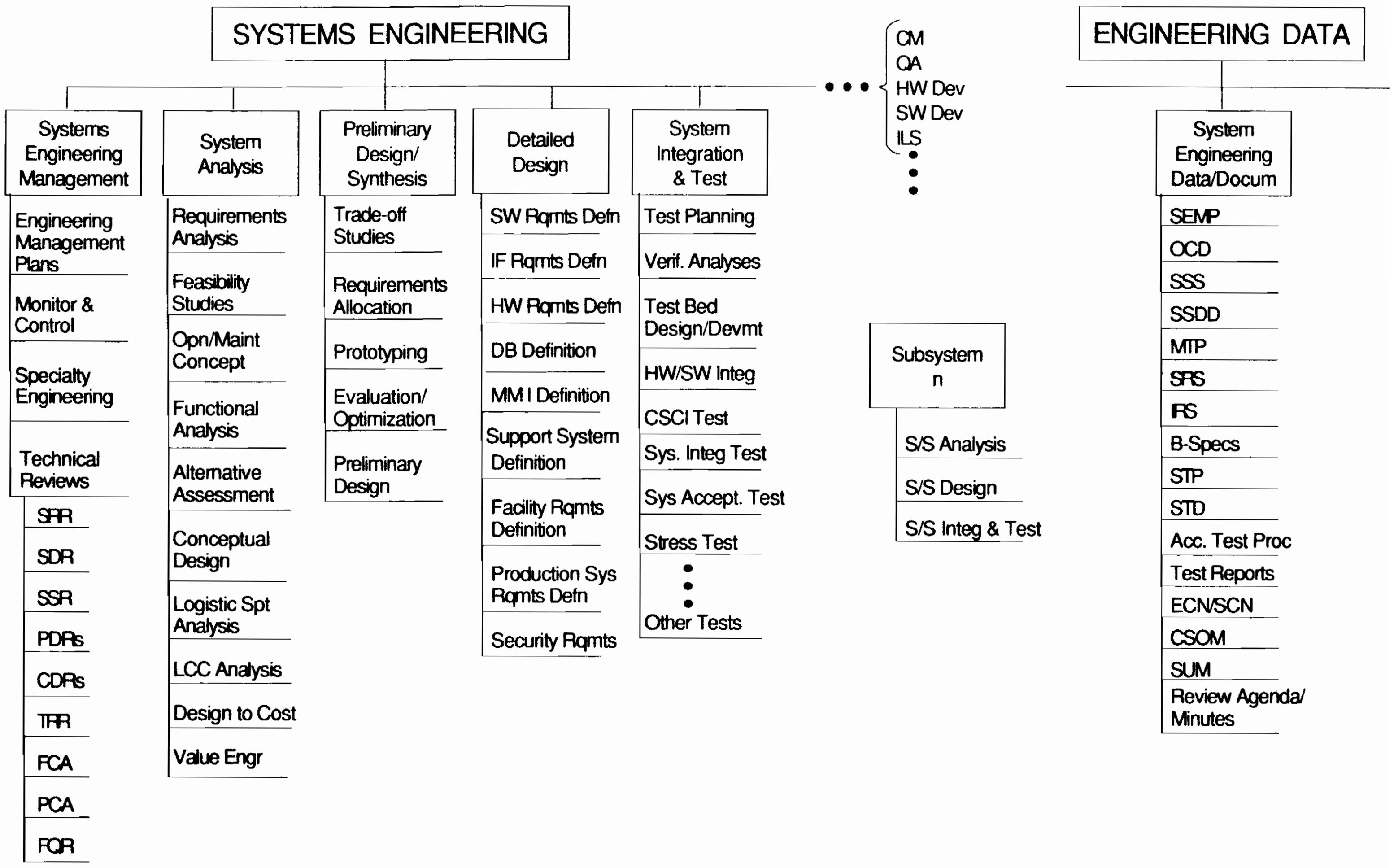

Figure 1. Proposed Systems Engineering WBS

GLOSSARY -

Systems Engineering: "The effective application of scientific and engineering efforts to transform an operational need into a defined system configuration through the top-down iterative process of requirements definition, functional analysis, synthesis, optimization, design, test, and evaluation."

Cost Estimation: An evaluation of the amount of resources required to perform a particular task or set of tasks or to produce a particular product or set of products. The value may be given in labor hours or dollars.

Parametric Model: The use of Cost Estimating Relationships (CERs) that make use of product characteristics (such as hardware weight or software language) to estimate costs and schedules.

Analogy: The use of historical data from similar programs/systems to extrapolate the cost of similar elements of a new program.

Level of Effort: Estimating cost by determining manning requirements over the program schedule, then summing.

Reverse Calculation: Starting from a cost "bogey", usually provided by marketing, and backfitting costs into the structure until the estimate matches the bogey.

Percentage: Estimating one cost element (or set of elements) from the estimated value of other loosely related cost elements.

WBS: Work Breakdown Structure. A hierarchial breakout of cost elements from higher to lower levels until all cost elements are accounted for.

Appendix C

Survey Results

Table 6. Questionnaire Results

QUES #	QUES TITLE	# OF RESPONSES	RANGE OF VALUES	# TIMES SELECTED	% SELECTED	MEAN	MODE	MEDIAN	STD DEV
1	CURRENT POSITION	15	PE - DIRECTOR	NA	NA	ENGR MGR	NA	NA	NA
2	YEARS EXPER.	15	10 - 35	NA	NA	21.6	10	22.5	9.5
3	# OF PROGRAMS	15	4 - 50	NA	NA	16.5	20	27.0	12.3
4	SIZE OF PROGRAMS	15	.1 - 2000	NA	NA	137.6	50	503	243
5	# OF QEs	14	5 - 500	NA	NA	63.0	20	253	124
6	TYPES OF SYSTEMS	15	7 - 16	NA	NA	11.4	12	11.5	2.7
			ELECTRONIC	12	80	NA	NA	NA	NA
			CMPTR BASED	15	100	NA	NA	NA	NA
			WEAPONS	4	27	NA	NA	NA	NA
			COMMUNIC	8	53	NA	NA	NA	NA
			CMD & CTRL	14	93	NA	NA	NA	NA
			NAVIGATION	8	53	NA	NA	NA	NA
			MIL/DEFENSE	14	93	NA	NA	NA	NA
			CIV/COMMER	5	33	NA	NA	NA	NA
			LARGE	8	53	NA	NA	NA	NA
			MEDIUM	13	87	NA	NA	NA	NA
			SMALL	15	100	NA	NA	NA	NA
			HARDWARE	4	27	NA	NA	NA	NA
			SOFTWARE	8	53	NA	NA	NA	NA
			HW & SW	12	80	NA	NA	NA	NA
			FFP	14	93	NA	NA	NA	NA
			CPFF	14	93	NA	NA	NA	NA
			OTHER	3	20	NA	NA	NA	NA

Table 6. Questionnaire Results (Cont.)

QUES #	QUES TITLE	# OF RESPONSES	RANGE OF VALUES	# TIMES SELECTED	% SELECTED	MEAN	MODE	MEDIAN	STD DEV
7	STANDARD PROCESS	15	YES	3	20	NA	NA	NA	NA
			NO	12	80	NA	NA	NA	NA
8	PERSONAL METHODS	13	YES	10	77	NA	NA	NA	NA
			NO	3	23	NA	NA	NA	NA
9	MODELS USED	15	1 - 6	NA	NA	3.3	2	3.5	1.6
			PARAMETRIC	6	40	NA	NA	NA	NA
			ANALOGY	14	93	NA	NA	NA	NA
			LOE	13	87	NA	NA	NA	NA
			REV. CALC.	5	33	NA	NA	NA	NA
			PERCENTAGE	5	33	NA	NA	NA	NA
			GUESS	6	40	NA	NA	NA	NA
10	ACCESS TO HISTORICAL	15	YES	8	53	NA	NA	NA	NA
			NO	3	20	NA	NA	NA	NA
			QUALIFIED	4	27	NA	NA	NA	NA
	ADEQUATE DETAIL	14	YES	3	21	NA	NA	NA	NA
			NO	9	64	NA	NA	NA	NA
			QUALIFIED	2	14	NA	NA	NA	NA
11	CONSISTENCY	14	YES	1	7	NA	NA	NA	NA
			NO	13	93	NA	NA	NA	NA
	STD WBS	14	YES	4	29	NA	NA	NA	NA
			NO	10	71	NA	NA	NA	NA
12	ADEQUATE DESCR INFO	14	YES	3	21	NA	NA	NA	NA
			NO	11	79	NA	NA	NA	NA
13	METHODS OF ESTIMATION	13	See Text	NA	NA	NA	NA	NA	NA

Table 6. Questionnaire Results (Cont.)

QUES #	QUES TITLE	# OF RESPONSES	RANGE OF VALUES	# TIMES SELECTED	% SELECTED	MEAN	MODE	MEDIAN	STD DEV
14	PERFORMANCE TO BUDGET	13	OVERRUN	10	77	NA	NA	NA	NA
			UNDERRUN	1	8	NA	NA	NA	NA
			BREAK EVEN	6	46	NA	NA	NA	NA
15	OMIT/REDUCE ACTIVITIES	14	YES	11	79	NA	NA	NA	NA
			NO	3	21	NA	NA	NA	NA
16	COST ESTIM TOOLS	15	YES	0	0	NA	NA	NA	NA
			NO	15	100	NA	NA	NA	NA
17	AUDIT DEFENSE	11	EASY	5	45	NA	NA	NA	NA
			DIFFICULT	6	55	NA	NA	NA	NA
	MGMT DEFENSE	11	EASY	5	45	NA	NA	NA	NA
			DIFFICULT	6	55	NA	NA	NA	NA
18	TOP 5 COST FACTORS	14	See Text	NA	NA	NA	NA	NA	NA
19	HIGH COST TASKS	14	See Text	NA	NA	NA	NA	NA	NA
20	DEFINE COMPLEXITY	12	See Text	NA	NA	NA	NA	NA	NA
	COMPLEXITY FACTORS	13	See Text	NA	NA	NA	NA	NA	NA
21	PARAMETER MATRIX	7	See Table 7	NA	NA	NA	NA	NA	NA
22	LEARNING CURVE	14	YES	6	43	NA	NA	NA	NA
			NO	5	36	NA	NA	NA	NA
			SOMETIMES	3	21	NA	NA	NA	NA
	HOW APPLY	9	See Text	NA	NA	NA	NA	NA	NA

Table 6. Questionnaire Results (Cont.)

QUES #	QUES TITLE	# OF RESPONSES	RANGE OF VALUES	# TIMES SELECTED	% SELECTED	MEAN	MODE	MEDIAN	STD DEV
23	CALIBRATION USED	13	YES	1	8	NA	NA	NA	NA
			NO	5	38	NA	NA	NA	NA
			N/A	7	54	NA	NA	NA	NA
	CALIBRATION METHOD	1	See Text	NA	NA	NA	NA	NA	NA
24	WBS CMNTS	12	See Text	NA	NA	NA	NA	NA	NA
	ADVANTAGES/ DISADVANT	12	See Text	NA	NA	NA	NA	NA	NA
	UTILITY OF STD WBS	12	YES	12	100	NA	NA	NA	NA
			NO	0	0	NA	NA	NA	NA
25	WOULD USE MODEL	15	YES	15	100	NA	NA	NA	NA
			NO	0	0	NA	NA	NA	NA
	LEVEL OF FAITH	15	HIGH	0	0	NA	NA	NA	NA
			MEDIUM	6	40	NA	NA	NA	NA
			LOW	4	27	NA	NA	NA	NA
			NONE	1	7	NA	NA	NA	NA
			UNKNOWN	4	27	NA	NA	NA	NA
	USE IN CONJUNCT	15	YES	15	100	NA	NA	NA	NA
			NO	0	0	NA	NA	NA	NA
	WHAT WAYS	10	See Text	NA	NA	NA	NA	NA	NA
26	METHODS OF OTHER CO.	14	YES	5	36	NA	NA	NA	NA
			NO	9	64	NA	NA	NA	NA
	COMPARE	5	See Text	NA	NA	NA	NA	NA	NA
27	INSIGHTS/ COMMENTS	8	See Text	NA	NA	NA	NA	NA	NA

Table 7. Parameter Matrix Response Summary

TASKS PARAMETERS	SP EL N	CE SS TT	MC OT NL	MA SN NL	FS ED AY	RA SN KL	OC &P MT	FA NN CL	SE PN CG	CD PS TN	TS RD DY	LA CN CL	RA QN TL	PD RS LN	M T P	PM RD FL	PT RY OP	EO VP LT	DD ES TN	SR WQ A	IR /Q FA	MR MQ IA	DR BQ A	HR WQ A	MH OW N	MS OW N	RM QG TT	PR RP BT	CC HT GL	TP SL TN	TP SR TO	PV RA OL	HI /N ST	CT SS IT	RT ES GT	SI YN ST	S A T	AD FE TL	TOT
RSP	5	5	5	5	5	5	5	5	4	5	4	3	4	4	3	3	3	3	3	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	
$ VALUE	1					1				1				1	2	1	1	1					1	1	2	2											1		16
# RQMTS	3	2		2		2		4	1	4	2		3	4	2	2		3	1	1				1	1	2	1	1	1	1	1	1	1	1	1	1	2	1	53
# FUNC	2	2	3	4	1	1		4	1	5	2		3	3		1	3	3		2		1	1	1	1	2	2	1	2	2	2	1	1	1	2	2	2	1	65
# SUBSYS	1	3	3	3	1	1	4	3	1	4	2		2	3	1	2	1	2	2	1			1	2	1	2	2	1	2	2	2	1	1	1	2	2	2		64
# HWCIs	1	4	2	2	1	2	3	1		2	2	2	2	2	1		2	2	1	1			1	1	1	1	2	2	2	1	1	2	1			1	1		50
# CSCIs	1	4	2	2		3	1	1		2	2	2	2	2	1		1	2	2	1			1		1	2	2	2	2	1	1	2	2	1	2	2	1		53
# SLOC	1	4	1	1		3	1	1		1	1	2	1	1	1		1	2	2	1			1		1	1	1	2	1	1	1	1	1	1	1	1	1		40
# INTERFACES	1	3	2	2	1	2	3	4	1	1	2		2	2	1	1	1	2	2	2	1		2	2	2	2	2	2	2	2	2	2	2	1	2	2	2		65
# ALGORITHMS	1	3	1	2	1	2		3	1	1	1		1	2	1	2	2	2	2	1	1	1		1	1	2	2	2	2	1	1	2	2	1	2	2	2		54
REAL TIME/NRT	1	1	1	2				2	1	2	1		1	2	1	2	1	1	1		1			1	1	1	2		1			1	1	1	2	1	2		35
# TPMs	1	2	1			1					1																1	1	1										9
# DIFF PROC			1	1	1	2	3	4	1	2	1		1	1	1	1	1	2	1	2		1	1	1	2	2	1		1	1	1	1	2	1	1	2	2		46
# DISP SCRN			2	1	1	1	2	4	1	2	1		1	2	1	1		2	1		1			1	2	2	1	1	1	1	1		2	1	2	2	2	1	44
PERF CHALL				1	1	3		2	1	4	2			1	1	2	1	1	1			1			1	1				2	2	1	1	1	1		2	1	35
TYPE/MISS	3		2	1	1	2	2	3	2	4	2				2	1		2		1		1				1				1	1	1					2	1	36
NEW/OLD CUST	2		1			1								1	1			1		1	1		1					1	2	1	1					1	2	1	19
DEG OF COOP	2		1	1		1								1	1			1		1	1		1		1	1	1	1	2							1	2	1	21
SPEC QUAL	4	1	1	2	1	2		3	2	1				3	1	1	1	1	2	1	1	1	1		1	2		1	2	1				1		1	2	1	42
MIL STDS	1	3		2			1	1	2	1				1	1			1	1		1		1	1	1	1	1	1	2	1	1			1	1	1			29
LEV OF DOCUM	1	3	1	1		1	2	1	3	1			1	1	1			1	1	1	1	1			1	2		1	2					1	1	1	1	1	33
SUPPORTABILITY				1			4		2		1	2		1		1		1						1										1	1	1	1	1	19
RUGGEDIZATION						1	4		2		1	1		1	1		1	1						2					1			1				1	1	1	20
OPNL ENVIR				1		1	4	1	2		1	3		1	3			1						2					1							1	2	1	25
SIM W/PREV JOB	4	4	2	2	1	2		2	2	2	1		2	1	1	1		1	1	1		1	1	1	2	2	1	1	1	1	1	1	2	2	2	2	2		53
EXP W/MSN AREA	2	4	1	2	1	1	1	2	1	2	1			1	1			2	1	1		1	1		2	1				1	1		1	1	2	2	2		39
AMT OF IR&D		2			1	1		1						1		1		1																					8
PREV PROTO		4			1	2		1		1				1	1	1		1					1		1	1							1	1	1	1	1		21
SE DURING PROP	2	4		1	1			1		1				1		1		1							1	1								1	1		1		18
EXER OF TEAM	2	4	1	2	1	2	1	3	1	2	1	1	2	1	1	1	1	1	1	1	1	1	1	1	2	2	1		1	1	1	1	2	2	2	2	2		53
PERF OF TEAM	1	3	1	1	1	1	1	3		1			1	1	1	1	1	1	1	1	1				1	1				1	1	1	2	2	2	2	2		37
LEV OF AUTO		2	1	1			1						1			1	1	1	1						1	1				1			1	1	1	1	2		19
DEP NEW TECH	1	3	1		2	4	3	2	1	1	3	1		1	2	1	1	1		1		1	1	1	1					1						1	2		37
NEW/UPGRADE	1	3	1	1		4	2	1		1	2	1		1	2		1	1		1		1	1	1											1	1	2		30
FFP/CPFF	1	3	2	1		4	1			1	1			1				1																					16
DTC	1	2	2	1		3	1	1		1	2	1		1				2						1														1	20
SCHED CONSTR	1	3	2	1		4		1			1			1	1			1																				1	17
TOTAL	43	76	39	45	19	61	45	60	29	51	37	16	26	48	35	26	22	50	25	23	11	12	19	23	32	38	23	21	32	25	22	20	26	25	33	38	51	14	
AVG	9	15	8	9	4	12	9	12	7	10	9	5	7	12	12	9	7	17	8	12	11	12	10	12	16	19	12	11	16	13	11	10	13	13	17	19	26	14	

Appendix D

Historical Cost Data Examples

Table 8. Example Program Work Breakdown Structure

```
                                                                                                DATE 120991        PAGE    1
.DATE 09 DEC 91  12:42:07  RID     148   09 DEC 91  JL7411
.@                    AO DIRECTORY                                       H005116
*         .RESP.PRIME A O.DUMMY/2ND. CHRG.3RD.4TH.5TH. .                                      .TSK. OPEN .CLOSE .
* ITEM NO .DEPT.-SUB ACCT.-SUB ACCT. NO  .SUB.SUB.SUB.F.TITLE OF TASK                         .STA. DATE . DATE .REMARKS
*---------.----.---------.---------.-----.---.---.---.-.--------------------------------------.---.------.------.-----------------
  47.0     7414 81095-000                             F                                        PRO 880302        REVISION 16
  47.01    7414           81095-010                   F                                        PRO 880302
  47.011   7414                     81095 100           PROGRAM MANAGEMENT                     CSC
  47.0111  7414                     81095     110     F PROGRAM DIRECTION                      OLM 880302
  47.0112  7414                     81095     120     F PROGRESS REVIEWS/CONFERENCES           CLS 880429 890718
  47.0113  7414                     81095     130     F COST ACCOUNTING                        OLM 880302
  47.0114  7414                     81095     140     F ENGINEERING CHANGE PROPOSALS (ECPS)    CLS 881027 890915
  47.0116  7414                     81095     150     F ENGINEERING SERVICES                   MTL 881027
  47.0117  7414                     81095     151     F ENGINEERING MANAGEMENT                 CLS 890905 910308
  47.0118  7414                     81095     152     F DATA MANAGEMENT                        CLS 890905 900131
  47.012   7414                     81095 200           SYSTEMS ENGINEERING & TESTING          CSC
  47.0121  7414                     81095     210       SYSTEMS & TEST ENGRG (IGRV)            CSC
  47.01211 7414                     81095         201 F SYSTEM DESIGN & REQUIREMENTS           CLS 880302 880725
  47.01212 7414                     81095         202 F SOFTWARE REQUIREMENTS ANALYSIS         CLS 880329 890510
  47.01213 7414                     81095         203 F TEST PLAN                              CLS 880329 890718
  47.01214 7414                     81095         204 F TRAINING DEVICE TASA                   CLS 880302 890510
  47.01215 7414                     81095         205 F SOFTWARE DESIGN REVIEWS                CLS 880613 890523
  47.01216 7414                     81095         206 F TEST DESCRIPTIONS & PROCEDURES         CLS 880531 890913
  47.01217 7414                     81095         207 F PERFORMANCE TESTING                    CLS 890913 900131
  47.01218 7414                     81095         208 F IN-PLANT ACCEPTANCE TEST               CLS 900131 900320
  47.0122  7414                     81095     220       SYSTEMS & TEST ENGINEERING (CS)        CSC
  47.01221 7414                     81095         221 F SYSTEM DESIGN & REQUIREMENTS (CS)      CLS 890905 900312
  47.01222 7414                     81095         222 F GR/CS SIMULATION                       CLS 900312 900810
  47.01223 7414                     81095         223 F GR/CS TEST PROCEDURES                  CLS 900607 910308
  47.01224 7414                     81095         224 F GR/CS PERFORMANCE TESTING              CLS 900815 910308
  47.01225 7414                     81095         225 F AQL/CHAALS SIMULATION                  CLS 900312 900810
  47.01226 7414                     81095         226 F AQL/CHAALS TEST PROCEDURES             CLS 900607 910308
  47.01227 7414                     81095         227 F AQL/CHAALS PERFORMANCE TESTING         CLS 900810 910308
  47.01228 7414                     81095         228 F STE SIMULATION                         CLS 900312 900810
  47.01229 7414                     81095         229 F STE TEST PROCEDURES                    CLS 900607 910308
  47.01231 7414                     81095         230 F STE PERFORMANCE TESTING                CLS 900810 910308
  47.0124  7414                     81095     240     F IN-PLANT ACCEPTANCE TEST               CLS 900924 910308
  47.0125  7414                     81095     250     F ON-SITE ACCEPTANCE TEST                CLS 901011 910308
  47.013   7414                     81095 260           SYSTEM EFFECTIVENESS ENGINEERING       CSC
  47.0132  7414                     81095     740     F HFE PROGRAM                            CLS 880531 910308
  47.0133  7414                     81095     750     F SAFETY PROGRAM                         CLS
  47.0134  7414                     81095     751     F TASK 100 - SYS SAFETY PROGRAM          CLS 880713 910308
  47.0135  7414                     81095     752     F TASK 103 - SYS SAFETY REV              CLS
  47.014   7414                     81095 280           CONFIGURATION MANAGEMENT               CSC
  47.0141  7414                     81095     771     F HCM PROGRAM                            OLM 880329
  47.0142  7414                     81095     283     F FCA                                    CLS        910308
  47.0143  7414                     81095     284     F PCA                                    CLS 901011 910308
  47.015   7414                     81095 290           GR/CS TASA                             CSC
  47.0151  7414                     81095     291     F TOP DOWSN ANALYSIS (TDA)               CLS 890905 901011
  47.0152  7414                     81095     292       TASA DATA                              CSC
  47.01521 7414                     81095         293 F TASK LISTINGS REPORT (CS)              CLS 891006 900131
  47.01522 7414                     81095         294 F JOB ANALYSIS TASK LIST (CS)            CLS 891116 900312
  47.01523 7414                     81095         295 F TASA REPORT (CS)                       CLS 891220 901011
  47.01524 7414                     81095         296 F TASA MANAGEMENT PLAN (CS)              CLS 890905 891108
  47.016   7414                     81095 300           HARDWARE ENGINEERING                   CSC
  47.0161  7414                     81095     320       HARDWARE ENGINEERING (IGRV)            CSC
  47.01611 7414                     81095         301 F HARDWARE SYSTEM DESIGN (IGRV)          CLS        910308
```

Table 9. Example Program WBS Dictionary

WBS Element Number: 201
Name: System Design & Requirements (IGRV)
Element Task Description: This element provides for the effort associated with the detailed technical program to design and fabricate the GRMT to meet the performance requirements of the specifications. Additionally, travel is included to meet and discuss requirements and design with users and visit ESL and Ft. Devens to observe operational equipment. Data is created for CDRL 3013. Engineering labor and travel.

WBS Element Number: 202
Name: Software Requirements Analysis (IGRV)
Element Task Description: This element provides for the effort associated with the effort to prepare data for SRS and IRS documents. Includes research of all requirements and defining of functions. Insures all I/O are included and fully defined. Data feeds CRDLs 3074 and 3075. Engineering labor.

WBS Element Number: 203
Name: Test Plan (IGRV)
Element Task Description: This element provides for the effort associated with developing and outlining a methodology for all test plans. Feeds data to CDRL 3056. Engineering labor.

WBS Element Number: 204
Name: Tasks and Skills Analysis (TASA) (IGRV)
Element Task Description: This element provides for the effort associated with the tasking, scheduling, conduct and documentation of a TASA for MOS 33R10 to identify critical tasks and functions for training on GRMT. This will include planning and scheduling, establishing the job task list, and performance of actual analysis. Also includes preparation time for monthly report. Engineering labor and travel expenses. Feeds CDRLs 3029, 3030, 3031 and 3050. Technical documentation is GFI. Does not include TASA for GR/CS.

WBS Element Number: 205
Name: Software Design Reviews (IGRV)
Element Task Description: This element provides for the effort associated with the monitor of the IPF software design reviews, AGE/ARF software design reviews, and STE software design reviews. Cost of CDR included. It is anticipated that these meetings will be on a monthly basis after the 7th month ARO. Engineering labor.

Table 10. Example Summary Cost Output

```
WEEK ENDING 01/19/92                 JV81 MONTHLY DETAIL MPG REPORT                                          PAGE   1047
                    DIVISION 7                                           CONTROL ACCOUNT 18        MPG 703
       MONTH END 01/92             REPORT SEQUENCE (CA,MPG,AO,TC,TASK,ACCT,JV)     RUN-DATE-TIME: 012192021305

  A.O.     O                                    A M O U N T                                         H O U R S
BASE TASK H MPG  TC  ACCT J.V.    INCREMENT        M T D       F Y T D  CUMULATIVE   INCREMENT        M T D     F Y T D  CUMULATIVE


81095-206 7 7030 16 10/89                                               164492.52   *                                  4161.8

81095-207 7 7030 16 08/90                                               181899.95   *                                  4999.6

81095-208 7 7030 16 08/90                                                 8144.00   *                                   221.5

81095-221 7 7030 16 08/90                                                44076.50   *                                   931.2

81095-222 7 7030 16 09/90                                                20407.96   *                                   533.9

81095-223 7 7030 16 12/90                                                28878.38   *                                   681.3

81095-224 7 7030 16 12/90                                                39260.42   *                                   916.2

81095-225 7 7030 16 09/90                                                   62.44   *                                     1.5

81095-226 7 7030 16 11/90                                                 1769.23   *                                    42.5

81095-227 7 7030 16 11/90                                                 5222.85   *                                   137.0

81095-228 7 7030 16 09/90                                                 7552.92   *                                   195.5

81095-229 7 7030 16 10/90                                                 9887.84   *                                   237.7

81095-230 7 7030 16 11/90                                                25970.26   *                                   626.5

81095-240 7 7030 16 12/90                                                 9677.08   *                                   233.5
81095-250 7 7030 16 18013                                                 6272.01   *                                   295.5
          7 7030 16 18014                                                   71.23   *                                     7.0
          7 7030 16 18301                                                   22.00   *
          7 7030 16 18344 1000                  120.75                              *
          7 7030 16 18344                       120.75      120.75         342.75   *
          7 7030 16 18346 1000                 1038.86                              *
          7 7030 16 18346                      1038.86     1038.86        1516.46   *
          7 7030 16 18947                                                 6234.85   *
          7 7030 16 18987                                                     .83   *

       250  TSK TOTAL                          1159.61     1159.61       14460.13                                      302.5

81095-284 7 7030 16 09/91                                                 4420.43   *                                    78.1
```

Table 11. Example Costs by Labor Level

```
.DATE 23 SEP 91  12:38:27  RID   1328D   23 SEP 91  SF7411
.0920323              COST STATUS REPORT             BY: K. JACKSON          D005106
*AO       .JV   .FYTD AMOUNT.FYTD AMOUNT.PRIOR FYTD .CUM COSTS  .PRIOR FYTD .ACTUAL  .CUM COSTS  .                                .
*NUMBER   .ACCNT.(DIRECT)   .(THRU G&A) .(DIRECT)   .(DIRECT)   .(THRU G&A) .HOURS   .(THRU G&A) .                                .
*=========.=====.===========.===========.===========.===========.===========.=========.===========.==============================.
 81095140  18014                                   0           0                  0.00
 81095140  18017                                   0           0                  0.00
 81095140  18051                                   0           0                  0.00
 81095140  18344                                   0           0                  0.00
 81095140  18346                                   0           0                  0.00
 81095150  18494                                2597        2597                  0.00
 81095151  18011     1204.69                   27087       28292                876.70
 81095151  18014        2.78                       2           5                  0.50
 81095151  18304       20.47                       0          20                  0.00
 81095151  18344       51.75                       0          52                  0.00
 81095151  18346      653.00                       0         653                  0.00
 81095152  18012                                6938        6938                261.70
 81095201  18012                               17412       17412                648.20
 81095201  18013                                7208        7208                385.30
 81095201  18344                                 390         390                  0.00
 81095201  18346                                4833        4833
 81095202  18012                               50273       50273               1860.20
 81095202  18013                               37177       37177               2120.50
 81095202  18344                                 476         476                  0.00
 81095202  18346                                3552        3552                  0.00
 81095202  18368                                  20          20                  0.00
 81095203  18012                                7604        7604                255.90
 81095203  18301                                   8           8                  0.00
 81095203  18493                                  95          95                  0.00
 81095204  18011                                 150         150                  4.50
 81095204  18012                               29943       29943               1144.50
 81095204  18013                                9449        9449                514.00
 81095204  18014                                 537         537                 65.40
 81095204  18344                                 642         642                  0.00
 81095204  18346                                5269        5269                  0.00
 81095205  18012                                1880        1880                 69.50
 81095205  18013                                 607         607                 30.80
 81095206  18011                                  17          17                  0.50
 81095206  18012                               20575       20575                778.30
 81095206  18013                               62239       62239               3351.00
 81095206  18014                                 332         332                 32.00
 81095206  18344                                  55          55                  0.00
 81095206  18346                                 645         645                  0.00
 81095207  18012                                5864        5864                219.70
 81095207  18013                               82630       82630               4399.10
 81095207  18014                                3951        3951                380.80
 81095208  18013                                4152        4152                221.50
 81095221  18012                                5899        5899                215.00
 81095221  18013                               12806       12806                671.50
 81095221  18014                                   5           5                  0.50
 81095221  18051                                 616         616                 40.30
 81095221  18052                                  32          32                  2.00
 81095221  18054                                  13          13                  1.90
 81095221  18096                                   9           9                  0.00
 81095221  18320                                 708         708                  0.00
 81095221  18322                                 560         560                  0.00
 81095221  18344                                 595         595                  0.00
```

Table 12. Subsystem Cost Matrix

PROGRAM C

ELEMENT	SYSTEM	S/S #1	S/S #2	S/S #3	S/S #4	S/S #5	S/S #6	S/S #7	TOTAL
SE MGMT									
TECH REVIEWS	1944								1944
ANALYSIS \									
DESIGN /	2749	848	915	1559	1775	949	1394	962	11151
SPECIFICATION									
SW DEFN	5703								5703
IF DEFN									
HW DEFN									
DB DEFN	280								280
ALL OTHER									
INTEGRATION		1049	2421	1025	1092	2375	291	557	8810
TEST	4939								
DOCUMENTATION									
SRS/IRS	2908								2908
TEST PLAN/PROC	8931	188		428	95	89	89		9820
ALL OTHER									
SW ENGR	36593	17086	10280	12469	5986	9796	9124	3157	104491
HW ENGR	20703	3582	6352	5793	4410	3786	1376	4850	50852
ILS									
PROG MGMT	11294								11294

Appendix E

Project Engineer Parameter Questionnaire

SYSTEM PARAMETERS QUESTIONNAIRE

To be administered orally to key project engineer.

1. Enter name of program: ________________________________

   Year contract awarded: ________

2. What type of program was it?

   ____ CPFF/CPAF

   ____ CPIF

   ____ FFP

   ____ Sole Source

   ____ Competitive Bid

3. Who was the customer?

   ____ US Navy

   ____ US Army

   ____ US Air Force

   ____ US Marine Corps

   ____ US Coast Guard

   ____ NSA/CIA/FBI/DIA

   ____ Other US Govt Agency

   ____ NATO country

   ____ Other foreign country

   ____ Civilian customer

4. Had we dealt with this customer/program office previously?

   ____ yes ____ no

5. How would you characterize the relationship with this customer on this program?

   ____ Excellent (mutual trust/respect, good communications)

   ____ Good

   ____ Fair

   ____ Poor (mistrust, adversarial, poor communications)

6. How would you rate the quality of the SOW/specification received in the contract package?

_____ Excellent (clear, complete)

_____ Good

_____ Fair

_____ Poor (incomplete, ambiguous)

7. What type of system is it?

_____ Command & Control

_____ Navigation

_____ Sensor/Sensor Control/Signal Processing

_____ Communications

_____ General Data Processing

_____ Decision Aiding/Mission Planning

_____ Machinery/Ship Control

_____ Trainer

_____ Weapons/Weapons Control

_____ Special Purpose

_____ Other (specify: ______________________________)

8. What is the operational environment in which the system will be deployed?

_____ Surface ship

_____ Subsurface

_____ Airborne

_____ Ground Vehicular

_____ Shore/Ground Fixed Station

_____ Space

9. What degree of ruggedization was required?

_____ Full-MIL

_____ Rugged

_____ Nuclear hardened/survivable

_____ Commercial grade

10. Were there any special requirements as listed below?

_____ EMP

_____ TEMPEST

_____ EMI/EMC

_____ Other (specify _______________)

11. Were there any special reliability/maintainability requirements?

_____ yes _____ no

12. What is the mission area of the system? (check all that apply)

_____ Tactical

_____ Combat Arms

_____ Combat Svc Spt/ Logistics

_____ Intelligence

_____ Special Operations

_____ Mine Warfare

_____ Strategic

_____ Combat Support

_____ Navigation/Collision Avoidance

_____ Administrative

_____ Law Enforcement

_____ Electronic Warfare

_____ Other (_______________)

13. How many Mil Standards and Specifications were imposed?

_____

14. Check any of the following process standards that were prescribed.

_____ DOD-STD-2167/2167A

_____ MIL-STD-1679

_____ MIL-STD-499

_____ MIL-STD-2168

_____ MIL-STD-1521

_____ MIL-STD-480/481

15. How many CDRLs were required for delivery? _____

16. How much experience did the company/division have with similar programs in the past?

_____ Alot

_____ Some

_____ None

17. How much experience did the company/division have with the mission area/operational domain?

_____ Alot

_____ Some

_____ None

18. Had any previous IR&D/applied research been performed related to the program prior to award?

_____ yes _____ no

19. Was the program for:

_____ Analysis/Design _____ Production

_____ Development

20. Had a prototype system been previously developed (either internally or under a separate contract)?

_____ yes _____ no

21. What percentage of the up-front systems engineering (i.e, from requirements analysis through HW/SW specification) was performed prior to award?

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

22. Was this program for:

_____ a new system _____ upgrade to existing system

23. Was design-to-cost a consideration on this program?

_____ yes _____ no

24. At the time that the contract was bid/awarded, was it dependent on new technology?

____ yes ____ no

25. On a scale of 1 to 10, how would you have rated the technology level of this program/development at the time of bid/award?

Lo tech 1 2 3 4 5 6 7 8 9 10 Hi tech

26. What type of schedule constraints was the program under (relative to the complexity of the development)?

____ reasonable

____ moderately aggressive

____ very challenging

____ nearly impossible

27. How long was the development (from award to delivery of the 1st system)? _____ months/years

28. What was the dollar value of the contract? $____ K M B

29. How much was bid for the total systems engineering effort? $____ K M

30. Was this system development

____ more hardware intensive

____ more software intensive

____ balanced

31. How would you rate the complexity of this system with respect to other systems the company/division has developed?

simple 1 2 3 4 5 6 7 8 9 10 complex

32. How many individual source requirements for the system were included in the contract? ______

33. How many critical TPMs were called out/identified? ____

34. What was the size of the system?

_____ small _____ medium _____ large

35. Check the description which best applies:

_____ single equipment

_____ single subsystem, multiple equipments

_____ multiple subsystems, each with multiple equipments

36. How many subsystems did the system consist of? ______

37. How many racks of equipment (total)? ______

38. How many unique HWCIs composed the system? ______

39. How many unique computers/processors were used? ______

40. How many major functional areas comprised the system?_____

How many total lowest level functions? _____

41. How many unique CSCIs composed the system (exclusive of OTS software)? ______

42. How many SLOCs were written? ______ K

Language:

______ ADA ______ FORTRAN ______ 'C' ______ PASCAL

______ ASSY ______ COBOL ______ CMS-2 ______ BASIC

43. How many external interfaces? ______

44. How many internal interfaces? ______

45. How many algorithms were developed for this program? _____

46. Was the system:

_____ real-time/near real-time

_____ non-real time

_____ batch (or equivalent)

47. What degree of man-machine interaction existed?

____ little/none (stand-alone/unattended operation)

____ some interaction

____ manned full time/highly interactive

48. How many display screens/windows were designed? _____

How many unique menus were designed? _____

49. Describe any unique performance challenges of this program.

50. What was the average experience level of the engineers assigned (applicable experience only)?

____ 1-3 years

____ 4-6 years

____ 7-10 years

____ 11-15 years

____ over 15 years

51. What was the average performance rating of the engineers assigned?

low 1 2 3 4 5 high

52. How much overtime was typically put in per week by the engineers?

Hours 0 5 10 15 20 25 30 35 40

53. Would you say this program was:

____ understaffed ____ overstaffed ____ appropriately staffed

54. What degree of automation was available to support systems engineering activities?

_____ Little/none

_____ PCs with standard software available to each engineer

_____ Some special tools available

_____ Several special tools available

_____ Many special tools available

_____ Tools available, but counterproductive

55. How would you rate the planning and overall systems engineering process used on this program?

POOR 1 2 3 4 5 6 7 8 9 10 EXCELLENT
(undisciplined) (structured)
(ad hoc) (well planned)

Appendix F

Acronym List

Appendix F

AACE	American Association of Cost Engineers
ADP	Automatic Data Processing
AI	Artificial Intelligence
ANAL	Analysis
AO	Accounting Order
BSPEC	Type B (Development) Specification
BYL	Before You Leap
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CASA	Cost Analysis Strategy Assessment
CCC	Certified Cost Consultant
CCDR	Contractor Cost Data Reporting
CCE	Certified Cost Engineer
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CELSA	Cost Estimating Methodology for Logistics Support Analysis
CER	Cost Estimating Relationship
CI	Configuration Item
CIA	Central Intelligence Agency
CIV	Civilian

CMD	Command
CMPTR	Computer
CMTS	Comments
COCOMO	Constructive Cost Model
CPAF	Cost Plus Award Fee
CPFF	Cost Plus Fixed Fee
CPIF	Cost Plus Incentive Fee
CSCI	Computer Software Configuration Item
C/SCS	Cost/Schedule Control System
CSOM	Computer System Operators Manual
CTL	Control
CTRL	Control

DB	Database
DBMS	Database Management System
DEV, DEVMT	Development
DIA	Defense Intelligence Agency
DOD	Department of Defense
DTC	Design to Cost
DT&E	Developmental Test and Evaluation

EAC	Estimate at Completion
ECN	Engineering Change Notice
ECP	Engineering Change Proposal
EDCAS	Equipment Designers Cost Analysis System

EDSS	Estimation Decision Support System
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
ENGR	Engineer, Engineering
ES	Expert System
ETC	Estimate to Complete
EXPER	Experience
FAT	Factory Acceptance Test
FBI	Federal Bureau of Investigation
FCA	Functional Configuration Audit
FQR	Final Qualification Review
HSR	Hardware Specification Review
HW	Hardware
HWCI	Hardware Configuration Item
IEEE	Institute of Electrical and Electronic Engineers
IF, I/F	Interface(s)
ILS	Integrated Logistic Support
INTEG	Integration
IR&D	Internal Research and Development
IRS	Interface Requirements Specification

KBS	Knowledge Based System
LAN	Local Area Network
LCC	Life Cycle Cost
LCCC	Life Cycle Cost Calculator
LOC	Lines of Code
LOE	Level of Effort
LSA	Logistics Support Analysis
MGMT	Management
MGT	Management
MH	Manhours
MIL	Military
MMI	Man-Machine Interface
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
MTTR	Mean Time to Repair
MTP	Master Test Plan
NA, N/A	Not Applicable
NATO	North Atlantic Treaty Organization
NRT	Near Real Time
NSA	National Security Agency
OCD	Operational Concept Document

OPN	Operation
ORLA	Optimum Repair Level Analysis
OSAMM	Optimum Supply and Maintenance Module
OT&E	Operational Test and Evaluation
PC	Personal Computer
PCA	Physical Configuration Audit
PDR	Preliminary Design Review
PERF	Performance
PRR	Production Readiness Review
PUBS	Publications
QA	Quality Assurance
QE	Quotation Estimate
R&M	Reliability and Maintainability
RPT	Report, Reporting
RQMT	Requirement
RTM	Requirements Traceability Matrix
SCHED	Schedule
SCN	Specification Change Notice
SE	Systems Engineer(ing)
SECDEF	Secretary of Defense
SEMP	Systems Engineering Management Plan

SDR	System Design Review
SLOC	Software Lines of Code
SOW	Statement of Work
SPEC	Specification
SPT	Support
SRR	System Requirements Review
SRS	Software Requirements Specification
SSDD	System/Segment Design Document
SSR	Software Specification Review
SSS	System/Segment Specification
STD	Software Test Description; Standard
STD DEV	Standard Deviation
STP	Software Test Plan
SUM	Software Users Manual
SW	Software
SYS	System
TECH	Technical; Technician
T&E	Test and Evaluation
TPM	Technical Performance Measure
TR	Test Report
TRK	Track, Tracking
TRR	Test Readiness Review
WBS	Work Breakdown Structure