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ISSUES INVOLVING UNCERTAINTIES IN DEFENSE ACQUISITION
AND A METHOD FOR DEALING WITH THEM

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ABSTRACT

This paper analyzes two work processes involved in defense acquisition which are replete with uncertainties. These are the proposal phase and the architectural design phase. Both phases involve a vendor designing alternative system in response to a set of stated (and perceived) requirements, followed by the government agency's final selection of a preferred system design (and a preferred contractor). Since these efforts many times occur during the preliminary phases of the acquisition process, many uncertainties are present, including: technological uncertainties, uncertainties in the timely availability of inputs, workload uncertainties, and equipment reliability and maintainability, all of which lead to performance, schedule, and cost uncertainties.

Several issues involving these uncertainties are identified:

- 1) Do government agencies provide vendors with sufficient information to enable them to design their most cost-effective systems with respect to these uncertainties?
- 2) What additional information should be provided which will enable vendors to do so?
- 3) What credible evidence should vendors provide in their proposals and system designs which can increase the government's confidence that the system being proposed will in fact be delivered within the schedule and cost estimated?

Finally, a systems evaluation methodology is described and illustrated, providing a recommended way of dealing with these issues.

OVERVIEW

Defense systems are composed of elements which inherently involve various uncertainties, including technological uncertainties, transportation uncertainties, equipment un-

reliability. In general, we know how to deal with these factors. This paper focuses on certain deficiencies in the systems acquisition process itself, which prevent the government from obtaining the most cost-effective system meeting the needs and constraints. The paper also presents a method of overcoming these deficiencies.

The specific parts of the system acquisition process to be focused upon are:

- o The proposal phase from RFP to Source Selection
- o The architectural design phase in which a preferred preliminary design best meeting the government agency's needs and constraints is provided.

The specific improvement I have in mind is an increased involvement of the Government agency in the two processes being treated.

This paper analyzes the work process involved in systems design in which a set of user requirements and environmental constraints are converted into alternative system designs and a preferred design selected. It identifies some basic problems encountered when a systems design organization is used to initiate this process of designing a new system for a client organization. These problems fall into two major classes: 1) how to properly state the requirements and constraints which the system must meet, and 2) how to properly evaluate the systems proposed by the system designers. A major thesis of this paper is that the systems planning process is a cooperative effort between the client and the designer. If the latter is to properly design a system he must not only thoroughly understand the requirements, but also develop an evaluation procedure which is acceptable to the client and meets his needs.

An analysis of various evaluation methods used is also provided. The factors often used for evaluation include: 1) System Performance or other Technical Factors, 2) Date of Availability of the System, 3) System

Cost, 4) Risks (in performance, schedule and cost which arise when all system components are not available "off the shelf," but some have to be developed), and 5) other miscellaneous factors. Generally the values of each key factor for various alternatives are assembled in matrix form for validation and comparison purposes. Unfortunately, it is rare that one alternative is superior to all others for all descriptors (often the alternative offering superior performance is more costly or has higher risk). Thus some means of relating all of the evaluation factors must be used. This is frequently done by applying weighting factors (generally selected heuristically), which causes the final "score" to be highly dependent on the values of the weights. Furthermore clients often have difficulty in defending this approach to others requiring such justification.

This paper examines in detail the basic process of specifying requirements, creating design alternatives, and evaluating them against a set of criteria. It describes a number of key pitfalls faced by the systems designers as well as the evaluators which normally occur and which should be avoided during a systems planning effort. An improved evaluation process avoiding these pitfalls is presented for use by the evaluation team, allowing them to select the preferred alternative in a more rational, defensible fashion. Finally, a method of presenting evidence which supports and enhances the preferred design alternative is described.

While the main focus of the paper is on the architectural design process in which there can be close cooperation between the system designers and the client, many of the techniques described also apply to the systems design effort which occurs during a proposal generation effort when such cooperation does not exist. Thus the paper is extended to show how to deal with these problems during a proposal effort.

This paper builds on work in source selection of EDP systems previously performed by the author for the Assistant Secretary of the Air Force (Financial Management). The evaluation process presented now includes the element of developmental uncertainties which was not required in the original work. While the paper has greatest value for contractors and Government agencies involved in the design of large, complex systems requiring development, it is also applicable to smaller projects in the private sector as well.

PART I. PROBLEM DEFINITION

PART I reviews the architectural systems design process, indicating the various work functions involved, and the information required by a systems designer if he is to pro-

vide a preferred system design to a client. Some of the difficulties in obtaining this information are described.

1. INTRODUCTION

A major objective of this paper is to identify a number of pitfalls which can prevent a systems designer from proposing and designing the most cost-effective system for a client, taking into account risks and uncertainties, and to indicate ways of avoiding such pitfalls.

At the heart of these problems is that the entire work process is generally divided among those major contributors, each of whom contributes his own expertise to the process:

- o The system user, who will operate and support the system once it is completed, provides a statement of his needs (and desires), as well as the environmental constraints which are present.
- o The system designer (generally a contractor experienced in this area) who translates the user needs into a set of feasible design alternatives making whatever trade-offs are necessary, and recommends the preferred system.
- o The procurement organization which serves as the point of contact with the system designer, generally is heavily involved in the evaluation of the design alternatives in terms of the trade-offs of performance, cost, availability date and risk, and makes the ultimate decision regarding the preferred system selected.

For purposes of this paper we shall define these participants in the following way:

- o The term "Client" will represent the procurement organization who is funding the architectural study. The client will be responsible for obtaining the specifications from the users. Since the client knows the budgetary constraints, he plays a large role in the ultimate systems evaluation function leading to the selection of the preferred system.
- o The term "Designer" represents the systems analysis and design organization who has been contracted to perform the design study.

Although a systems designer works with the client under varying circumstances, this paper concentrates on two disparate situations which bound most of the set. The first example is an architectural design effort in

which the designer maintains a close interface with the client. In the second example, the systems designer is a vendor proposing a system design to a client. In this situation there is generally minimal contact with the client during preparation of the design proposal.¹

2. WORK PROCESS INVOLVED

Both situations involve a common work process which typically includes these functions (Figure 1):

- o Client sets system specifications, including desired performance, system availability date, and constraints.
- o Designer proposes one or more design alternatives potentially meeting the system specifications.
- o Designer develops an evaluation model based on his understanding of the job to be done and his perception of the evaluation model to be used by the client.
- o Designer uses the evaluation model to evaluate alternative system design configurations and selects the preferred system design.
- o Designer submits his proposed system design to the client for his evaluation.
- o Client validates that all specifications have been met, and in a design competition, evaluates all proposals submitted by vendors, and selects the preferred proposal.
- o Client makes final selection of the preferred system.

¹This situation is quite common in the development of systems for the government, particularly the Department of Defense.

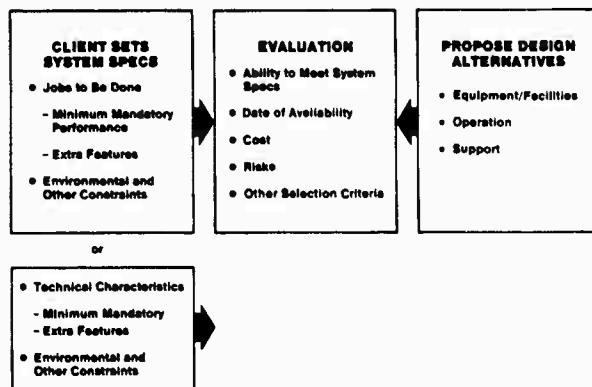


Figure 1. Systems Planning Work Process

Having presented an overview of this process, we shall now examine each of the steps in greater detail, focusing on some of the pitfalls which may arise.

3. POTENTIAL PITFALLS IN THE WORK PROCESS

It should be obvious that the two major drivers of the design effort are the designer's understanding and perception of: 1) the client's specifications, and 2) the client's evaluation model. Unless the designer understands what the client has specified, the final system design may be configured to produce the wrong system. Specifically, unless the designer knows and understands the evaluation model to be used by the client, the designer will not be able to properly make his performance, cost, availability, and risk trade-offs to produce the "optimal" system desired. During an architectural design effort, there are usually opportunities to meet with the client to obtain a good mutual understanding of what the client really desires (the "real" system specifications), as well as the proper evaluation model which should be used. Unfortunately, this type of information is generally not available from the client during a proposal effort. Thus in the next four sections we shall describe a process for providing designers with a better understanding of system requirements and the system evaluation process, using the case of an architectural study as an example. We shall then consider the analogous planning problem which should occur during a proposal effort.

4. UNDERSTANDING THE SYSTEM SPECIFICATIONS

The first part of a client's specifications typically describes characteristics needed by the designer to synthesize the system. Sometimes these descriptors indicate the concept of operation, the missions, functions and jobs to be done, and the performance characteristics (e.g., speed of response, reliability and maintainability) required. Sometimes these descriptors consist of a set of technical or design characteristics (e.g., core size and number and type of displays for a data processing system).

The second part of the specifications may consist of a set of environmental or operational constraints that must be observed. This set could include operational temperature, humidity, shock and vibration, as well as specifications which must be met so that this system can interface with other systems. In addition, the set of requirements should include the date when the system must be operational.

These specifications are generally stated in two ways. The first is a set of minimum mandatory requirements that must be met or else the design will be considered non-responsive to the specifications. Sometimes

the client indicates a desire for additional capabilities if they are available. These "desirable features" are not made part of the mandatory requirements since the designer may not be capable of providing these.

Early in the planning effort, the designer should review the system specifications. Any questions about these should be resolved during a conference with the client early in the design study effort.

5. UNDERSTANDING THIS EVALUATION MODEL

Having established a mutual understanding of the initial system "requirements" as the baseline for the architectural design study, the next step is to obtain a mutual agreement with the client of the evaluation model to be used. Here we are concerned with three major points:

- o The evaluation model or method should be explicit so that the designer can perform various cost-performance trade-offs to arrive at a preferred solution.
- o The evaluation model should be rational, credible and defensible.
- o The evaluation model should be agreed to by the client. If not, the final results obtained may not be acceptable.

With the preceding discussion in mind, let us now examine various evaluation methods which are used by various government agencies, and describe how designers may respond to each.¹ This will be helpful in determining whether such responses are desirable, or if the evaluation method should be modified accordingly to produce the results desired.

5.1 The "Extra Performance Is Overkill" Evaluation Method

The first evaluation method examined, illustrated in Figure 2, operates as follows:

- o All evaluation factors and their minimum mandatory requirements as contained in the Statement of Work (SOW) are listed in column form.
- o The actual values provided by each alternative system being evaluated are then listed and validated by the evaluator that these values each meet its requirement.
- o Any system characteristic which is over the minimum level specified can

¹While this discussion specifically applies to government contracts, it also applies to many non-government contracts as well.

be considered "overkill", and has no additional value as compared to the minimum level.

- o The selection criterion used is as follows: choose that system whose characteristics individually meet or exceed all constraints and minimum specifications, and whose Present Value Life Cycle Cost (PVLCC) is least among all alternatives under consideration.

The main advantage of this approach is that it explicitly states the "rules of the game". Ideally each system would be designed to exactly equal the design specifications since any larger values would generally result in higher cost. In this case the evaluator might select as the preferred system alternative the one which has the least PVLCC.

Unfortunately system components come in discrete units rather than from a continuous array, and the specifications of similar units generally differ from vendor to vendor. Thus to be entirely responsive to the specifications which have been issued, the only feasible design solution may be to use components which individually meet or surpass the minimum requirements which have been stated. In this case, excess performance may be provided, and the key deficiency of this approach is that extra performance is ignored. It should not be. There may be justification in giving some extra credit for

EVALUATION MATRIX

Descriptions/ Evaluation Factors	Minimum Values	System A	System B
Technical Factors -Required Throughput -Capacity -Response Time			
Performance and Other Factors -Capability Requirements -Reliability -Maintainability -Availability to User -Date of Availability (IOC) -Schedule Risk -Performance Risk -Upward Compatibility -Growth Potential -Flexibility			
Cost Factors			

Validate That Each Vendor Meets All Minimum Requirements
Excess Performance Is "Overkill"
Choose by PVLCC

Pitfalls:

- Excess Performance Has Worth
- Trade-Offs Among Factors Are Possible

Figure 2. Evaluation Method 1

extra performance to counter balance the additional cost which generally accompanies extra performance.

If extra credit cannot be given for excess performance, the designer might be permitted to compensate for a performance deficiency by providing excess value of some related characteristic. For example, the same probability of kill for a missile could be obtained by either having a highly accurate guidance system and a low yield warhead, or having a lower accuracy guidance system and a higher yield warhead. Thus it may be possible to achieve the same end result at lower cost to the client by using a component which may not quite meet an "arbitrary" minimum specification if another related, higher value component is used as compensation. The designer can best make such determinations since the designer usually knows the relationship between performance characteristics and cost, and hence can decide which set of his available characteristics can best perform a defined job (within constraints) at lowest total cost.

Thus the major improvements which can be made to the "Extra Performance is Overkill" method are to define the jobs to be done at the mission or functional level and allow inter-system trade-offs to be made within a constrained set of boundary conditions. Note that the system design task will also permit trade-offs between quality and quantity. Thus, in the case of a missile system, if the probability of kill of one missile is greater than another, it may be possible to configure both systems to achieve a given level of target destruction, in which a lower performance missile will require the use of more missiles to do the same job than a higher performance missile. The PVLCC calculations will determine the preferred system. To protect the client against unacceptable design features (such as the proposal of a very low performance missile in the previous example), the client can specify a minimum value that must be provided for any characteristic (such as the missile probability of kill must exceed 0.5).

5.2 The "Point Scoring" Evaluation Method

Another disadvantage of the previous evaluation method is as follows. The client may have in mind a minimum level of capability, but may desire additional capability if obtainable at a reasonable cost. Thus, some way must be found to give "additional credit" to those vendors which can provide these desirable features or superior characteristics beyond the minimum specifications. This can be accomplished by using the so-called "point scoring" method, illustrated in Figure 3. In this method the key evaluation factors are listed again as one dimension of the evaluation matrix, and their values for each alternative constitute the

other dimension. As in the previous evaluation method, the next step in this evaluation method is to validate that each of the mandatory requirements has been met. Then each of the key factors where a value other than a fixed mandatory value is desired is assigned two numbers which will translate its value into a point score. The first number (V in Figure 3) translates the extra amount of performance provided into a normalized value (say from 0 to 10 to normalize the worth of each factor). The second number (W in Figure 3) provides the Weighting Factor or relative worth of this factor compared to all of the other factors involved. For example, cost may constitute 60% of the total score possible. Choosing the latter as 1000 points, the value of W for cost may be chosen as 600 points. Thus the lowest cost design could be given a V = 1, and each design would receive a V equal to the ratio of the cost of the lowest cost design to the cost of the design under consideration. Thus if one cost were twice as much as another alternative, the lowest cost system would receive 600 points and the other system would receive 300 points. These numerical values chosen for V and W would be based either on available operational data or on the judgment of the technical evaluators.

Each system alternative would then be evaluated with respect to each factor in order to determine how many of the maximum points allocated would go to each of the proposed alternatives. A total score for each alternative is then obtained by summing each of its factor scores.

This method does have the advantage of providing credits for extra performance.

EVALUATION METHOD 2

POINT SCORING METHOD

Descriptions/ Evaluation Factors	Weight	System A	System B
Technical Factors			
- Required Throughput	W_1	$W_1 V_{1A} \cdot 10^{P_{1A}}$	$W_1 V_{1B} \cdot 10^{P_{1B}}$
- Capacity	W_2	$W_2 V_{2A} \cdot 10^{P_{2A}}$	$W_2 V_{2B} \cdot 10^{P_{2B}}$
- Response Time	-	-	-
Performance and Other Factors			
- Capability Requirements	-	-	-
- Reliability	-	-	-
- Maintainability	-	-	-
- Availability	-	-	-
- Date of Availability (IOC)	-	-	-
- Schedule Risk	-	-	-
- Performance Risk	-	-	-
- Upward Compatibility	-	-	-
- Growth Potential	-	-	-
- Flexibility	W_R	$W_R V_{RA} \cdot 10^{P_{RA}}$	$W_R V_{RB} \cdot 10^{P_{RB}}$
Cost Factors			
		Score A	Score B

Give Credits for Excess Values

Choose by "Highest Score"

Pitfalls:

- Can Not Agree on Weights and Value Coefficients
- Adding Points Is Artificial

Figure 3. Evaluation Method 2

However, it also has several difficulties. First, while the key factors contributing to the worth of a system may be identified, the use of value and weighting factors (V and W) as the method of combining factors is always subject to challenge by other evaluators or decisionmakers. Thus, what is needed is a more defensible way of combining the factors listed.

The second difficulty inherent in the point-scoring method is even more serious. This method combines cost values with the technical or performance values through the vehicle of points. Yet while selecting the preferred system based on highest score is intuitively sound, there is no scientific justification for the use of such a "figure of merit" approach. There are two more widely accepted methods of selecting a preferred alternative. The first is to select that system alternative which will perform the operational functions and meet all constraints at the lowest total cost to a defined organization (i.e., pivoting on equal effectiveness). The second approach is to select that alternative which will yield the highest performance of the operational functions at a fixed total cost (i.e., pivoting on equal cost). Such a method must also take into account the risks and uncertainties involved.

Lastly, experience has shown that when a large list of factors are included in the evaluation, the final score for each system is often very close to one another, rendering this evaluation method ineffective. One reason for this closeness in score is because the value of most of the large number of factors being added together are fairly close to one another since most values correspond to the minimum mandatory requirements. These values overpower value of the few remaining factors which describe the real differences

among the system alternatives. Thus, while these "matrix evaluation methods" enable the evaluator to rapidly focus on the relative differences among systems, they have basic flaws as positive selectors of the preferred system.

PART II. GENERATING AN IMPROVED EVALUATION METHOD

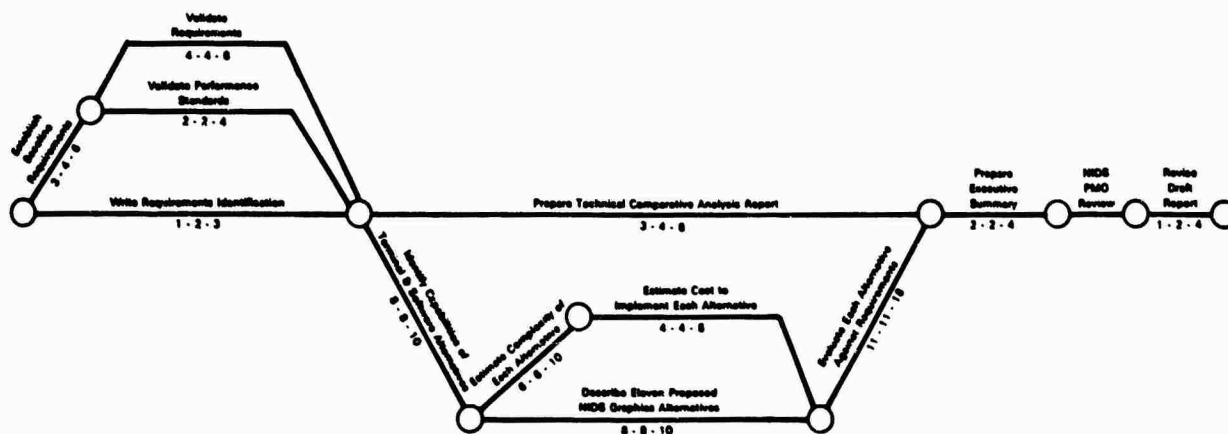
PART II returns to fundamentals and analyzes the key factors which represent the results of an effort of developing and constructing a system which involves components that are either beyond the state of the art or are not readily available "off-the-shelf" and thus have to be developed. From this scenario we develop an improved method for evaluating proposed system alternatives.

6. CONSIDERATION OF DATE OF AVAILABILITY AND ITS UNCERTAINTY

The previous discussion of the two commonly used evaluation methods and their deficiencies concentrated on the two key evaluation factors of system performance (getting the jobs done) and cost. In this section we shall consider two other evaluation factors which must be considered when the design contains elements which must be developed. In this case the system designer (and client) must also consider technological or developmental uncertainties which are further reflected into:

- o The date when the system will be available for use
- o The final system cost
- o The system performance achieved

To perform this analysis we need to consider the entire effort of developing and constructing the system as a work process which can be modeled as a series-parallel network as shown in Figure 4. This network indicates



Include All Work Elements: RDT&E, Procurement, Installation, Operations, Maintenance, Support
 Indicate Required Deliverables
 Indicate Completion Time and Their Uncertainties

Figure 4. Project Activities Network

that this entire work effort (defined as "the project") consists of a group of work activities arranged in a preferred sequence or order. Some of these activities (when completed satisfactorily) produce outputs or deliverables required as part of the Statement of Work. Each of the activities requires time and the expenditure of manpower and other resources. Thus using Critical Path Scheduling techniques the network can be analyzed and the project completion time can be calculated (based on the sum of the times of those activities along the "critical path"). In addition, the man-hours required can be summed and converted into manpower costs and total costs.

Having described the project effort as a work process, two observations can be made. First, the entire project effort can be completed in an acceptable fashion only if all of the various work activities shown in figure 4 are completed in the sequence shown, resulting in the completion of the various required deliverables. It can be assumed that if an activity is not completed satisfactorily, the project effort cannot continue and it will be aborted, unless a complementary activity which should also be shown in the network can be completed as a substitute.

Secondly, given that an activity is completed satisfactorily, the time and man-hours required for such completion can rarely be estimated exactly for all development type activities. This uncertainty in completion time can best be represented by a three-point estimate: the most likely value, and the limits of uncertainty at the 5th to the 95th percentile, as illustrated in figure 5a. The

completion time of the entire project will similarly have a range of uncertainty as illustrated by the probability distribution of figures 5b and 5c.

6.1 Evaluation Calculations to be Made

To simplify the calculations involved, it will be assumed that the project activity network constructed describes exactly the work process to be employed. Since this assumption will be applied to all alternatives, the relative accuracy of the evaluation should not be greatly impaired. Here are the calculations to be made:

- o Determine the level of acceptability for each activity in the network. Assign the planned resources to each activity and provide a three-point estimate of the time required to complete each activity in an acceptable fashion using these resources.
- o Estimate the maximum time each activity will be permitted to continue before the activity, and hence the project, will be terminated. If desired, parallel paths can be inserted into the network to reduce the chance of project termination.
- o From the individual probabilities of activity failure, calculate the probability of project termination (failure). Then calculate the project completion time as a probability distribution when the project is successful, as illustrated in Figure 5c.
- o Using the same time estimates, calculate the manpower cost and other

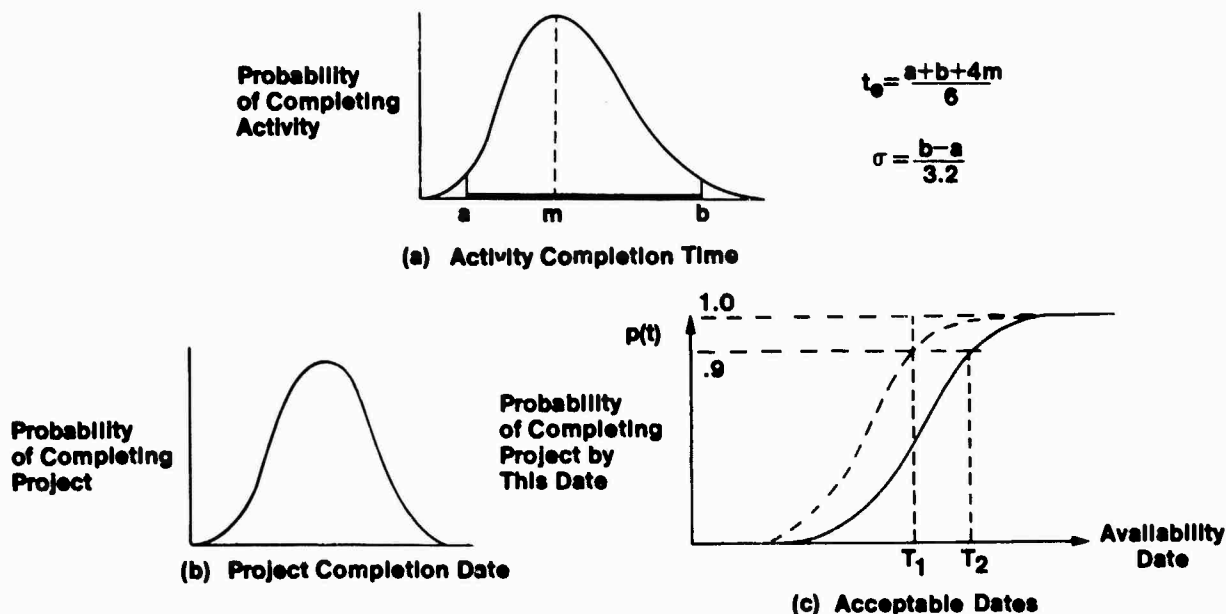


Figure 5. Schedule Risk (From Developmental Uncertainties)

costs associated with each activity and the entire project as a probability distribution. This will be similar to Figure 5b.

6.2 Representing the Project Results

From the previous calculations, the key evaluation characteristics of the project may be expressed as a three-dimensional probability distribution, as illustrated in figure 6. This figure should be interpreted as illustrating the statistical set of results of performing all development activities a large number of times. Each vector (having one of the end points shown) represents one of the results described by each of those coordinates: 1) the system capability of meeting the entire set of mandatory specifications, 2) the date when the system will become available, and 3) the total cost required to obtain the results. Applied to these results are two threshold levels of acceptability of: 1) minimum level of system capability, and 2) maximum allowable availability date. Applying these levels of acceptability (to both the project deliverables and to the system implementation process itself as it progresses), from a statistical point of view, it can be seen that certain of these "trials" are defined as being "unsuccessful", since they do not meet the minimum level of acceptability. These trials result in zero system capability, but do consume both time and cost, as represented by the cluster of points on the YZ plan (zero system capability). Note that the times spent on the project vary from early cancellation of the project to later cancellation. Costs of the unsuccessful project "trials" are also shown. The other points of Figure 6 represent the results of the successful "trials." Note that all successful trials meet at least the minimum level of system capability and all trials complete the

project in less than the maximum acceptable date. The resulting capabilities, dates, and total costs are as shown in the three-dimensional, bell-shaped set of points.

This method of analyzing and evaluating results shows that performance risk can be defined as the probability of meeting the minimum set of requirements. By making the assumption that all activities (of the project network) are independent of one another and each must be completed by some specified date (or the entire project will be terminated), the probability of project success can be calculated as the joint probability that all activities will be successful (the product of the probabilities of success of all activities).¹

Schedule Risk and Cost Risk will be treated in a later section.

7. DEFINING THE EVALUATION OBJECTIVE

Having defined the analytical structure for the evaluation approach, we can now explicitly define the selection objective as follows:

"To select a proposed system which performs a set of future required jobs at given work load levels and meets all required constraints including maximum availability date at the lowest total cost, taking into account all uncertainties."

This objective includes the following three major concepts:

¹Note that if the assumption of activity independence is not acceptable, a similar, but more difficult, analysis can be made taking the pertinent dependencies into account.

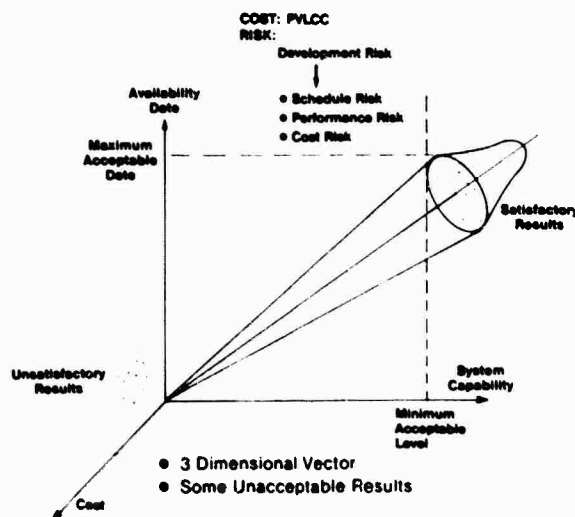


Figure 6. Measuring Project Output

a. The contractor must show that each of his system alternatives can perform all of the future jobs and meet all the constraints.

b. Lowest total present value life cycle cost should be the selection criterion.

c. Development and job uncertainties are the key factors which make the evaluation selection process a difficult one.

8. SUMMARY OF SYSTEMS PLANNING APPROACH

Figure 7 summarizes the steps to be followed in an architectural design study:

a. The client will define one or more sets of mandatory system requirements in terms of jobs to be done and constraints to be met. The client will also specify a set of desirable features over and above the mandatory requirements which they would like to obtain, if possible, and a set of jobs which would use such desirable features.

b. The designer will design a number of system alternatives which meet each set of mandatory requirements, on or before a specified availability date, at a level of risk specified by the client.

c. The designer will calculate the present value life cycle cost (PVLCC) of meeting the stated set of requirements at a level of risk specified by the client.

d. The designer will also provide total cost data relevant to providing and operating each desirable feature he provides, as embedded in the representative jobs for which the desirable feature is to be used.

a. Based on this data, the designer will calculate the cost of performing the set

of jobs associated with each Desirable Feature proposed by the designer. This cost will be compared against the cost of performing the set of jobs if the proposed Desirable Feature were not available. For each of these sets of jobs, the least costly way of performing these jobs will be chosen and this cost added to the cost of performing the mandatory jobs.

f. These results (the preferred system for each level of system capability) will be shown to the client.

g. The client will select the final preferred system based on a comparison of the incremental cost to the incremental gain for increasing levels of system capability.

PART III. APPLYING EVALUATION METHOD IN AN ARCHITECTURAL DESIGN STUDY

PART III amplifies the description of the design approach by showing how to apply the approach in an architectural design study.

9. AN EXAMPLE OF THIS PROPOSED APPROACH

Having described the approach to be followed, we shall now consider an example of how the approach would operate in practice. The example used is that of an architectural design study of an information system.

9.1 Client Issues the Total Set of Requirements

As mentioned previously, this would include:

- o The basic system workload (as characterized by a representative set of EDP jobs), in terms of the mandatory

1. Client will specify alternative sets of design requirements in terms of jobs to be done, performance and constraints.
2. Client will specify minimum mandatory requirements and extra features desired.
3. Constrain designers to provide alternative designs which meet the set of system requirements, including maximum availability date and level of risk.
4. For each alternative, calculate the present value life-cycle cost (PVLCC).
5. Determine the worth of any significant extra performance.
6. Select the system which meets the set of requirements and constraints at lowest PVLCC to client while accounting for risks and uncertainties.
7. Show preliminary results to client and trade-off specifications with feasible system results.
8. Designer assists the client in finalizing on Preferred System.

Figure 7. Summary of Architectural Design Approach

capabilities to be met over time, as illustrated in Figure 8

- o All mandatory constraints to be met
- o A statement of Desirable Features (or extra capability desired), and a statement of the set of jobs for which each desirable feature would be used if provided by the designer

9.2 Consideration of Mandatory System Capability

The first step which the designer must take is to configure one or more system alternatives which will meet or exceed the minimum mandatory workload requirement. Figure 8a shows the "input demand function" (in this case a workload which will be increasing over time). The increase shown is expected to be gradual from start until t_1 , when a large increase is expected. The workload then continues to increase gradually until t_2 when a second large increase will occur. After t_2 the increase is again gradual. The planned system life is five years, which occurs at t_3 .

In the example being presented, the objective of the system is to provide sufficient capability to process the forecasted daily workload within a 24-hour period. However, as shown in Figure 8b, the 24-hour period must also include time for Rework to correct all errors detected, and Down Time (for both preventive and corrective maintenance). With

this in mind we shall define the term "Reliability" to represent the frequency of malfunctions, and "Maintainability" to represent the amount of time when the system has reduced capability due to required repairs or replacement. Thus the system designer must make certain that the net system capability will enable the workload to be processed in the required time.

These failure and down time considerations are illustrated in Figure 9. System Availability is defined as the proportion of Up Time to Total Time. The set of these factors may be treated in the following way:

a. Make certain that the total down time and associated reduction in system capability is taken into account when designing the system to meet the required workload.

b. Frequency of failure or system availability may also be treated as a system constraint, i.e., the maximum frequency of failure that can be tolerated.

c. All of the maintenance factors finally result in added cost, and will be accounted for in the Present Value Life Cycle Cost (PVLCC) analysis of each system.

9.3 Dealing With an Uncertain Workload

The previous analysis of system capability was based on the assumption that the input workload was known exactly, as illustrated in Figure 8a. Sometimes the assump-

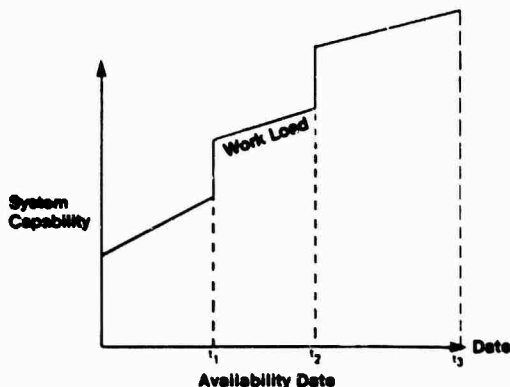


Figure 8a. Meeting the Workload

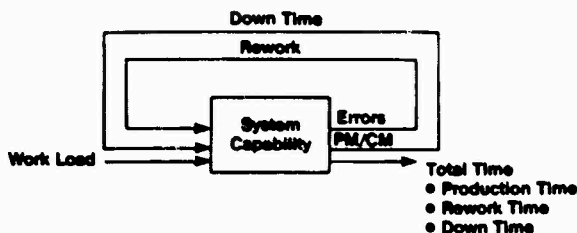


Figure 8b. Factor Affecting Time to Complete Workload

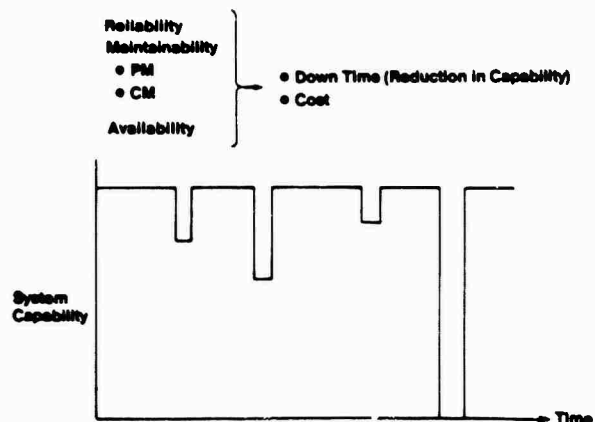


Figure 9. Down-Time Considerations

tion is made that this is the minimum mandatory workload but that extra credit will be given for systems having the capability greater than the minimum. The designer's problem is, how much extra capability is desired over time? Many times the client cannot accurately predict what the actual workload may be. However, some limits must be set if appropriate guidance is to be given to the designers.

One way of dealing with this uncertainty is to express the workload as a probability distribution as shown in Figure 10. Setting the upper limit is fairly straightforward, since this can be set as an arbitrary design limit beyond which additional capability is assumed to have no value. Intermediate probability values can then be inserted, as shown in Figure 10, using whatever data the client has available (either statistical data or judgmental estimates).

Based on this assumed workload, the designer must then design the system to be able to meet the entire range of workload levels, over time, adding additional system increments whenever required. In the illustration of Figure 10, the designer proposed System A₁ as the initial system. This system will "absolutely" meet the workload requirement in Years 1 and 2 and will "absolutely not" meet the requirement in Year 5. However, the designer proposed to add an additional capability to A₁, to yield System A₂, whenever A₂ is needed. Generally two constraints are placed on the designer for purposes of design and evaluation:

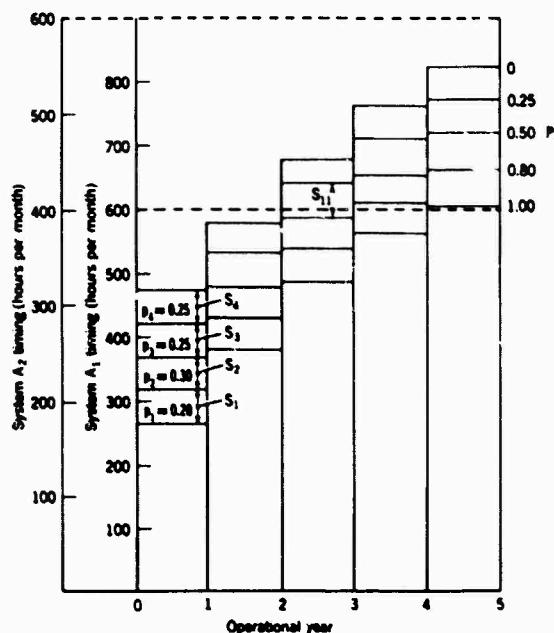


Figure 10. Designer Response to Meeting Workload probabilities

- o No more than one or two growth additions will be permitted to keep disruptions within acceptable limits.
- o An addition will be required whenever the operational hours per month reaches some upper limit (say, 600 hours per month as shown in Figure 10). This will permit sufficient time for corrective and preventive maintenance. Alternatively, this limit could be a function of the system's demonstrated maintainability.

Providing such system "upgrades" during its operational life saves the user money since it prevents the user from having to buy more capability than is required (like A₂) at the beginning of system operations rather than when it is actually needed.

Finally the designer should provide "credible evidence" for the client that the preferred system can in fact meet the entire defined workload (as shown in Figure 10) over its entire levels, as well as all constraints. For off-the-shelf systems, this could be validated by live test demonstrations. For development type projects this could be shown by simulation or analysis.

9.4 Availability Dates and Schedule Risk

Given that each system has been designed to provide the required net productivity to meet the incoming workload specified in Figures 8a or 10, we shall now describe how the designer plans the development effort to meet the required availability dates (t_1 and t_2) and provides the necessary date to the client, enabling him to perform his validation function. Recall that Figure 4, which displays the project work process in network form and the time estimates of the activities along the critical path, was used to calculate the project completion date as the normal distribution of Figure 5c. In the example shown, there is approximately a 40% chance of successfully completing the project by date T_1 (60% chance of schedule overrun). However, the client may not be comfortable with this degree of risk. Thus, the system designer must find out what risk of overrun the client is willing to accept. Assume a 10% risk is acceptable. As shown in Figure 5c, for this 10% risk the project would be completed on or before T_2 which is later than T_1 and hence unacceptable. Thus, the system designer must reconfigure the project plan to reduce completion date. Generally this is done by adding more resources on one or more activities on the critical path until the new completion date probability function satisfying the requirement (10% chance of overrun at time T_1) is obtained, as shown in Figure 5c.

In summary, Schedule Risk is defined as the probability that the project will overrun a

required delivery data. For purposes of the planning and evaluation efforts, the value of Schedule Risk acceptable to the client should be provided to the designer at the beginning of the study. Then it is up to the designer to construct the project work plan accordingly and provide the project activities network plus all time calculations to show that the completion data, as a probability function, satisfies both the time and risk requirements.

9.5 Consideration of Total Cost

The project activities network (Figure 4) is also the starting point for the cost calculations. From this network the cost of all work and cost elements (RDT&E, procurement, installation, operations, maintenance, and support) borne by the client must be calculated for each year.¹ Here the standard formulas for calculating the cost of an activity are used (e.g., labor cost equals the product of man-hours and labor rate). When the activity time is expressed as a three-point estimate, these times must be converted to an expected value and a standard deviation (as shown previously in Figure 5e). These values for time are then converted to labor cost values by multiplying each by the labor rate. Costs are then accumulated by year, and the expected value of cost and the cost variance for each year are calculated as follows: The expected total cost for the year is equal to the sum of the expected costs. The total cost variance for each year is equal to the sum of the squares of the individual standard deviations for that year.

When a probabilistic workload is assumed (as discussed in the previous section), each yearly cost must be handled as a frequency distribution. Operations, maintenance, or leasing costs must be calculated for each probability segment. Using Figure 10 as an example, first calculate the cost of segment S_1 as a function of its operating time. Using the time of the mid-point of the p_1 segment, and using the pricing data supplied the designer as well as the user labor cost, calculate the cost associated with this mid-point time. This cost has the probability $p_1 = .20$ associated with it. Make a similar calculation for the other segments, S_2 , S_3 , and S_4 . Then calculate the expected value and standard deviation for these four probabilities. These terms are then added as part of the sum of the other expected values and the squares of the

standard deviations of the cost terms of that year as described previously.

The expected value and standard deviation of cost for each year must then be incorporated into a present value analysis in the following way. First, apply the appropriate discount rate to each of the yearly expected values of cost. The sum of this result is the present value of expected cost. The present value standard deviation is calculated as follows:

- o Find the standard deviation of cost for each year as the square root of the variance of cost for each year.
- o Apply the appropriate discount factor to each year's standard deviation. This yields the present value of each year's standard deviation.
- o Square each of these factors to obtain the present value of each year's variance.
- o Sum each of these present value variances.
- o Take the square root of this sum. This is the standard deviation of total cost.

A lease-versus-buy calculation can also be made by including the purchase cost of the system. But this must also be handled on a probabilistic basis. In the example of Figure 10, there is a 100% chance that System A_1 will be required for the initial installation. As seen in Figure 10, there is a 56% chance that System A_2 will be needed in Year 3, 85% chance in Year 4, and 100% chance in Year 5. Using this data, the probability of purchasing A_2 is each year (given that it was not purchased previously) can be calculated. This data can be converted into an expected value and standard deviation of purchase price for that year and these values added to the other yearly expected values and standard deviations as described previously.

Having calculated the present value of the expected value and standard deviation of cost, the PVLCU can be obtained as a normal distribution, similar to Figures 5b and 5c. Now the factor of cost risk can be introduced in the same way as schedule risk was treated. Namely, the client should indicate the cost risk they are willing to assume, where cost risk is defined as the probability of cost overrun. For example, the expected value of cost has a 50% chance of overrun and this may be unsatisfactory to the client. If the client is only willing to assume a 10% chance of overrun, for example, this amount is applied to the cost probabilistic values, as

¹In this section we assume that the cost of all work performed by the client and the user is included in the analysis. If other organizations or the public also perform work or bear any of the costs, such costs must also be factored into the analysis.

illustrated in Figure 5c, and the value of cost obtained. For this example of a 10% chance of overrun, the value of cost = $C_a + 1.28$.

where C_a = expected value of cost

σ = standard deviation of cost

Values of cost for other values of risk may be similarly calculated using data from a standard normal probability distribution.

9.6 Consideration of Growth Factors

Here are three other related factors which often arise in an evaluation:

- o Upward Compatibility
- o Growth Potential
- o Flexibility

Here is a description of how they would be treated under this evaluation method.

The first step is to understand and define what the client means by these terms. Generally the term "Upward Compatibility" is used to connote that the system can be reconfigured to provide greater capability by adding additional elements. That is, it can be modified by using all or part of the original system, thus providing the greater capability at less cost and disruption than if a second, totally new system were used.

"Growth Potential" is quite related to the previous definition of Upward Compatibility. In this case the size of the job may be "growing" or increasing, and hence a larger capability may be needed.

"Flexibility" generally means that the set of jobs may change, and the client would like the original system to be sufficiently general-purpose so that its capabilities are sufficient to perform the new set of jobs rather than just the original set of jobs.

Thus, all three of these terms suggest that the client has some other set of jobs in mind besides the originally defined set of jobs. In keeping with the evaluation approach described, here is how these terms may be included in the evaluation. First, explicitly define a representative set of other jobs which may be required to be performed by the system. Second, indicate both the dates when these jobs will be performed (such as in Years 4 and 5) and the probability that the jobs will occur. This may be a subjective estimate of the probabilities. Thus both sets of workloads now become the total requirement. And the designer is required to configure his system design to accommodate the total set of jobs. In general, the design and evaluation approach used is the

same one used in the case of job uncertainties (Figure 10). That is, the client will validate that the total system, including changes, is capable of handling the total workload, with proper response times, if it should occur. In addition, the client's evaluator will calculate the total cost on a probabilistic basis and apply the cost risk factor to estimate the total cost to be used in the evaluation.

9.7 Consideration of Superior Characteristics

The recommended evaluation approach described thus far can be summarized as follows:

- o All systems have been designed to perform the same set of operational jobs and to meet all specified constraints.
- o All systems will become available at the specified date(s), taking into account an acceptable risk of schedule overrun.
- o The preferred system is the one which requires the lowest cost (PVLCC), taking into account an acceptable risk of cost overrun.

However, sometimes a designer provides one or more characteristics (generally at greater cost) which are clearly superior to the lowest cost system alternative. Now the question raised is, are these incremental superiorities provided worth the difference in cost?

The key factor to be analyzed is, have these superior characteristics been considered in performing the operational jobs which have been evaluated? Or are there other jobs which would demonstrate each of the superior system's characteristics? In the former case, a system's superior characteristics may have already been accounted for in the cost calculations. Hence, no further "credits" need be given to that system. In the latter case, the evaluator can calculate the additional "credits" to be given as follows:

- o Clearly define all other jobs to which these superior characteristics would apply.
- o Estimate how much additional cost would have to be paid by the client if the lowest cost system were used for these jobs rather than the superior system. This cost is obviously a function of how often each job is performed during the system life cycle, or the probability of its being performed. This additional cost should be added to the lowest cost system to determine what the true PVLCC would be for all systems.

Note that what we have done is to enlarge the set of operational jobs to be done, and enlarged the total costs required to do them. Thus this new total cost can be the basis of the system selection.

PART IV. APPLYING EVALUATION METHOD TO A PROPOSAL

The previous sections presented a method for performing an architectural design study (involving systems analysis, synthesis and evaluation of alternatives) in an environment where there is close contact with the client. A proposal effort fundamentally involves the same systems planning functions as described for the architectural study. However, instead of the designer synthesizing and evaluating all of the system alternatives and selecting the preferred one, a set of competing designers each designs a proposed system and submits these to the client evaluators for their selection. Here are the differences which make it more difficult to "optimize" a system in a proposal effort than in an architectural design study:

- o First, the system requirements are generally in the form of technical specifications with firm mandatory requirements. This may force the designer to provide extra capabilities if the off-the-shelf entities to be employed do not exactly match the mandatory requirements.
- o The second and most important difference is that there generally is little opportunity to make contact with the client prior to submission of the proposal, and hence it is more difficult to "optimize" the design in terms of the client's desires. Thus it is very important that the designer review the Request for Proposal and make certain that he understands what the client is requesting and the details of the evaluation method to be used. There should be an opportunity for the designer to obtain clarification of any fact which is ambiguous to him.

With these differences in mind, we shall now describe how to apply the previous systems planning approach to the client proposal process.

10. APPLICATION OF METHOD TO A TECHNICAL CHARACTERISTICS TYPE OF PROCUREMENT

In this scenario it is assumed that the client provides the system requirements primarily in the form of technical specifications rather than operationally oriented jobs. The system design and evaluation approach now recommended will still be based

on the approach previously presented but with the following changes as indicated.

- o Technical specifications are again presented as two levels: 1) a mandatory minimum, and 2) desirable features.
- o An additional aid to the designers would be the inclusion of operationally oriented information regarding the operational use of the system (jobs and functions to be performed).
- o All desirable features will be described, and the value of providing each of these features will be provided to all designers. These values will be derived from the architectural design studies which were performed at some previous time, and which were the basis of the technical specifications. Based on the architectural studies, the client should also provide the designers with evaluation functions indicating the worth of exceeding the mandatory minimum requirements. That is, what is the value of exceeding a minimum mandatory requirement in terms of its dollar savings somewhere else. As described previously, each of these values is equal to the lowest additional cost of performing the jobs needing these functions (or providing additional performance) if the functions (or additional performance) were not provided.
- o Each designer would then attempt to design a system exactly meeting each mandatory requirement. However, the designer will also consider if it is possible to make trade-offs among related parameters which will meet a joint requirement at lower cost than the cost of meeting (or exceeding) the requirements singularly, taking into account the value of the additional features or performance.
- o Ideally, the client would provide the designer with the value of exceeding the mandatory requirements. Each designer could then properly "optimize" his proposal in terms of meeting all requirements at lowest PVLC to the client, taking into account the value of desirable features as well as all significantly superior characteristics. However, if the client does not provide these values and the designer finds he must include these "extras" in his design, he should estimate its value using the method described previously.
- o In either case the client should also validate such calculations and select

that designer which meets all requirements and performs all jobs at lowest total PVLCC.

- o Developmental uncertainties as reflected into schedule risk and cost risk would be treated in the same way as previously described.

PART V. CONCLUSIONS

In this paper we have presented several potential pitfalls which can occur in the process of designing, evaluating and selecting the preferred system for clients. Some are fairly obvious; some are not. These pitfalls and other conclusions reached in this paper can be summarized as follows:

a. Unless the requirements of the job are clearly stated and understood by the designers, they will not be able to design their systems appropriately. Thus, some means should always be available for further discussion and clarification of these requirements prior to the start of system design efforts. This opportunity is generally available to designers, and should be utilized early in the design process.

b. Unless an objective procedure for evaluating system alternatives is provided to the designers by the client, designers will not be able to perform their cost-performance trade-offs effectively to arrive at the system design preferred by the client.

c. The system requirements should be stated in a way that will enable the designer to provide what is desired by the client at lowest total cost. In architectural studies where the client desires the designer to make systems engineering trade-offs among the key design parameters, it is preferable that the requirements should be stated as operational jobs to be done rather than a set of detailed system characteristics. If the client also wishes to include a set of technical characteristics as mandatory minimum requirements, with additional desirable features, it would be helpful to list each design constraint in two ways: 1) a design goal, indicating the client's mandatory minimum value which must be equalled or surpassed, and 2) the worth of exceeding this minimum value. By doing this the designer should be permitted to make appropriate trade-offs among design parameters and thus be better able to satisfy the user needs at lowest cost. The same approach should be used in proposal efforts.

d. Credible evidence of the accuracy and reliability of the proposed work plan should be provided to the client as part of the architectural design study and proposal efforts. Such evidence includes: 1) performance validation through live test demonstrations, simulations or analysis; 2) reliability, maintainability data, when available; 3) schedule analysis, including critical path analyses; 4) cost analyses; and 5) risk analyses.

