AN INTEGRATED DECISION APPROACH: COMBINING THE
DEMAND-REVEALING, QUALITY FUNCTION DEPLOYMENT, AND
ELEMENTS OF THE SYSTEMS ENGINEERING PROCESSES

by

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(ABSTRACT)

This research provides an Integrated Decision Approach which makes operational a three step-decision process applicable to the development of publicly used systems. The research is important because solution approaches typically used for these types of problems have been inefficient, thus resulting in the consumption of large amounts of public resources. The Integrated Decision Approach enables group decision making when: (1) a definite number of users exists, (2) users pay all costs associated with the system, and (3) users may not use an alternate system once the system begins operation. Decision making is enabled by the Demand-Revealing Process, a decentralized decision mechanism, while feasible alternatives are developed through elements of the Systems Engineering Process and the Quality Function Deployment Process if necessary.

It is demonstrated through an hypothetical example that: (1) these three processes, when taken in a proper sequence, will enable decision making which
meets the three stated conditions, (2) the Demand-Revealing Process will provide better results when applied within the Integrated Decision Approach, (3) face validity of the Integrated Decision Approach can be established. Thus, further research may show that the Integrated Decision Approach may be employed to solve these type of public sector problems. In addition, Demand-Revealing Processes may gain greater acceptance due to improved results when applied in proper sequence within the Integrated Decision Approach.
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I. INTRODUCTION

1.1 Problem Identification

Private and public\(^1\) organizations routinely make decisions resulting in the allocation of resources to programs and projects. These programs and projects often entail the development of large-scale systems. In the private sector, a car manufacturer developing a new automobile must create a program to design the car, and all systems associated with its production, and repair. Ultimately, the set of systems chosen must result in a positive life-cycle cost (e.g., the overall system must be profitable). Contrast this to public programs where life-cycle cost can be negative (cost exceeds revenues), but benefits accruing to the public are positive.

Government agencies are typically tasked with developing large systems, that are too cost-prohibitive for private organizations to invest in, or will result in no profit. In many cases these programs will benefit the public, and as such, are appropriately undertaken by government. An example of one such program would be the development of a system for the long-term storage of nuclear waste. Such a system may be costly, require years to develop, but would result in benefits accruing to the public.

The organization developing the program, whether it is publicly or privately run, should be committed to using a sound methodology for developing and discriminating between system alternatives as early as possible in the design

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1. For this research, public organizations are non-profit, and usually run by some government agency. This is in contrast to some definitions of public organizations which may state that the organization is publicly owned, i.e., stock may be purchased by the general public.
process. Such a methodology would result in the maximization of resource utilization after resources have been allocated to programs and also would generate a minimum number of dissatisfied users.

With this in mind, it becomes apparent that decisions made early in the design process must be substantiated with sufficient data so as to distinguish between seemingly equally desirable designs.

1.2 Research Purpose

The purpose of this research is to develop an approach to obtain sufficient data, and then provide a basis to make early design decisions to ensure the most efficient use of organizational resources. The approach is applicable to organizational decisions where:

1) It is possible to identify all users of the proposed system.

2) System users may use no alternate system once the proposed system begins operation.

3) System users pay for all design, development, construction, operating, and phaseout costs associated with the system.

These restrictions exclude privately produced competitive goods, but do not exclude systems shared by functional organizations within a private company. Possible applications of the proposed approach include mainframe computer selection in universities, large copier selection in private and government organizations, etc. In these examples, it is assumed that the resulting system resource is shared and self-supporting.
Users of the system are assumed to be the individual, organizational unit, or agency paying for use of the system. In the case of a university with a shared photocopying machine, the users may be the individual departments. Each department would be restricted to running copies on the shared machine, and it would be assessed a cost of operation plus a part of the acquisition cost. These costs should be based upon the department's percentage of use of the machine.

1.3 Problem Statement

The problem investigated in this thesis is to develop and demonstrate through an hypothetical example a new approach (henceforth referred to as the Integrated Decision Approach) based on a three-step decision process and combining the Demand-Revealing Process, the Quality Function Deployment Process, and elements of the Systems Engineering Process (Figure 1.1) to facilitate the allocation of resources to systems where:

1) A definite number of users for the proposed system exist, and they can be identified.

2) Users can be restricted from using an alternate system once the proposed system begins operation.

3) All design, development, construction, operating, and phase-out costs associated with the system can be collected from users.

A number of approaches currently exist that are applicable to this type of problem. These will be discussed, and their limitations made explicit. It should be noted that the Demand-Revealing Process, the Systems Engineering Process, and the Quality Function Deployment Process already exist. However, they have
not been combined to solve these types of problems. Therefore, this research will be integrative in nature.

1.4 Research Hypotheses

It is hypothesized that Demand-Revealing mechanisms, a class of decentralized decision mechanisms, will accurately facilitate step three of a three-step decision process if their inherent deficiencies are mitigated or eliminated by the inclusion of the Quality Function Deployment Process, and elements of the Systems Engineering Process. It is further hypothesized that Systems Engineering and Quality Function Deployment must be enacted prior to implementation of the Demand-Revealing Process.

1.5 Research Objectives

This research will pursue six specific objectives to test these hypotheses. These are:

1) Discuss approaches used in the past to solve problems that meet the conditions set forth in Section 1.3 (and identify their inherent limitations).

2) Determine how the Quality Function Deployment Process may be made applicable to the Integrated Decision Approach.

3) Determine what elements of the Systems Engineering Process are applicable to the Integrated Decision Approach.

4) Show how the Integrated Decision Approach mitigates or eliminates problems inherent to Demand-Revealing Processes.
5) Construct an hypothetical example to show how the Integrated Decision Approach can be applied to decision problems that meets the conditions of Section 1.3.

6) Demonstrate the applicability of the Integrated Decision Approach.

These research objectives may be reflected in the research method for the research shown in Figure 1.2. As indicated, the research will begin with the reasons for selection of the Demand-Revealing Process over other possible decision mechanisms. A history of the Demand-Revealing Process, and an example of its correct application will be given. A discussion of the deficiencies of the Demand-Revealing Process will then be given.

1.6 Research Approach

Of the deficiencies inherent within the Demand-Revealing Process, some can be dismissed because they may not apply under the decision domain specified by this research, or, they are not likely to occur. However, the remaining deficiencies cannot be dismissed so readily. In this thesis, an Integrated Decision Approach will be developed that attempts to eliminate the remaining deficiencies. This approach will rely on Quality Function Deployment and elements of Systems Engineering, two existing processes. It will be shown that the use of elements of Systems Engineering that treat the conceptual phase and most of the preliminary design phase of the system life-cycle will remove or mitigate many of the deficiencies inherent in the Demand-Revealing Process.

Successful implementation of the Systems Engineering Process relies upon accurate development of requirements during conceptual design. If sufficient information does not exist in the internal measurement system to reveal user
1. Select preferred decision mechanism

2. Determine applicable elements of the Systems Engineering Process

3. Discuss the Quality Function Deployment Process

4. Discuss the Demand-Revealing Process

5. Negation or mitigation of Demand-Revealing Process deficiencies

6. Construct the Hypothetical Example

7. Demonstrate the applicability of the Integrated Decision Approach

Figure 1.2 Research Method
requirements, then Quality Function Deployment may be employed to facilitate the development of requirements and engineering performance measures. The conditions under which the Quality Function Deployment Process should be used will be given. It will then be shown how the Integrated Decision Approach minimizes the problems associated with Demand-Revealing Processes. A hypothetical example will be constructed to show how this integrated decision approach will work. Finally, the applicability of this integrated decision approach will be discussed.

1.7 Research Significance

Of primary significance is that this research addresses an important class of problems in the public sector by bringing knowledge together from three diverse areas (i.e., Public Choice, Systems Engineering, and Quality). Research conducted in support of this thesis may be beneficial since solutions to problems of the type described in Section 1.3 consume large sums of money and may not be handled well now. By bringing knowledge together from these three areas, an approach is developed which may save both time and money. In addition to the savings in time and money, users of the resulting system(s) may be more satisfied than if another decision approach had been applied to solve the problem.

Second, it is shown in this research that the Demand-Revealing Processes provide better results when they are applied as a component within the Integrated Decision Approach. This finding is significant because the Demand-Revealing Processes have not been applied in the past because of their inherent problems.
Third, by combining knowledge and ideas from the three areas in a new combination, better insight is gained. This is a significant contribution because the Integrated Decision Approach brings about a new way of thinking about, describing, and solving problems of the type described in Section 1.3.

Fourth, it is shown that decision making may be represented as a three-step process. Because of the steps involved, the accuracy of subsequent steps of the decision process are dependent upon the accuracy of former steps of the process. It is further shown that inception and correct implementation of the decision process is dependent upon accurate information. Out of this comes the idea that information should be gathered in different ways, depending upon how much accurate information can be obtained from the internal measurement system.

Fifth, an Integrated Decision Approach is postulated which ensures the accuracy of some steps of the decision process. The resulting approach will ensure that decisions are made using correct information and in accordance with a decision mechanism which encompasses all decision variables. Therefore, it can be shown that the Integrated Decision Approach provides accurate results in the selection from among alternatives.

Finally, the relative merits and deficiencies of various centralized and decentralized decision mechanisms are discussed. This discussion may prove beneficial when attempting to decide what decision mechanism is best for certain conditions.
1.8 Thesis Organization

This thesis is comprised of eight chapters and two appendices. An outline of the Systems Engineering Process developed at Virginia Tech is provided in Chapter Two. The basis for the development of the Integrated Decision Approach is given.

Chapter Three presents a discussion of the decision process, and then presents techniques that have been used in the past to solve problems that are of the type set forth in Section 1.3. Change is classified as either planned or unplanned. The Quality Function Deployment Process is then discussed as a means of accounting for unplanned change. A comparison of centralized and decentralized decision mechanisms is then provided. It is shown that decision mechanisms of the Demand-Revealing type facilitate decisions based on actual consumer preference, while the centralized decision mechanisms either rely on surrogate measures of preference, or attempt to measure preference indirectly. The chapter concludes with the basis for selecting Demand-Revealing over other decision mechanisms.

Chapter Four presents the history of the Demand-Revealing Processes and elaborates on problems associated with the Demand-Revealing class of decision mechanisms. In addition, problems associated with Demand-Revealing decision mechanisms are explored and techniques to alleviate the problems are offered. The chapter concludes with a number of problems that must be rectified before Demand-Revealing mechanisms can adequately address the stated problem types.
Chapter Five begins by discussing decision making as a three step process. Reasons for the inclusion of the Quality Function Deployment Process and elements of the Systems Engineering Process are given and confirmed by showing how these elements solve problems specific to Demand-Revealing mechanisms. The implementation order of the Quality Function Deployment, Systems Engineering, and Demand-Revealing Processes and the interconnections is developed; and it is shown how these interconnections combine to eliminate or mitigate problems inherent in Demand-Revealing Processes.

Chapter Six comprises the construction of an hypothetical example to demonstrate the use of the approach. The example is derived from a real-world system but the decision problem is completely hypothetical. As an addition to Chapter Six, an appendix is provided that contains the detailed Systems Engineering development process for improvements.

Chapter Seven, entitled Applicability of the Integrated Decision Approach, demonstrates the types of problems the approach may be used to solve. The Chapter shows that the results should be correct for problems of the type considered by this research effort, if the Integrated Decision Approach is employed.

Chapter Eight, entitled Summary, Conclusions, and Extensions, begins by providing a summary of the research. Conclusions are then presented. Finally, a discussion of further research that may be done in this area is provided.
The Appendix provided presents the development of two independent projects to be used in the hypothetical example. The Systems Engineering tool RDD-100 (Requirements Driven Development) is used to facilitate development of these two projects.
II. SYSTEM DEVELOPMENT PROCESSES

2.1 Background

The Systems Engineering Process is used by organizations to provide a sound basis for system design. The process begins with the identification of a specific need (or needs) for a system, and ends with the selection of a specific design. The process is most effective during the early phases of a system's life-cycle, but must account for all activities over all phases of the life-cycle (Figure 2.1). The emphasis in this thesis is to determine how the Systems Engineering Process can be used with a specific decision mechanism (the Demand-Revealing Process) to make early system design decisions.

Since use of the Systems Engineering Process necessitates the development of requirements, the Quality Deployment Function Process to enable this will be studied. The resulting approach will include all activities conducted through the selection of a specific candidate system to be implemented. The objective is to combine three processes (Demand-Revealing, Quality Function Deployment, and Systems Engineering) to create an integrated decision approach to facilitate the selection of the preferred alternative.

2.2 System Development

To fulfill a specific need, organizations must allocate resources to programs and projects. This need will result from "a want or desire for something arising from a deficiency (perceived or real) (Blanchard and Fabrycky, 1990)." The resulting architecture developed to fulfill the need will, in most cases, constitute a system
Figure 2.1 The Earlier Systems Selection Is Made, the Lower the System Cost (Fabrycky and Blanchard, 1991).
composed of interrelated parts, all of which work to fulfill a common purpose. In Systems Engineering terminology the system's purpose is its mission.

Systems are composed of three elements. They are: 1) Components, 2) Attributes, and 3) Relationships (Blanchard and Fabrycky, 1990). Components are the system's input, output, and process mechanisms. Components can assume several "...values to describe a system state as set by control action and one or more restrictions." "Attributes characterize the system...[and] are the properties or discernible manifestations of the components." Finally, "relationships form the linkages between components (Blanchard and Fabrycky, 1990)."

A detailed definition of a system can now be offered (Blanchard and Fabrycky, 1990):

"A system is a set of interrelated components working together toward some common objective. The set of components has the following properties:

1) The properties and behavior of each component of the set has an effect on the properties and behavior of the set as a whole.

2) The properties and behavior of each component of the set depends upon the properties and behavior of at least one other component in the set.

3) Each possible subset of components has the two properties listed above; the components cannot be divided into independent subsets."

Organizations chartered to fulfill certain missions may adopt the Systems Engineering Process to provide a sound basis for the controlled development of a system. The Systems Engineering Process provides a comprehensive approach to convert system mission requirements into a completed system architecture.
The architecture of a system is the physical entities with which it fulfills its mission. The architecture of a single system can be comprised of such dissimilar components as software, hardware, people, and procedures. Further, any system can be decomposed. By this it is meant that one architecture component can be treated separately from another as long as all interfaces between the two components are known, accounted for, and understood. For example, software can be treated separately from hardware during the design of a computer system as long as all interactions are identified. Furthermore, behavior of the system can be specified prior to allocation of functions to architecture by the assignment of requirements to functions.

In many cases the Systems Engineering Process parallels or subsumes portions of the decision process. However, it is important to realize that the Systems Engineering Process does not specify decision mechanisms or analysis techniques. Instead, it indicates where analyses and decisions may be required. Therefore, it is essential that organizations using Systems Engineering also adopt some formal analysis and decision mechanisms.

While analysis techniques may be specific to a certain type of technology, decision mechanisms should not vary. For example, the development of a satellite system may necessitate the use of performance measures constructed specifically to address satellites. These specific measures will constitute only one of many analysis techniques that must be employed to assess overall system performance. However, since the satellite system is part of the larger system, a single decision mechanism should be used to aggregate performance of all subsystem analysis results. In this way, the decision maker can be assured that all
important system attributes (i.e., performance measures) will be balanced when deciding upon over-all system selection (Keeny and Raiffa, 1976).

Since decision mechanisms comprise a set of rules, the same mechanism must be employed across all possible architectures. This is because the use of a single decision mechanism across all possible system alternative architectures assures that decisions are made based upon the same rules. It follows that systems are then compared on a similar basis, and the best available alternative will be chosen.

2.3 Steps in the Systems Engineering Process

Systems Engineering is a process, and as such, it can be divided into a set of steps. Since there are different views on what steps should be included in the Systems Engineering Process, this research will concentrate on the process developed at Virginia Tech and published by Prentice-Hall (Blanchard and Fabrycky, 1990).

At the top level, the Systems Engineering Process can be divided into three main steps. They are (1) conceptual system design, (2) preliminary design, and (3) detail design and development. These top-level steps can be further divided into a series of stages.

2.3.1 Conceptual System Design

Conceptual system design consists of several stages. They are (1) definition of requirements, (2) preliminary systems analysis, (3) advance system planning, and (4) conceptual design review. This first step in systems design begins with the
definition of a system's need, and terminates with a conceptual design review. This first step in the Systems Engineering Process can be viewed as a roadmap for all future phases. This is because all requirements and measures for the system are derived, and a plan for carrying them out is created.

The first stage in conceptual design, definition of requirements, consists of (1) definition of need, (2) feasibility studies, (3) system operational requirements, and (4) system maintenance concept. The definition of need is based on a requirement for a system to fulfill a certain want or desire. Feasibility studies should be conducted after the needs analysis is completed. The purposes of feasibility analysis are to determine what technology is appropriate to fulfill the needs, and what cost would be involved. Systems operational requirements are comprise seven requirement areas. They are (1) mission definition, (2) performance and physical characteristics, (3) use requirements, (4) operational deployment or distribution, (5) operational life-cycle, (6) effectiveness factors, and (7) environment. To complete system requirements, all these areas must be addressed. The systems maintenance concept is developed to determine how repairs should be made on to the system. System repairs should be broken down into depot, intermediate, and organizational maintenance levels. At this stage it may be appropriate to specify what percentage of repairs should be performed at each level².

2. It should be noted that some systems cannot be taken back to the shop for repair. If this condition occurs, then it may be necessary to specify all repairs be conducted at the organizational level. Further, some elements of a system may not be allowed to fail during the mission life. In this case, maintenance for these elements may not be considered at all.
The second stage in conceptual design, preliminary systems analysis, consists of (1) the definition of problem, (2) identification of feasible alternatives, (3) selection of evaluation criteria, (4) application of modeling techniques, (5) generation of input data, and (6) manipulation of the model. The purpose of preliminary systems analysis is to retain the most feasible technologies while technologies that do not seem too promising are ruled out. It should be noted that this step is carried out with a limited amount of information.

The third stage in conceptual design, advance system planning, consists of (1) developing system specification and (2) the development of the Systems Engineering Management Plan (SEMP). The purpose of the system specification is to provide a guideline for further system development. Specifications are typically used by the DOD, and may be given to contractors with the expectation the specifications would impart understanding as to what the system is supposed to do. It should be noted that the system specification should include "...information derived from the definition of operational requirements and the maintenance concept and the results of the feasibility analysis (Blanchard and Fabrycky, 1990)." In this way, the system may be developed in a holistic manner. The SEMP should be developed along with the system specifications. The SEMP includes the areas of (1) technical planning and control, (2) systems engineering process, and (3) engineering specialty integration.

The final stage in conceptual design, conceptual design review, is essentially a check to make sure all previous stages in conceptual system design were carried
out effectively. The conceptual design review should include methods to
determine that no mistakes or oversights were made during the preceding stages.

2.3.2 Preliminary System Design

Preliminary system design consists of five stages. They are (1) system functional
analysis, (2) allocation of requirements, (3) trade-off and optimization, (4)
synthesis and definition, and (5) system design review. This second step in the
Systems Engineering Process begins with the input of specifications generated
during the conceptual design stage and terminates with requirements being
allocated to a specific system architecture.

The first stage in preliminary system design, system function analysis, is
comprised of functional analysis. Further, functional analysis should be of two
forms: (1) operational functional analysis and (2) maintenance functional
analysis. The objective during this stage of the Systems Engineering Process is to
develop all functions that the system must perform. These functions should
result from specifications developed during conceptual system design. It should
be noted that behavior diagrams may be substituted for functional analysis.
Behavior diagrams provide a better description of expected system behavior
than do functional diagrams\(^3\). This is because behavior diagrams explicitly link
inputs and outputs to functions, while functional diagrams only provide
information about the functions themselves.

The second stage in preliminary system design, allocation of requirements, is
comprised of allocating requirements to components within the system.

3. Behavior diagrams will be used later in this thesis to develop expected behavior for the system
presented in the hypothetical example.
Functions should also be linked to components at this point so that it is known that all system functions (both operational and maintenance) will be performed by the system components. During this stage, the maximum and minimum performance for each component are established. These maxima and minima should derive from the requirements that were linked to the functions. At the end of this stage, it should be known how each component will behave (i.e., performance requirements are attached to the components), and what the interfaces are between the components.

The third stage in preliminary system design, trade-off and optimization allows the systems engineer to try different system configurations, each fulfilling the requirements stated earlier in the process. This stage necessitates the development of mathematical models for both life-cycle cost and performance to facilitate the timely evaluation of system design alternatives. At the end of the trade-off and optimization stage, a single system should be identified that has been optimized. That is, given the components that make up the system, it would be impossible to achieve better performance (either life-cycle or performance). It be noted that several alternative design approaches may emerge during this stage, and each will have trade-off and optimization analysis performed on it. At that point, the best alternative approach will be selected from among a set of alternative approaches.

The fourth stage in preliminary system design, synthesis and definition, refers to the combining of various elements of the alternative to "form a functional entity (Blanchard and Fabrycky, 1990)." Output for this stage will be the specifications
to guide the detail design and development phase of the Systems Engineering Process.

The fifth and final stage in preliminary system design, system design review, is essentially a check to make sure that all means have been employed to achieve the best design. Since mistakes or oversights made in the preliminary design phase could result in costly changes during detail design and development, and later, it is essential that the preliminary design review be thorough enough to uncover these mistakes or oversights.

2.3.3 Detail Design and Development

Detail design activities refine design further by taking as input the specifications from synthesis and definition stage of preliminary design. It has been noted that the Systems Engineering Process extends through the detail design and development phase of the system life-cycle, the purpose of this thesis is to provide an integrated decision approach that can be used to provide early design commitment to a specific architecture. Therefore, the outputs from the Integrated Decision Approach will be in the form of a system architecture or an approach. This system architecture will then be used as the basis for detail design and development activities within the Systems Engineering Process. With this in mind, no further mention of activities related to detail design and development will be made, with the exception that, if the Integrated Decision Approach is employed, all activities of the Integrated Decision Approach must be completed prior to the inception of detail design and development activities.
Since a decentralized decision mechanism was chosen to facilitate the decision process contained in system trade-off and optimization, all identified and optimized alternatives should be passed on to the decision mechanism so that selection can be made by the group of users. This is in contrast to the approach taken by Blanchard and Fabrycky that calls for the engineer or design team to determine which system alternative or approach is preferred.\(^4\)

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4. Decision making in this way will require that system synthesis and definition and the preliminary design review not be enacted until the system approach is selected by the users through the decentralized decision mechanism.
III. THE DECISION ENVIRONMENT

3.1 Decision Making

3.1.1 The Decision Process

Organizations adopting the Systems Engineering Process will encounter the need to make many decisions during the development phase. "Decision making is the process of selecting a possible course of action from all the available alternatives (Hwang and Masud, 1979)." The decision process is enabled by a decision mechanism and is preceded by (1) the determination that a situation exists in which the making of a decision would be beneficial, and (2) the formulation of alternatives. The selection and implementation of an alternative is facilitated by a decision mechanism. It will be shown in Chapter Five that the use of the Systems Engineering Process may be used to implement step two of the decision process, but does not address step three. In addition, SE does not directly address the choice of a decision mechanism.

3.1.2 Indicators of Need

Whether organizations are privately or publicly run, the determination that decisions must be made can originate from two sources: (1) externally (i.e., through informal channels), or (2) internally (e.g., by the use of an internal performance measurement system).

As shown in the Management System Model (MSM) (Figure 3.1), decisions will result from information provided by internal measurement systems (Kurstedt, 1989). Since the MSM is based on a closed system, it may be necessary to
Figure 3.1 The Management System Model (Kurstedt, 1989)

Figure 3.2 The Modified Management Systems Model (Sink and Tuttle, 1989)
formulate a linkage between system users who are external to the system and managers within the system (Figure 3.2) as postulated by Sink and Tuttle (1989). In the former case, if a measurement system exists, then indicators may exist to indicate that decisions must be made. If the measurement system is inadequate, or does not exist at all, then a linkage must be established between management and the users. Therefore, it can be concluded that an internal measurement system is necessary but not sufficient to provide all information used by the organization. In addition, the continuous improvement of measurement systems (as suggested by Sink and Tuttle) is necessary for the survival of organizations, but does not ensure that organizations will have all needed information to make decisions.

According to Sink and Tuttle (1989), the measurement system modifications should originate from strategic plans. Therefore, it can be concluded that only changes in the environment that were anticipated will be represented by the internal measurement system. As such, it can be said that change will be necessitated by external or internal changes. If the change is internal, then it should be accounted for by some internal measure. If the change is external to the organization, then the measurement system may account for it if it was planned for. If the change was not planned for, then information must be gained informally for the organization to detect it. This leads to the conclusion that there are two classes of change (1) planned, and (2) unplanned.

To show that organizations use both formal and informal information to make decisions, picture all of the data in the world at one instant in time being contained in a set R. It can be concluded that both versions of the MSM contain
a formal function \( F(R) \) where \( F:R \to S \) forms a set \( S \). Now it can be seen that \( S' \) is all information in \( R \) that is excluded by \( S \). If it is to be believed, as assumed by both versions of the MSM, that the organization is a closed system, then decisions can never be made using information in \( S' \). But it is well documented that organizations routinely make decisions using information that is not formally gathered. So in this case the rational (or closed system) view of an organization breaks down (Thompson, 1967).

This leads to the conclusion that information to make decisions is gained formally and informally (Barnard, 1938; Thompson, 1967). It is further implied that a decision can be based upon information gained from both informal and formal channels. From this, it becomes obvious that a decision is, in reality, a function \( D \), and uses information contained in both \( S \) and \( S' \). Now, it can be seen that (as Thompson states) views directly concerned with closed-systems or open-systems, tend to distort the models they create, and hence, will break down when placed under scrutiny.

In summary, information used to make decisions arrives from two sources. Closed-system models ignore information gathered from informal sources. By the strict definition of a closed system, an organization may never know a problem exists because they have failed to measure it. It is known from experience that this is not usually the case. Therefore, it is known that organizations are neither completely closed nor open systems. From this, it is known that information comes from both informal and formal sources on a regular basis. Finally, closed system representations of organizations will account for planned change, but may fail to account for unplanned change.
3.1.3 A Means to Account for Unplanned Change

Since it is known that organizations will react to unplanned change, a process must be provided to reflect this change within the organization's measurement system. One technique that may be used (after information is gained formally or informally that a change has occurred) is the Quality Function Deployment Process. The process allows organizations to determine user requirements for a product or system, and then convert these "attributes" into detailed engineering measures (Hauser and Clausing, 1988). The Quality Function Deployment Process, developed by Akao in 1966, provides a means of building desired levels of quality into a product (Akao, 1990). The Quality Function Deployment Process is conducted early in the design process to enhance the design quality and minimize design changes. It is important to realize that planning for design quality should extend over the entire system life cycle (i.e., quality levels during design, production, utilization, and phaseout should be studied).

In industry and government, there is a tendency to ignore some of the phases of the system life-cycle. This failure to recognize the importance of all phases of the system life-cycle (especially phase-out/disposal) may have serious consequences. Take for example the problem that nuclear power generation has created. At this time, the Department of Energy is struggling to dispose of waste that has already been created. And worse, no short-term solution exists. If planning for disposal had been conducted, we may never have used nuclear power. This points to the need for a process such as Quality Function Deployment to evaluate quality elements of a product or system over all phases of the system life cycle.
Quality Function Deployment depends on the development of three charts (Akao, 1990). These are: (1) the demanded quality chart, (2) the quality elements deployment chart, and (3) the quality chart. The demanded quality chart provides information collected from consumers concerning the quality attributes and desired quality levels for a product. The quality elements deployment chart is a list of elements contained within a product that, when taken as a whole, constitute the product's overall quality (i.e., how we can measure the quality of the product). The quality chart forms the linkage between the quality elements deployment chart and the demanded quality chart. Further, the quality chart may be used to represent the dependencies that exist between consumer attributes and performance measures.

The demanded quality chart requires the solicitation of information about quality from consumers. Several techniques exist that enable this step. Some of these are: (1) parametric estimation, (2) conjoint measurement, (3) surveys/questionnaires, and (4) internal measurement systems. Some organizations collect information by positioning their product and some design staff where they can get direct feedback from consumers. For example, one Japanese automobile company determined the best design for a trunk opening by parking the car at a supermarket and asking shoppers to try it (Clausing and Hauser, 1988).

It should be noted that all three charts (demanded quality, quality elements, and quality) can be represented on a single chart called the House of Quality (Clausing and Hauser, 1988). The House of Quality (Figure 3.3) allows the system design staff to enter information concerning desired consumer
Figure 3.3 An Example of the House of Quality (Clausing and Hauser, 1988)
attributes and their respective levels of importance. These consumer attributes are then linked to technical performance measures (i.e., ways of measuring system/product performance). These measures are specific to a portion of the system life-cycle, and thus, one House of Quality should be constructed for each phase of the life cycle. This will ensure that all relevant information that affects consumer satisfaction is assessed and addressed early in the system life-cycle.

When applied to competitive products, the House of Quality allows system developers to compare their organization's product performance against other organization's product performance. In this way, the House of Quality can be used to derive the most profitable areas for improvement. In the case of government activities, the House of Quality may be used to identify the areas that contribute the most benefit for the least cost. After the best areas for improvement are made explicit, a process such as Systems Engineering may be used to develop product/system alternatives.

3.1.4 Formulation of Alternatives

Formulation of alternatives, as the step directly preceding the alternative selection process is essential to ensure that (1) all facets of the decision to be made are identified and understood, and (2) all possible solutions to the problem (where feasible) can be formulated. Since decisions can range from relatively simple (e.g., the selection of a single personal computer) to extremely complicated (e.g., the selection of a network comprised of computers, satellites, and ground antennas) the formulation of alternatives will also vary in time and complexity. It is also apparent that the number of staff members and their knowledge will vary according to the complexity of the decision to be made. The
process taken to formulate alternatives generally will not depend upon the level of system complexity. By this, it is meant that the formulation of alternatives usually follows a specific set of steps or prescribed sequence.

3.1.5 Alternative Selection

Alternative selection is the final step in the Systems Engineering Process considered in this thesis. It also constitutes the final step in the decision making process and involves comparing alternatives by the use of specific rules. Selecting one or more of the alternatives for implementation based upon the decision making process outcome concludes the effort.

The decision making process is facilitated by a decision mechanism containing the set of rules by which alternatives will be compared. Choice of an alternative selection mechanism will depend upon several factors. Some of them are: (1) knowledge of the staff, (2) complexity of the decision to be made, (3) desired accuracy of the device, (4) desire to convey constituent understanding, (5) amount of time allowed to make decision, and (6) amount of funding allocated to the decision making process. Implementation should be concerned with the provision and operation of the system, along with the establishment of measurement devices to assess the system's performance.

3.2 Decision Mechanisms

Alternative selection, as the final step considered in the Systems Engineering Process, necessarily begins with the adoption of a decision mechanism. Decision mechanisms can be classified into two broad categories: (1) centralized and (2) decentralized. The objective of mechanisms in both categories is to choose the
best alternatives from a set of alternatives, but the way in which selection occurs differs significantly depending upon whether the selection mechanism is centralized or decentralized.

Some mechanisms are inferior to others in certain situations. The purpose of this section is to discuss some mechanisms that exist in each category, and then to discuss their relative merits and deficiencies. It is not the intention here to cover every possible decision mechanism that exists, but rather to cover each category in a sufficient manner so as to convey the reason for choosing the Demand-Revealing Process over all others for the decision domain covered by this thesis.

3.2.1 Centralized Mechanisms

Centralized mechanisms can be divided into three categories: (1) monetary, (2) weighting approaches, and (3) utility theory. Monetary decision mechanisms facilitate selection of alternatives based upon evaluation over the expected cash flow profiles for all alternatives. Weighting approaches facilitate alternative selection by ranking and subsequent rating of decision selection attributes and then comparing all alternatives actual performance based upon the rating scheme. Utility mechanisms attempt to assess the aggregate or multiplicative level of desirability a user has for a specific alternative based upon level of preference for specific performance attributes.
3.2.1.1 Monetary Decision Mechanisms

Three decision mechanisms in this category will be discussed: (1) numerical criteria, (2) cost-benefit analysis, and (3) deterministic capital budgeting models. Numerical criteria and cost-benefit mechanisms facilitate selection of the best alternative based solely on life cycle cost. It should be noted that cost-benefit is a special case of numerical criterion and is generally only applicable to public activities. Since numerical criterion and cost-benefit mechanisms are concerned solely with life-cycle cost, they may fail to consider intangible factors such as perceived quality and its effects on re-purchase, obsolescence of the product, etc. (Park and Sharp-Bette, 1990). Deterministic capital budgeting models alleviate some of the criticisms of numerical criteria and cost-benefit mechanisms, but fail to consider risk and uncertainty (Park and Sharp-Bette, 1990).

In the case of numerical criterion mechanisms, a certain discount rate is chosen (usually the minimum attractive rate of return - MARR), and the alternative with the least present equivalent life-cycle cost is selected. Numerical criteria mechanisms are comprised of a host of numerical criteria methods. In fact, an analyst could use any one of ten criteria to accomplish this type of alternative selection. As Park and Sharp-Bette point out though, "...the proper use of any of the ten criteria will always result in decision consistent with present equivalent (PE) analysis (Park and Sharp-Bette, 1990)." Therefore, selection of the best alternative can be facilitated by using the MARR or another discount rate and calculating the PE (i.e., in today's dollars) for an alternative. Alternative selection will be based on the most positive present equivalent life-cycle cost (if profit is required) or the least negative present equivalent life-cycle cost (if
selection involves new equipment with tax considerations and revenues cannot be directly attributed to equipment).

Many assumptions are required for the correct implementation of this mechanism. One is that the alternatives life lengths must be the same. If they are not, then one of two assumptions must be made. Either it must be assumed that re-investment will occur until the least common multiple of all alternative's lives are met, or the alternative with the longer life will have its salvage value (if any exists) adjusted upward to coincide with retirement of the shorter lived alternative, less other cash flows adjusted to the horizon. In many cases both are poor assumptions. One problem associated with the first assumption is that different lending rates could occur over these long lifetimes. The main problem associated with the second assumption is over or under statement of the salvage value. This adjustment of the salvage value may be enough to prevent selection of the best alternative.

Another problem with numerical criteria is the difficulty involved in selecting the MARR (Kaplan, 1986). In many cases, organizations choose an MARR that is too high and, as such, reject many projects that would have been acceptable. One reason given for overstatement of MARR is the use of constant dollar values for expenses and revenues, while simultaneously using an MARR that included inflation (Kaplan, 1986).

Numerical criterion mechanisms are sufficient for selection of small systems where parameters such as reliability, quality, and other performance characteristics do not have to be explicitly addressed. But in the development of large-scale systems (such as satellite systems) numerical criterion mechanisms
would not be sufficient in themselves to lead to the best alternative. It has also been indicated that satisfactory results are obtained when numerical criteria alone are used in system selection at the shop-floor level (Kaplan, 1986). Therefore, we may use numerical criteria at low levels (e.g., deciding between two lathes) and other mechanisms at higher levels (e.g., deciding whether or not to automate the shop).

Cost-benefit mechanisms are a special case of numerical criterion mechanisms (Thuesen and Fabrycky, 1989). Cost-benefit mechanisms are often applied in public activities when it is possible to identify constituent benefits, disbenefits, and costs. Benefits are monetary expressions denoting the level of satisfaction constituents will gain from the system. They can be in the form of real savings (e.g., a reduction in taxes due to subcontracting) or non-monetary savings (e.g., the widening of a road may save constituents time in traffic). Likewise, disbenefits are the amount of dissatisfaction a constituent experiences with a system. Costs are the amount in dollars experienced if the alternative is selected. It should be noted that cost-benefit should be done using life-cycle costs. A MARR or borrowing rate should be selected as a basis for choosing the alternative with the best incremental PE(benefits) divided by PE(costs).

It should be noted that real savings are typically easy to quantify (although these may be expected values, and thus, not reflect variance), while the non-monetary savings are difficult to quantify. This difficulty is further extended since all non-monetary savings must be termed in dollars. For some problems it may be difficult to express benefits in dollars. For example, how can the proposed widening of a road and the resulting savings in lives be put in terms of dollars?
The cost of widening the road may be well known, but it is not likely that all constituents will value life the same. If they do not, then how can a dollar saving per life be derived? Cost-benefit also is subject to the assumptions made for numerical criteria. If alternative lives are different then as in numerical criteria one of the two stated assumptions must be made.

The main assumptions made when using numerical criteria techniques are (Park and Sharp-Bette, 1990):

1) Mutually exclusive alternatives can be easily formed and listed.

2) "There is an underlying assumption of [the] ability to borrow and lend unlimited amounts at a single, fixed interest rate. When budget limits are imposed, the borrowing ability at time 0 is restricted, and we are left with a single, fixed interest rate for future lending, or reinvestment."

Deterministic capital budgeting models alleviate some but not all of the difficulties encountered with numerical criteria mechanisms. With capital budgeting models, the imposition of project limits and interdependencies can be handled. Deterministic capital budgeting models can be placed in one of three categories: (1) present value objective function, (2) horizon models, and (3) multiple criterion variables (Park and Sharp-Bette, 1990). Models in the third category can handle objective functions variables that represent non-monetary resource constraints (e.g., manpower limitation) (Park and Sharp-Bette, 1990).

Deterministic capital budgeting models generally yield results that are superior to numerical criteria methods, but fail to consider the effects of uncertainty and risk. In addition, these models are of a linear form, and hence, cannot handle non-linear objective functions and constraints.
3.2.1.2 Weighting Approach Mechanisms

Weighting approach mechanisms are typically used when evaluation is across many candidate systems (Boehm, 1981; Keeny and Raiffa, 1976). Decision makers will first rank all system decision attributes. After ranking is completed, ratings will be assigned to attributes. This ranking is usually done in descending order. Actual performance or expected performance of candidate systems is then placed against the rating criteria and either a multiplicative, additive, or a combination of both weights against criteria is used to select the best alternative.

It has been noted that weighting approaches tend to wash out system effects that, at the time of analysis, do not seem to be important, but later are found to have a great impact on overall system operation. One case in which this happened is described by Boehm (1981). It is as follows: During the selection of a computer system, all important performance measures were identified, and relative levels of importance placed on them by the prospective users. After selection of the computer, jobs were not being processed as fast as was initially desired. Upon inspection of the weighting approach mechanism, it was found that the measure, throughput, was assigned a relatively low weight. Consequently, other desirable qualities of the system selected, and their respective weights, washed-out the "effects" of low throughput during decision selection.

A problem associated with weighting approach mechanisms (in addition to the one noted above) is that even if quadratic or polynomial forms are expressed as weights, the problem of identifying and quantifying all benefits still exists (Keeny and Raiffa, 1976). Here again, as in cost-benefit analysis, it may not feasible to
quantify all benefits in like terms. In cases such as these, utility theory approaches would be preferred.

Weighting approach mechanisms are considered to be superior to numerical criteria in some cases. This is because the preference's of the decision maker can be partially accounted for by the weights placed on their respective attributes. However, weighting approach mechanisms do not provide results that are as good as utility function mechanisms.

### 3.2.1.3 Utility Functions

Utility functions are decision mechanisms that allow analysts to select an alternative from a set of alternatives based upon several objectives and their corresponding attributes. "The major advantage of utility function methods is that if [the decision maker's utility function] \( U(f) \) has been correctly assessed and used, it will ensure the most satisfactory solution to the [decision maker] DM (Hwang and Masud, 1979)." This observation leads to the conclusion that some method must be employed to elicit the decision maker's utility function. We can say functions here, because we will need a utility function for each attribute we wish to assess (Keeny and Raiffa, 1976). For alternatives that are complicated, a large number of attributes may exist. This makes utility function mechanisms time consuming to use since a utility function must be created for each attribute associated with the system. However, utility mechanism's ability to deal with risky and uncertain projects have made them quite important techniques.
There are five axioms of utility theory (Park and Sharp-Bette, 1990)\(^5\). These axioms specify behavior characteristics of individuals. It is assumed that individuals will follow these axioms during decision making. The five axioms are: (1) orderability, (2) transitivity, (3) continuity, (4) monotonicity, and (5) decomposability. Orderability states that preferences can be established between any two alternatives. For two alternatives \(X\) and \(Y\), the individual (1) Prefers \(X\) to \(Y\) is written by \(X > Y\), (2) Prefers \(Y\) to \(X\) is written by \(X < Y\), and (3) Is indifferent to \(X\) or \(Y\) is written by \(X - Y\). Transitivity is defined as: If \(X > Y\) and \(Y > Z\), then \(X > Z\). In addition, if \(X - Y\) and \(Y - Z\), then \(X - Z\). Continuity states that there exists a probability \(p\) for which the individual is indifferent to receiving \(X\) with a probability of \(p\) and \(Z\) with a probability \((1-p)\) or a certain amount \(Y\) if \(X > Y > Z\). Monotonicity implies that for two alternatives \(X\) and \(Y\) where \(X > Y\), and two lotteries with probabilities \(p_1\) and \(p_2\) where \(p_1 > p_2\) involving only \(X\) and \(Y\), an individual will prefer the lottery \((p_1, X)\) over \((p_2, X)\). This can be written as \(\{(p_1, X), (1-p_1, Y)\} > \{(p_2, X), (1-p_2, Y)\}\). Decomposability, sometimes called the no fun in gambling axiom, states that "a risky option containing another risky option may be reduced to its more fundamental components (Park and Sharp-Bette, 1990)."

Use of utility function mechanisms requires that utility user's utility functions be developed. The development of an individual's utility functions will follow one of two approaches: (1) the numerical approach or (2) the functional approach (Park and Sharp-Bette, 1990). Both methods rely on developing an individual's

\(^5\) It should be noted that some authors consider some of the given axioms to be subsumed by others. For example, Fishburn offers three axioms: Order, Independence, and Continuity.
certainty equivalent (CE), but differ in that for the latter case, a functional representation of the utility function must be postulated in advance.

"A certainty equivalent is a certain cash amount that an individual values as being as desirable as a particular risky option (Park and Sharp-Bette, 1990)."

The following example shows how to determine a CE for a specific prospect.

Prospect 1: Assume that an individual with zero wealth is told that he may win $10,000 or nothing at all. The probability of winning $10,000 is stated to be $p = 0.5$, while the probability of winning $0$ is stated to be $1 - p = 0.5$.

Prospect 2: Now ask the individual what amount of money, $C$, with a probability of $p = 1$ provides the same value as Prospect 1.

This amount $C$ is the individual's certainty equivalent (CE), and is be the amount that would make the individual indifferent to choosing Prospect 1 or Prospect 2. Now, if the individual is presented with a choice between a certain prospect where the amount is less than $C$ and prospect 1, the individual will choose Prospect 1. However, if the individual is presented with the choice between a certain prospect whose payoff is greater than $C$, the individual will choose the new prospect.

An individual's utility function may be developed by constructing many such risky prospects (termed lotteries) (e.g., Prospect 1), and then determining each CE. If a utility functional form has been postulated, then only one lottery is required to develop the complete function. However, if the numerical approach were chosen, then several lotteries are required to develop the utility function.
It should be noted that utility functions for non-monetary measures of system performance can be developed by the use of lotteries. The lotteries would follow the same form as that given above, and would rely on: (1) the postulation of a functional form, or (2) utilization of the numerical approach.

It is generally recognized that utility analysis yields better results than the other centralized decision mechanisms (Keeny and Raiffa, 1976). While it has been indicated by Keeny and Raiffa (1976) that utility based decision mechanisms are superior to the other forms of centralized decision mechanisms discussed, they are not always the most convenient mechanism to use. This is because it is particularly difficult to develop utility functions for individuals. Further, it is even harder to develop utility functions for groups. Since many decisions that must be made are dependent upon group concensus, it is necessary to use methods for establishing group utility functions. Because of the volatile nature of individual utility functions (i.e., susceptibility to change over time) (Fishburn, 1988) it is suspected that group utility curves must be more volatile.

Research has shown that utility function mechanisms suffer from several deficiencies. Some of these deficiencies violate the five axioms. The violations are: (1) framing effects, (2) preference reversal, (3) preference cycles, (4) nontransitive indifference, (5) certainty effects, (6) inability to handle probabilities in the loss region (7) overvaluation of small probabilities and undervaluation of large probabilities, and (8) common ratio effect (Fishburn, 1988).

Framing effects occur when the answer given depends upon the way a question is asked. Therefore, the way questions are asked will have a great consequence of
the resulting utility function. Preference reversal occurs when an individual states A > B, but then states CE(A) < CE(B). This indicates that the individual prefers A to B, but prefers the certainty equivalent of B to A. Preference cycles occur when an individual states (1) A > B > C > D > A, or (2) A > B > C - A. Both are cases of nontransitive preference patterns. The first case is referred to as a cycle, and the second as non-cyclic. Nontransitive indifference occurs when an individual reports A - B, B - C, and A > C. Certainty effects occur when an individual is faced with two independent prospects whose payoff is the same, but have probabilities associated with them that are proportional (i.e., a common ratio of probabilities is shared). For example, an individual faced with revealing a preference for \( \{g: g = \$10,000 \text{ with a probability } p = 1\} \) or \( \{h: h = \$30,000 \text{ with a probability } p = 0.98\} \) will usually choose g since the pay off is certain. Now, when the individual considers two prospects \( \{i: i = \$10,000 \text{ with a probability } p = 0.50\} \) and \( \{j: j = \$30,000 \text{ with a probability of } p = 0.49\} \) will usually choose j over i since the difference in the probabilities are small and the payoff is great. However, this violates an axiom and is known as the certainty effect. The common ratio effect is similar to the certainty effect, but certainty does not enter into the selection. In this case, as the probabilities increase proportionally, decision reversal will occur. Another common violation of the five axioms occurs when individuals overvalue small probabilities and undervalue large probabilities. It was shown by Fishburn (1988) that "if \( T(L) \) denotes a person's valuation of probability \( L \), with \( T(L)x \) the holistic value for a random prospect with probability \( L \) for \( x \) and 1 - \( L \) for 0, then \( T(L) > L \) for small \( L \), \( T(L) < L \) for large \( L \) (Fishburn, 1988)." Further, it was shown that \( T(0.2) \) approximately equaled 0.2.
It is concluded here that decision mechanisms employing utility functions are the best of the centralized decision mechanisms, but are also the most time consuming and costly centralized mechanisms to use because of the necessity to make decision maker's utility explicit for each attribute. Therefore, to get the best results from a centralized decision mechanism, utility analysis must be employed.

3.2.2 Decentralized Mechanisms

Decentralized mechanisms are voting procedures, and fall under the area of collective action. "The goal of collective action is the improvement of allocative efficiency not the achievement of distributive justice (Mueller, 1979)." That is, there is a desire to retain as many resources as possible after the alternative selection, and no effort is made to allocate resources among constituents in a fair manner. In decentralized decision making, constituents influence alternative selection directly by providing their preferences to a Central Agency (Figure 3.4). Research has been conducted in the areas of political science and public choice to determine the best voting mechanism under varying conditions. New mechanisms have emerged in recent years as a response to deficiencies inherent in mechanisms employing the unanimity rule, or the majority rule (Mueller, 1979). One such mechanism is the Demand-Revealing Process.

The Demand-Revealing Process may be used to select the preferred alternative from among several mutually exclusive alternatives. The process works by providing information (e.g., life-cycle cost, expected performance, etc.) to constituents concerning the set of available alternatives. The individual constituent then reports how much they will be willing to pay to retain one
Figure 3.4 A Model of Decentralized Decision Making
alternative (a tax is based upon this amount). To avoid the possibility of cycling (e.g., a voter chooses A > B, B > C, and C > A or C < A) comparison can be restricted to the do nothing alternative (e.g., A against D_n, B against D_n, etc). Demand-Revealing processes avoid many problems associated with centralized decision mechanisms, but do have problems of their own.

Demand-Revealing Processes do not require that objectives be formed. Not requiring that objectives be formed is important since each user may have his or her own set of objectives and, as such, it may be impossible to form the complete set of all user's objectives. Probably the best feature of Demand-Revealing Processes derives from this property since objectives do not have to be defined, specific attributes do not have to be aggregated centrally. Not requiring attributes be formed means that a mechanism does not have to be employed to aggregate all desires based upon many attributes. Aggregation results since user's are asked to specify an aggregate amount they will pay to retain an alternative.

It should be clear that reporting preferences in this fashion greatly simplifies analysis at the central level. However, in effect, by employing a mechanism of this type, we have shifted analysis to determine preferences from the Central Agency to all users. By requiring a single preference for an alternative, the Demand-Revealing Process requires that all users determine their own set of objectives, attributes, and benefits, and then report to the Central Agency their preference for an alternative. To enable this, the Demand-Revealing Process requires that each user receive information from the Central Agency, and then must employ some centralized decision mechanism to determine their net
benefits (e.g., benefit less cost, performance gains, etc. for each alternative). Centralized mechanisms employed by the users can be any of those identified in this thesis, or others that are not discussed. Therefore, users employing sophisticated decision mechanisms may achieve better estimates of their set of expected net benefits, and hence, understand their preferences' better than those using less sophisticated mechanisms.

The Demand-Revealing Process may be quite costly to use, and as such, should not be employed unless group consensus is required. Other limitations of Demand-Revealing Processes are: (1) income effects, (2) information incentives, (3) coalitions, (4) bankruptcy, and (5) cycling (Mueller, 1979; Groves and Ledyard, 1977; Tideman and Tullock, 1976). Techniques have been developed to address these deficiencies, and will be discussed briefly here. A more in depth treatment of these deficiencies will be offered in Chapter four and Chapter five.

Income effects are caused by the fact that since users "...will not know precisely how much income they have, they will not be able to specify exactly how much they would be willing to pay for public goods (Tideman, 1983)." It follows then that income effects occur when the value placed on the good by an individual is not independent of the individual's wealth (Groves and Ledyard, 1977a). In this case, strategizing by the individual may occur, since the tax collected may have an effect on other's incomes (Groves and Ledyard, 1977a). It was noted by Groves and Ledyard (1977a) that no equilibrium point for the process might not be reached if income effects occurred. This is because the Demand-Revealing Process would start cycling and no solution would be reached. Tideman however has argued that income effects would be of little consequence since the goal is to
"...elicit one set of responses and come to a final decision (Tideman, 1983)." In any case, techniques to control or interpret cycling are well known and may be applied here.

Information incentives deal with the fact that as the number of voters increase, the tax imposed will decrease (Mueller, 1979; Tideman and Tullock, 1976). As the level of tax decreases, so to will the incentive to vote. Thus, if there are many voters, then the tax will be low and the information collected presumed to be inaccurate. If the number of voters is small, then the taxes will be high, and the information collected presumed to be accurate. In short, this phenomenon can be explained by the observation that when the number of voters is large, individual voters will feel that their vote will make little difference. Therefore, they will have little incentive to collect information from, and provide information to, the Central Agency. Thus, it follows that the information collected from these voters will be inaccurate since they are practicing uninformed voting (Tideman and Tullock, 1976). Measures designed to thwart information incentive problems rely on either systems of representatives (Clarke, 1977) or sampling techniques (Tullock, 1977). However, as pointed out by Mueller (1979) these measures allow for coalitions. It should be noted that coalitions would not normally exist without the introduction of these other measures.

Coalitions are formed when a group of voters feel they will be better off by a certain amount (e.g., $500) if an alternative (e.g., A) is selected. The coalition is then formed when all members in the coalition agree to overstate their preference for alternative A by reporting the amount they will pay to retain A
equal to $1,000. If A won by more than $1,000, or less than $500 "...they would be better off under the coalition than acting independently (Mueller, 1979)." Tullock (1977) though has argued that "...coalitions would be difficult or impossible to organize because...the coalition provides public good benefits which will motivate people to conceal their preferences (Clarke, 1977)."

In addition, bankruptcy may occur. This situation may arise, and is defined by the condition in which an individual loses all of his/her wealth following implementation of the Demand-Revealing Process (Groves and Ledyard, 1977a). As Mueller points out though, "...this is true with almost any voting procedure other than the unanimity rule, however, and is probably not a serious, practical problem (Mueller, 1979)." In addition, Tideman (1983) points out that if bankruptcy occurred, it would be as a result of the tax imposed by the Demand-Revealing Process, and for most cases, would be of little consequence. However, this does point to the need for some controls to prevent bankruptcy from occurring both by the tax, and in the case of completely supported goods, from the cost to enact a certain alternative.

Cycling may also occur in demand-revealing mechanisms (as in utility function mechanisms) if more than two alternatives are offered (Tideman and Tullock, 1976). However, many mechanisms exist to handle cycling problems. For instance, by restricting choices to (1) no more than two alternatives or (2) more than two alternatives with comparison of each only against the do nothing alternative, no cycling can occur.

In addition to the problems listed above, several other serious problems with the Demand-Revealing Process were reported. It was suggested by Kormendi
(1978) that the Central Agency may incur heavy administrative costs brought on by a large number of proposals. Tideman (1980) though replied that an agenda fee could be imposed if the number of proposals submitted were generating high administrative costs. It was also noted at that time that demand-revealing mechanisms have two additional problems that have not been fully explored. They are as follow: (1) "...decisions made by the Demand-Revealing Process may not be beneficial for all participants," and (2) "...the interests of different persons are weighted by their valuations in money terms (Tideman, 1985)." Problem two "...gives the process a bias against persons who have relatively little wealth (Tideman, 1985)."

3.3 Comparison of Decision Mechanisms

Of the centralized decision mechanisms reviewed, those mechanisms that rely on utility functions may yield the best results, both in the face of certainty and uncertainty, when the conditions stated in Section 1.3 are binding. However, as discussed, this class of centralized decision mechanisms has several problems: (1) the number of utility functions to be created rises proportionally to system complexity, (2) utility functions are highly subject to change (i.e., they are volatile), (3) groups may have conflicting objectives, and (4) utility functions may violate several axioms.

Many of the objections to utility function mechanisms may be overcome by the use of Demand-Revealing mechanisms. The Demand-Revealing class of decision mechanisms may yield results as good as those that could be obtained by the use of utility functions. This can be said because both utility function mechanisms and Demand-Revealing mechanisms measure overall preference
for a specific alternative. In addition, while Demand-Revealing mechanisms do have some problems associated with their use, techniques have been developed to handle them. For example, by controlling the usage (e.g., allowing only comparison to the do nothing alternative) of Demand-Revealing mechanisms, we can eliminate cycling and income effects. Some of these control techniques and the development of Demand-Revealing mechanisms will be discussed in Chapter Four.

When the condition stated in Section 1.3 are binding, Demand-Revealing mechanisms may accomplish the selection of alternatives as well as, or better than, utility function mechanisms, and with less time and cost involved. The use of Demand-Revealing mechanisms will require, as with all decision mechanisms, the knowledge that a decision must be made and the subsequent development of alternatives. However, Demand-Revealing mechanisms will also require that constituents be educated, and that the Central Agency administering the process provide sufficient information at the correct times so that the constituents may make informed decisions. In addition, because of the costs involved with the conducting the Demand-Revealing Process, the Central Agency must limit the use of Demand-Revealing mechanisms to only decisions that truly require group consensus. Finally, the problems inherent within Demand-Revealing Processes must be rectified to ensure satisfactory results.
IV. THE DEMAND-REVEALING PROCESSES

4.1 Demand-Revealing Principles

A decision must be made to determine if a highway improvement project should be funded. In this case, two mutually exclusive alternatives have been identified along with their relative merits and associated costs: (1) fund the project, and (2) do not fund the project. For simplicity, it will be assumed that only four users exist, and each has been told they will share all costs involved with the highway such that

\[
\text{Total Cost} = T_1 + T_2 + T_3 + T_4,
\]

where \( T_i \) is the \( i \)th user's portion of the total cost.

We now wish to determine whether or not to proceed with the project by enacting the Demand-Revealing Process as follows. First, we must determine each voter's preference for the two alternatives. Voter's preferences are how much they will pay to retain a specific alternative from among a set of mutually exclusive alternatives. Therefore, it is quite possible that a voter may choose to pay an amount to avoid widening the highway when faced with the share of the cost \( T_i \) they must incur if the highway is widened. Individual voter's preferences for these two mutually exclusive alternatives are displayed in Table 4.1.

A tax is collected from a voter if their vote has an effect on the final selection of the alternative. In other words, if the voter had not participated, the other alternative would have been selected. An example of this can be seen in the calculation of Voter One's tax share. From Table 4.1, Voter One has stated his/her preference for the road widening alternative to be $70. Now, the total
Table 4.1  The Demand-Revealing Mechanism Applied to the Road Widening Problem

<table>
<thead>
<tr>
<th>USER</th>
<th>REPORTED PREFERENCES FOR TWO ALTERNATIVES</th>
<th>ALTERNATIVE 1: WIDEN ROAD</th>
<th>TAX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALTERNATIVE 0: DO NOT WIDEN ROAD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td><strong>Totals</strong> 100</td>
<td><strong>120</strong></td>
<td><strong>80</strong></td>
</tr>
</tbody>
</table>
preferences for not widening the road are reported to be $100. If Voter One had not voted, then the not widen the road alternative would have been selected. Therefore, it is apparent that Voter One's reported preference has affected the alternative selection (i.e., without Voter One, decision reversal occurs).

As stated before, a tax is only levied if the voter's reported preferences change the alternative selection. In this case, the not widen road alternative would have been selected if Voter One had not voted. The tax levied on Voter One then is the difference between all benefits for the losing alternative less all preferences reported for the winning alternative (less Voter One's preference). For Voter One, this is: $100 - $50 = $50. The tax levied on Voter Three is similarly calculated. It is: $100 - $70 = $30. Thus, the total tax levied is: $50 + $30 = $80.

It should be noted that "a voter only pays a tax if his vote is decisive, and the tax he pays is always equal to or less than the benefits he receives (Mueller, 1979)." Because of this, "there is no incentive to understate one's gains, for then one risks foregoing the chance to cast the deciding vote at a cost less than the benefits (Mueller, 1979)." Likewise, "there is no incentive to overstate one's preferences, since this incurs the risk of becoming the decisive vote, and receiving a tax above one's actual benefits albeit less than one's declared benefits (Mueller, 1979)." Therefore, it is in the best interest of the voter to reveal his true preference for the alternative. Hence, the term demand-revealing.

Any tax collected as a result of the Demand-Revealing Process should be thrown out of the system. This is because the desirable properties stated above will be "distorted" if voters know that some of the money collected as taxes will be
placed back into the system (i.e., they will realize that they will accrue additional benefits from this money, and hence will overstate their preferences). Throwing away the tax does create a problem in itself, because now the system will be inefficient. In fact, the amount of inefficiency in the system is exactly the tax amount. It should be readily apparent that it is desirable to minimize this amount of tax. Another observation is that the quality of the analysis preceding voting will have a profound effect on this level of efficiency. Therefore, careful analysis is a prerequisite to ensure that an implementation of the Demand-Revealing Process will result in the lowest possible tax.

4.2 History of the Demand-Revealing Process

4.2.1 The Vickrey Mechanism

The Demand-Revealing Process has a rich history. The first form of the Demand-Revealing Process is attributed to a mechanism considered by William Vickrey to obtain user's true supply and demand schedules for private goods (Vickrey, 1961; Tideman and Tullock, 1976; Mueller, 1979; Loeb, 1977). The problem Vickrey addressed was how "...to attain efficiency in private goods markets when there are not enough buyers and sellers to bring about price-taking behavior (Loeb, 1977)." Vickrey approached the problem by defining a Central Agency "...which has the responsibility to bring about the optimal pattern of production and consumption (Loeb, 1977)." The mechanism works by first having the Central Agency collect supply and demand information from all users, and then determining "...the pattern of purchases and sales that maximize total reported social surplus (Loeb, 1977)." Next, "the center [i.e., Central Agency] collects as payment from each buyer: (1) the maximum reported social
surplus that the others could realize if the given buyer drops out of the market plus (2) the total reported costs of the sellers to produce the quantity exchanged less (3) the reported value to the other buyer of the quantity he receives (Loeb, 1977)." Finally, "the center makes payments to each seller equal to: (1) the total reported value to the buyers of the total quantity exchanged, less (2) the other seller's reported cost of production, less (3) the maximum reported social surplus others could realize, if the given seller drops out of the market (Loeb, 1977)."

Vickrey concluded by observing that "...suppliers and purchasers will maximize their profits, individually at least, by reporting correctly, so that any misrepresentation will subject them to risk of loss (Vickrey, 1961)." At the time, Vickrey dismissed this mechanism because of the inherent inefficiency involved. Basically, the Central Agency would operate under a non-negative deficit, and hence, would need to provide a subsidy so as to maintain equilibrium (Vickrey, 1961; Loeb, 1977).

4.2.2 The Clarke Mechanism

No further work with Demand-Revealing Processes was considered until papers published by Edward Clarke (1971, 1972) appeared that discussed a mechanism similar to the one offered by Vickrey to determine the allocation of public goods. According to Tideman and Tullock (1976), Clarke's papers had "...made little impact on the economics profession [until that time]...partly [because of] the nature of the idea Clarke put forward, which is counterintuitive to almost any welfare economist, and partly [due] to Clarke's difficult writing style." The mechanism is similar to the mechanism postulated by Vickrey since it attempts to get users to reveal their true preferences by means of a Clarke Tax. The tax
imposed in Clarke's mechanism has the same intent as that postulated by Vickrey, but is applied to public goods rather than private goods.

4.2.3 The Groves Mechanism

Clarke's papers were followed by a paper produced by Groves (1973) who discussed similar methods "...for allocating scarce private goods within an organization (Tideman and Tullock, 1976)." Entitled "Incentives in Teams," the paper discussed a technique for distributing scarce resources among entities within a firm. This approach developed by Groves described one possible solution to the problem of planning for resource allocation in large organizations. It was shown that resource planning in large organizations is analogous to the problems faced in centrally planned economies. The paper presented planning mechanisms for general organizations, and conglomerates.

In the case of general organizations, a team model was developed. The model relies on the assumption that the team shared a common objective, but does allow for team members possessing different information. For teams, "...the organization head's incentive problem [is to find] an optimal incentive structure, i.e., one inducing his employees to behave as if they formed a team (Groves, 1973)." "A payoff function reflecting the team's objectives and goals..." is developed, with the objective being to maximize the payoff function (Groves, 1973). Team members are paid based on the accuracy of the decisions they make. Thus, the team members are induced to make decisions that benefit the team rather than a sub-unit of the team.
The conglomerate model is similar to the team model, but differs in that a conglomerate is "...an organization consisting of many partially autonomous units linked only through a central administration (Groves, 1973)." Examples of a conglomerates are "...a large firm with many plants independently producing and marketing a wide variety of products, or a national economy with many sectors producing commodities in accordance with a centrally formulated national plan (Groves, 1973)." The problem with conglomerates is similar to the team problem in that the Central Agency wishes to maximize its return on resource allocation. To do this, accurate information must be received from the semi-autonomous units. Groves developed a reward system similar to the payoff function maximization technique used for teams that gave incentives for semi-autonomous units to reveal true information. This mechanism is again in the form of compensation.

Both models developed by Groves can be thought of as demand revealing mechanisms because they rely on taxing the members reporting needs to the Central Agency. If the information reported is inaccurate, then the member will pay a tax proportional to the error in the information. This tax is levied in the form of reduced income. Therefore, the more accurate the information reported, the more income the user will receive. This is a demand revealing mechanism since the user has sufficient incentive to reveal true information.

4.2.4 The Groves and Loeb Mechanism

In 1975, a paper by Groves and Loeb discussed a procedure similar to Clarke's for selecting the optimal quantities of public goods. The difference between Groves and Loeb's mechanism and Clarke's is in the calculation of the tax (Loeb,
1976). In all other regards, the mechanisms are the same. While Clarke's tax is the amount of surplus available to other consumers in the absence of a single consumer, the Groves and Loeb tax is the surplus available to other consumer in the absence of a single consumer plus "...consumer i's cost of the public good in the absence of coordination less the consumer's cost share, O_i, of the total cost of the public good without coordination (Loeb, 1977)." The advantage of the mechanism developed by Groves and Loeb is that it the tax guarantees that the Central Agency will incur a non-negative surplus (Groves and Loeb, 1975). This may be contrasted to the mechanism developed by Vickrey for which the Central Agency will "...run a non-negative deficit" when applied to public goods (Loeb, 1977).

4.2.5 The Groves and Ledyard Mechanism

A version attributed to Groves and Ledyard (1977) attempts to address the Free-Rider phenomenon that is prevalent in the provision of public goods. Basically, the problem is as follows: Public goods by definition may be consumed by several individuals simultaneously. One individual's consumption rate should have no effect on another's consumption rate. With a public good, such as a road, levels of use may start to impact individual's ability to use the road. In this case, the road is known as a congested public good.

A property of public goods is that it is not possible to exclude service to any users. A further restriction may be that it is not possible to restrict consumption of a good for a certain group of people. This type of good is a termed a club good (Buchanan, 1968), and is still a public good. Club goods, like all public goods, may suffer from congestion. This occurs when users within the group
decide to consume more of the good. In addition, club goods may suffer from availability. This occurs when more users are introduced into the system. Finally, club goods may suffer from congestion and availability problems at the same time.

The approach developed by Groves and Ledyard (1977) attempts to address a problem unique to public goods termed the Free-Rider problem (Buchanan, 1968). This problem occurs when a user is receiving more service than they are paying for\(^6\). This may happen when the user is paying no fee, or when they are paying a limited fee\(^7\). Further, the Free-Rider problem stems from the "reluctance of an individual to voluntarily support public goods (Stiglitz, 1988)." Efforts to thwart this are called rationing systems, and are of two types. First, the price may be raised to a level where the user will not want to pay for the good, or second, the amount of good that can be consumed may be limited by the formation of a long queue (Stiglitz, 1988). Raising prices is usually undesirable because, then the good becomes inefficient. The long queue solution seems to be the more preferred alternative in public activities because all people may consume the services if they want to. In addition the long queue serves the purpose of weeding out those people who really don't need the service. This is because the time spent on the queue may be more than the benefits the free-rider expects to receive from the service.

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6. Note that the good in question is public. Therefore, a consumer cannot be excluded from consumption of the good, nor can the consumption level be directly curtailed.

7. By the strict definition of public goods, a consumer pays no fee and may consume as much of the good as desired. A derivative of public goods known as impure public goods may not be infinitely consumable and may be charged for (Bodaway, 1979).
It should be noted that the Free-Rider problem is especially significant for group decision making. This stems from the fact that it may be more beneficial for an individual to not participate in the decision. The individual would still receive benefits since by the nature of public goods, it is not undesirable to exclude the Free-Rider. Since it is unlikely that any group decision reached without all consumer participating will be efficient, it becomes desirable to eliminate the possibility that some consumers may not participate if they do not want to. This may be done by implementing some rules that eliminate the possibility of non-participation. Thus, any potential Free-Riders will be forced to participate.

The mechanism developed by Groves and Ledyard (1977) overcomes some of the problems inherent in demand revealing mechanisms by restricting revelation to linear demand curves, as opposed to non-linear demand curves. It should be noted that the dominance property (i.e., given information about other user's preferences, the individual is still better off reporting their true preferences) does not apply to the Groves and Ledyard mechanism, but does apply to the Vickrey, Clarke, and Groves and Loeb mechanisms (Loeb, 1977). Groves and Ledyard note that since the dominance property is not satisfied, the mechanism "...is not, strictly speaking, a Demand Revealing Mechanism (Groves and Ledyard, 1977)."

4.2.6 Summary of Decision Mechanisms

Loeb (1977) provides a summary of these five versions (Vickrey, Clarke, Groves, Groves-Loeb, and Groves-Ledyard) of the Demand-Revealing process. Further,

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Loeb shows that the Vickrey, Clarke, and Groves and Loeb Demand-Revealing mechanisms differ only in that (1) they are either directed at public or private goods, and (2) the method of calculating and collecting the lump-sum sum charge varies from version to version. However, all share in common a tax designed to motivate users to reveal their true preferences.

4.3 Canonical Representation of Demand-Revealing Processes

The versions of the Demand-Revealing Process created by Vickrey, Groves and Loeb, and Clarke differ only by the means of calculating the lump-sum charge. These three versions of the Demand-Revealing Process have three important properties: (1) dominance, (2) centralization, and (3) full transfer of benefits (Loeb, 1977). The dominance property is that "...given any messages by the other agents, each individual is best off sending truthful information (Loeb, 1977)." The centralization property is that "...quantities are selected by the center to maximize reported net benefits (Loeb, 1977)." Finally, the full transfer property is that "...the center transfers to each agent the reported net benefits of all others at the quantities selected less a lump-sum charge, positive, negative, zero, which is independent of the agent's own reported benefits or costs [i.e., the imposed tax] (Loeb, 1977)."

The versions of the Demand-Revealing Process developed by Vickrey, Clarke, and Groves and Loeb are essentially optimization approaches, and as such, can be represented in canonical form. To do this, assume that $Q$ is the private or public good for which the Central Agency wishes to develop the optimal production and consumption schedules. Further, assume that there exist $n$ participants, $k$ users, and $n - k$ producers. $Q_i$ is then defined as the quantity
consumed by the $i$th user for $i = 1, 2, ..., k$, and the quantity to be supplied by the $i$th producer for $i = k + 1, k + 2, ..., n$. The inverse demand curve for the $i$th user is then denoted by $d_i(Q_i)$, while the inverse supply curve for the $i$th supplier is denoted by $s_i(Q_i)$. $D_i(Q_i)$ is then found by finding the integral of $d_i(q)$ from 0 to $Q_i$. This integral is the area under the $i$th user's demand curve from 0 to $Q_i$. $S_i(Q_i)$ may then be found by determining the integral of $s_i(q)$ from 0 to $Q_i$. This integral forms the area under the $i$th producer's supply curve from 0 to $Q_i$. From this, it can be determined that $D_i(Q_i)$ is the $i$th user's preference for consuming $Q_i$ units, while $S_i(Q_i)$ is the $i$th producer's cost of producing $Q_i$ units. With this information, the Central Agency may select the optimal pattern of production and consumption that can be represented by:

$$\hat{Q} = (\hat{Q}_1, ..., \hat{Q}_k, \hat{Q}_{k+1}, ..., \hat{Q}_n)$$

It can be further shown that $Q$ is the vector of production and consumption such that:

$$\hat{Q} \text{ Maximizes } \sum_{k=1}^{k} D_i(Q_i) - \sum_{k+1}^{n} S_i(Q_i)$$

with respect to $Q \in F$, where

$$F = F^1 = \{ (Q_1, Q_2, ..., Q_n) \mid Q_i \geq 0, i = 1, 2, ..., n \text{ and } \sum_{k=1}^{k} Q_i \leq \sum_{k+1}^{n} Q_i \}$$

if $Q$ is a private good and

$$F = F^2 = \{ (Q_1, Q_2, ..., Q_n) \mid Q_i \geq 0, i = 1, 2, ..., n \text{ and } Q_1 = Q_2 = ... = Q_k = \sum_{k+1}^{n} Q_i \}$$

if $Q$ is a public good.
The central agency will charge the \( i \) user the amount:

\[
C_i = -\sum_{j=1}^{k} D_j(\hat{Q}_j) + \sum_{j=k+1}^{n} S_j(\hat{Q}_j) + A_i, \quad i = 1, 2, \ldots, k
\]

and will pay the \( i \) producer the amount:

\[
C_i = \sum_{j=1}^{k} D_j(\hat{Q}_j) - \sum_{j=k+1}^{n} S_j(\hat{Q}_j) - A_i, \quad i = k + 1, k + 2, \ldots, n
\]

where \( A_i \) is the lump-sum charge, and amount calculated independently of agent \( i \)'s reported demand or supply curve.

The Vickrey lump-sum charge is actually a tax, and may be stated for users as:

\[
A_i^* = \max_{Q \in F_i} \left[ \sum_{j=1}^{k} D_j(Q_j) - \sum_{j=k+1}^{n} S_j(Q_j) \right]
\]

and for producers as

\[
A_i^* = \max_{Q \in F_i} \left[ \sum_{j=1}^{k} D_j(Q_j) - \sum_{j=k+1}^{n} S_j(Q_j) \right]
\]

where \( Q_i = (Q_{i,1}, Q_{i,2}, Q_{i,3}, \ldots, Q_{i,n}) \),

\[
F_i = \{ (Q_{i,1}, Q_{i,2}, Q_{i,3}, \ldots, Q_{i,n}) | (Q_{i,1}, Q_{i,2}, Q_{i,3}, \ldots, Q_{i,n}) \in F \}
\]

where \( Q \) is a public good and \( i = 1, 2, \ldots, k \). From this, it can be seen that "...\( A_i \) is equal to the reported social surplus attainable if agent \( i \) drops out of the market (Loeb, 1977)."
For the purposes of this research, we will examine only cases where the Central Agency is able to provide a public good from one supplier and at a constant marginal cost p. In this special case, the rule becomes:

$$\hat{Q} \text{ maximizes } \sum_{i=1}^{k} D_i(Q) - pQ \text{ with respect to } Q \in \mathbb{R}_+$$

The charge imposed on the \(i_{th}\) user then is

$$C_i = -\sum_{i=1}^{k} D_i(\hat{Q}) + p\hat{Q} + A_i, \ i = 1, 2, ..., k$$

The parameterized class of the lump-sum charge is

$$\bar{A}_i = \max_{Q \in \mathbb{R}_+} \left[ \sum_{i=1}^{k} D_i(Q) - (1 - \theta_i)pQ \right] + p\bar{Q}_i - \theta_i p \sum_{j=1}^{k} \bar{Q}_j, \ i = 1, 2, ..., k$$

and \(0 \leq \theta_i \leq 1, Q_i \geq 0\) are constant in \(i = 1, 2, ..., k\).

Vickrey's tax is then

$$\theta_i = Q_i = 0, \ i = 1, 2, ..., k.$$ 

It follows then that the tax "...is the maximum reported consumers surplus all others could obtain in the absence of consumer i (Loeb, 1977)."

Clarke's Tax is then:

$$Q_i = 0, \ i = 1, 2, ..., k, \text{ and } \sum_{i=1}^{k} \theta_i = 1$$
Each consumer is then assigned a percentage of the cost equal to $Q_i$. "The Clarke lump-sum charge is the maximum net consumer surplus all others could obtain in the absence of consumer $i$, provided they pay only the fraction $(1 - Q_i)$ of the costs of the public good (Loeb, 1977)." The calculation of the tax for the Groves and Loeb mechanism is similar to the Clarke mechanism, and will not be discussed here.

Turning now to the domain considered by this thesis, by the nature of the conditions stated in Section 1.3, the research only applies to public goods. In addition, the public good may be either pure or impure. Therefore, the mechanism developed by Vickrey will not be further considered. Since any deficit incurred by the Central Agency will be paid by the users, the Groves and Loeb mechanism will not be further considered. Finally, by the nature of the selection set forth in the necessary conditions, this research applies when a definite number of users and a single provider exist. For this research, the provider is the Central Agency itself. With these facts, it becomes apparent that the Clarke mechanism can be used if the conditions in Section 1.3 are binding. Therefore, the applicable Demand-Revealing Mechanism becomes:

Determine $\hat{Q} = (\hat{Q}_1, \hat{Q}_2, \ldots, \hat{Q}_n)$ such that

$$\hat{Q} \text{ maximizes } \sum_{i=1}^{k} D_i(Q_i) - S(Q_i)$$

with respect to $Q \in F$ where

$k + 1 = n$, i.e., there is only one producer, $k$ consumers, and
\[ F = \{ (Q_1, Q_2, \ldots, Q_n) | Q_i \geq 0, i = 1, 2, \ldots, n \text{ and } Q_1 = Q_2 = \ldots = Q_k = Q_n \} \]

Then users will be charged

\[ C_i = -\sum_{j=1}^{k} D_j(\hat{Q}_j) + S_n(\hat{Q}_n) + A_i, i = 1, 2, \ldots, k \]

and the central agency pays the producer:

\[ C_n = \sum_{j=1}^{k} D_j(\hat{Q}_j) \]

The tax for an individual user is then

\[ A_i = \text{Max}_{\alpha_{-i}, \theta_i} \left[ \sum_{j=1}^{k} D_j(Q_j) - S_n(Q_n) \right] \]

\[ F_{-i} = \{ (Q_1, \ldots, Q_{i-1}, Q_{i+1}, \ldots, Q_n) | Q_1 = Q_2 = \ldots = Q_{i-1} = Q_{i+1} = \ldots = Q_k = Q_n \} \]

Thus, the Clarke Tax is still

\[ Q_i = 0, i = 1, 2, \ldots, k, \text{ and } \sum_{i=1}^{k} \theta_i = 1. \]

As a summary, note that of the five versions of the Demand-Revealing Process discussed: (1) The version developed by Vickrey will not be considered further because of its inefficiency, (2) the Groves-Ledyard mechanism will not be
considered further because it is not truly a Demand-Revealing Mechanism, and (3) the Groves mechanisms will not be considered further since they deal specifically with the allocation of resources within firms. Finally, the version considered by Groves and Loeb should yield results similar to the mechanism developed by Clarke. Therefore, the Clarke mechanism will be considered as the Demand-Revealing Process for the remainder of this thesis. Further, we will consider only public goods, with a single producer.

4.4 Inherent Problems with Demand-Revealing Mechanisms

As discussed in Chapter three, Demand-Revealing mechanisms have many endearing qualities, but also have some inherent deficiencies. They are as follows: (1) income effects, and (2) information incentives, (3) coalitions, and (4) bankruptcy (Mueller, 1979). As noted by Mueller, if income effects are allowed, then the dominance property will disappear (i.e., voters will not reveal their true preferences, and in addition, start to strategize). Information incentives deal with the fact that as the numbers of voters increase, the tax imposed will decrease (Mueller, 1979; Tideman and Tullock, 1976). As the level of tax decreases, so to will the incentive to vote. Thus, the if there are few voters, the taxes may be high, and the information presumed to be accurate. If the number of voters is small, then the tax may be low and the information presumed to be inaccurate. Measures designed to thwart information incentive problems rely on either systems of representatives (Clarke, 1977) or sampling techniques (Tullock, 1977). However, as pointed out by Mueller (1979) these measures allow the formation of coalitions. In addition to these four problems, cycling, inordinate
number of proposals, mutual participant benefit, and money valuation were identified and discussed in chapter two.

Eight problems were identified with demand-revealing processes. To recapitulate, they are: (1) income effects, (2) information incentives, (3) coalitions, (4) bankruptcy, (5) cycling, (6) inordinate number of proposals, (7) mutual participant benefit, and (8) money valuations. For the purposes of this thesis, we can ignore the possibility of income effects and cycling by assuming that voting will always be against two alternatives; the first being the do nothing alternative and the second being the proposed change, or that if more than two alternatives exist, comparison will be done against the do nothing alternative and each alternative individually. The problem of an inordinate amount of items being placed on the agenda may be controlled with an agenda fee as Tideman suggests. In the problem domain discussed in this thesis, it is unlikely that proposals will be brought up too often anyway since we may assume that there are a limited number of shared resources. As pointed out by Mueller (1979), the problems of bankruptcy can be avoided by placing constraints on the problems to be considered. Therefore, we can assume that sufficient constraints exist such that no alternative will be voted upon which can potentially bankrupt an individual user. It may be further noted that bankruptcy could be caused either by the alternative’s cost or the tax burden resulting from the Demand-Revealing Process, or a combination of both.

After removing these four deficiencies, means of dealing with the problems of:

(1) information incentives, (2) mutual participant benefit, (3) coalitions, and (4)

9. Note: In discussions with Dr. Tideman, it was revealed that with a set of approximately one hundred voters, the likelihood of cycling occurring was about 5%.
money valuations must still be developed. As a means of removing these
deficiencies, it will be shown in Chapter five how the Quality Function
Deployment Process and elements of the Systems Engineering Process can be
combined and used prior to the Demand-Revealing Process. Further, it will be
shown that this combination alleviates some of the problems associated with
Demand-Revealing Processes when applied under the conditions stated in
Section 1.3.
V. DEVELOPMENT OF THE INTEGRATED DECISION APPROACH

5.1 Functional Representation of the Decision Process

The decision process can be divided into three stages: (1) realize that a decision should be made, (2) determine feasible alternatives, and (3) select the best alternative from among all available alternatives\(^\text{10}\) (Simon, 1960) (Figure 5.1). It has been shown that the Demand-Revealing Process, a decentralized decision mechanism, may facilitate the selection of alternatives (i.e., enable stage three of the decision process) as well as decision mechanisms that rely on utility functions when the conditions stated in Section 1.3 are binding. Further, it has been shown that decision mechanisms that rely on the creation of utility functions are the best of the centralized decision mechanisms. Therefore, it was concluded that the Demand-Revealing Process may provide selection from alternatives that is as good as all centralized decision mechanisms.

As with all decision mechanisms, the Demand-Revealing Process has some limitations. As was shown, many of these limitations are shared with utility mechanisms. This is not surprising since both utility mechanisms and Demand-Revealing mechanisms attempt to determine and assess user preferences. But apart from these problems shared with utility mechanisms, the Demand-Revealing Process suffers from problems specific to voting techniques. The issue that will be addressed in this chapter is how to alleviate inherent problems experienced by the Demand-Revealing Process.

\(^{10}\) Note that Simon refers to the three steps as (1) intelligence, (2) design, and (3) choice.
Figure 5.1 The Decision Process

- **Stage 1:** Realize that a decision should be made.
- **Stage 2:** Determine feasible alternatives.
- **Stage 3:** Select the best alternative.
5.2 The Integrated Decision Approach

The Demand-Revealing Process has been selected as the decision mechanism that will allow selection of the preferred alternative from a group of mutually exclusive alternatives. Selection of the Demand-Revealing Process partially fulfills the objective of this research that is to achieve commitment to an alternative before the inception of detail design and development activities. It is expected that decision making this early in the design process will minimize the number of changes that have to be made to the design, and also result in higher user satisfaction levels. However, the Demand-Revealing Process has four deficiencies that must be rectified before it can be considered a suitable decision mechanism. Since these deficiencies do not manifest themselves until the third stage of the decision making process, it is quite possible that activities performed in the second stage of the decision making process may mitigate or alleviate these deficiencies.

A proposed approach is to conduct the Quality Function Deployment Process and elements of the Systems Engineering Process during the second step of the decision making process. In fact, it will be shown that the introduction of these two processes in correct sequence will reduce or eliminate many of the deficiencies associated with the Demand-Revealing Process.
5.3 Systems Engineering as the Second Function in a Decision Process

5.3.1 Purposes of Systems Engineering

The Systems Engineering Process provides a sound methodology for the design, development, and implementation of systems. As shown in Chapter Two, the Systems Engineering Process is composed of three main steps. They are (1) conceptual system design, (2) preliminary system design, and (3) detailed design and development (Blanchard and Fabrycky, 1990). During these three stages, all aspects of the systems life-cycle must be accounted for (i.e., birth to death). This research is concerned with the selection of an alternative early in the system life-cycle. Therefore, the thesis is focused on early design commitment (Figure 5.2). Detailed design activities will not be considered in this thesis, since it is the intent here to allow for selection of a particular architecture prior to the inception of detailed design activities. We aim to achieve outputs from the Systems Engineering Process that are in the form of mutually exclusive, or at least independent, alternatives to pass on to stage three of the decision process. In addition, since the Demand-Revealing Process will be enacted after alternative approaches are identified during preliminary design, it is necessary that system synthesis and definition and system design review (both stages in preliminary design) follow implementation of the Demand-Revealing Process.

5.3.2 Applicable Elements of Systems Engineering

As stated previously, we assume that stage one is successful (i.e., we know that a decision must be made, and what elements are concerned). At this point, we
would begin using the Systems Engineering Process as promulgated by Blanchard and Fabrycky (1990) to develop alternatives to pass on to stage three of the decision process. Elements of the Systems Engineering Process that are applicable constitute conceptual design and preliminary design phases and are: (1) definition of need, (2) feasibility studies, (3) mission definition, (4) performance and physical parameters, (5) user requirements, (6) operational deployment or distribution, (7) operational life-cycle, (8) effectiveness factors, (9) environment, (10) maintenance concept, (11) technical requirements, (12) maintenance requirements, (13) conceptual design review, (14) functional analysis, (15) allocation of requirements to functions, and (16) trade-off and optimization. The steps to gather these elements would consist of: (1) enter system requirements, (2) conduct functional analysis, (3) link performance measures to functions, (4) allocate functions to components, (5) conduct alternative performance and cost estimation, and (6) conduct optimization of alternatives by cost and performance.

It is expected that conducting the Systems Engineering Process in this manner will provide alternatives that can be compared on an equivalent basis. Further, when the final system trade-off and optimization is completed, vital performance and cost for each of the alternative approaches should be known or have been estimated. After selection by the Demand-Revealing Process, the winning alternative will form the basis for system synthesis and definition. A preliminary design review will then be conducted. This will the form the basis for detail design and development activities as the Systems Engineering Process continues. It must be noted however that system synthesis and definition,
Figure 5.2 Applicable Elements of the Systems Engineering Process (Blanchard and Fabrycky, 1991).
preliminary design review, and detail design and development cannot proceed until a specific alternative approach is selected.

5.3.3 Systems Engineering Implementation Methodology

A stated above, the Systems Engineering Process will be enabled in 6 steps. They are: (1) development of system requirements, (2) the creation of functional analyses, (3) linkage of performance measures to functions, (4) allocation of functions to components, including interfaces, (5) the development of estimates of performance and cost for alternative architectures, and (6) optimization of alternatives by both life-cycle cost and performance.

5.3.4 Outputs from the Systems Engineering Process

The output from these six steps should be one or more system configurations, and their respective life-cycle cost and effectiveness estimates. These configurations may either be dependent, independent, or mutually exclusive. In any case, it should be possible to partition the resulting configurations into a set of mutually exclusive alternatives. If all resulting configurations are independent, then there will be \(2^n\) mutually exclusive alternatives where \(n\) is the number of independent configurations. These mutually exclusive alternatives will then form the input to the Demand-Revealing Process.

5.4 QFD to Facilitate Requirements Analysis

5.4.1 The Purpose of Quality Function Deployment

The use of the Quality Function Deployment Process will depend upon how stage one of the decision process was enabled (Figure 5.3). The Quality
Figure 5.3 The use of the Quality Function Deployment Process
Function Deployment Process will be used to facilitate requirements development within the Systems Engineering Process only if the information that a system must be conceived, or that an existing system must be modified, is obtained solely through the informal measurement system, or the information in the internal measurement system is not sufficient to develop user requirements. The reasons for this are as follows: If the Central Agency's internal measurement system has indicated that a change is required for an existing system, or that a new system must be provided, then most of the information needed to make the change may be contained within this internal measurement system. However, if the information that a change is required comes solely from the outside (i.e., through informal channels), then it can be assumed that the Central Agency possesses no information needed to make the changes. If the Central Agency does not possess any information needed to make the changes, or if the information contained in the internal measurement system is insufficient, then some technique for obtaining this information should be used. In this case, the technique chosen is the Quality Function Deployment Process.

It should be noted that the Central Agency will use the Quality Function Deployment Process as a means of facilitating requirements development within the Systems Engineering Process. In addition, there may be varying degrees of information coming from both sources simultaneously (i.e., some information gained internally while some is gained informally). It is not the intention of this research to determine when enough information is obtained to disregard use of the Quality Function Deployment Process. If the Quality Function Deployment Process is not used, then sufficient information to develop all requirements must
exist internally. If this information does not exist internally, then the Quality Function Deployment Process should be used.

5.4.2 Application of Quality Function Deployment

Since the Quality Function Deployment Process addresses all phases of the system life-cycle, quality needs that occur during all stages of the life-cycle can be developed. These requirements, that form input into the Systems Engineering Process, will then cover design, development, production, utilization, and phase-out. This will help ensure that the resulting system is robust across all life-cycle phases.

As outlined in Chapter Three, the House of Quality may be used to facilitate the Quality Function Deployment Process. The implementation of the House of Quality will yield information concerning: (1) the identification of attributes, (2) attribute weights, (3) engineering measures, (4) the linkage between engineering measures and customer satisfaction, (5) key areas for improvement, and (6) the technical baseline.

5.4.3 Implementation Methodology

The Quality Function Deployment Process will only be used if enough information does not exist in the internal measurement system to provide the basis for the development of requirements within the Systems Engineering Process. The Quality Function Deployment Process is comprised of six steps. They are (1) identify user attributes, and relative weights, (2) identify system performance measures, (3) develop relationships between various performance measures, and between performance measures and user attributes, (4) develop
technical baseline, and competitive performance indicators, (5) develop least costly or most beneficial areas for improvement, and (6) develop performance expectations. It should be noted that the performance measures developed should address all attributes identified by the users. Finally, the performance measures developed should then become part of the regular information system so that monitoring of the system, whether it is new or an older system that has been modified, can be assessed on an ongoing basis.

5.4.4 Outputs from the Quality Function Deployment Process

The Quality Function Deployment Process will serve as the requirements analysis step within the Systems Engineering Process. The outputs from the Quality Function Deployment Process will be specific performance measures, respective expectations by which system alternatives should be measured, and the best areas for improvement. Further, use of the Quality Function Deployment Process will help insure that all user requirements are merged into all system alternatives. Since selection will not occur until just before the completion of preliminary design, there is a significant risk that any system developed by the Systems Engineering Process would fail to meet requirements if the requirements were well known and stated explicitly. By using Quality Function Deployment prior to the Systems Engineering Process, much of this risk can be mitigated\textsuperscript{11}.

\textsuperscript{11} It should be noted that user requirements may change over time. Therefore, it is important that the Systems Engineering Process yield designs which are robust.
5.5 Formulation of the Integrated Decision Approach

5.5.1 Review of Demand-Revealing Process Deficiencies

As mentioned in the closing of Chapter Four, the Demand-Revealing Process has eight inherent problems. Of these eight problems, four were handled by arguments given in Chapter Four. However, four problems were left unanswered. They are (1) how to minimize the effects of information incentives, (2) how to ensure mutual participant benefit, (3) how to reduce the likelihood and effects of coalitions, and (4) how to assess the effects of money valuations?

5.5.2 How the Integrated Decision Approach Eliminates these Deficiencies

The Integrated Decision Approach was constructed to eliminate some of the Demand-Revealing Processes' limitations. Each of the four limitations will now be considered individually, and arguments constructed to show how the Integrated Decision Approach mitigates or eliminates these inherent deficiencies.

5.5.2.1 Information Incentives

In the domain considered by this research, a definite number of users will exist. Further, in most cases it is unlikely that this number of users will exceed one hundred. Therefore, this work treats the situation in which users have a high incentive to correctly report their preferences because the tax burden may be high. In fact, as was shown before, the tax burden will now be directly related to the quality of the analysis performed prior to alternative selection. The question then becomes, will the included elements of the Systems Engineering Process,
and the use of the Quality Function Deployment Process if needed, provide an analysis sufficient to minimize the resulting taxes? The answer is possibly. Let us examine why.

The quality of the analysis is still contingent upon some human intervention, and sufficient information received in stage one of the decision process. The human intervention will exist during the execution of the Systems Engineering Process, the Quality Function Deployment Process, and the Demand-Revealing Process. The quality of the staff conducting the Systems Engineering and Quality Function Deployment analyses may have a profound impact upon the success of system development. Techniques to minimize the human intervention are prevalent (e.g., computer based systems engineering tools) but reliance on the human element is still very high. Also, the preferences of individual users captured from the information system or developed through the Quality Function Deployment Process may change while the Systems Engineering Process is being conducted. This means that by the time the Demand-Revealing Process is conducted, user preferences may have changed. This points to the need for robust system design. Hence, robust system design should be an outcome of the Systems Engineering Process. Now, if we assume that the human component is as competent as possible, and therefore, no error could possibly result from the human component, then can it be said that the Integrated Decision Approach will minimize the information incentives?

The answer to this question is yes. If no errors from humans are considered (both analysts and individuals in user groups) then it can be inferred that this sequence of steps will provide all the information needed to develop the system
alternatives. We will still be restricted by the state of technology (e.g., in the 1950's it was uncommon to include transistors in radios) but we should achieve the creation of alternatives that are representative of the technology that exists at the time of system development. The Systems Engineering Process will force the systems developers to consider all issues that are essential to system success, and thus, force them to develop as many feasible alternatives as economically desirable. In addition, the Quality Function Deployment Process should reveal areas where the most benefit or excess profit may be obtained, thus, satisfying user demand.

Now, if these alternatives closely satisfy user demands, then it can be said that income effects will be minimized. It should be apparent by now that user demands should be satisfied since the Systems Engineering Process starts with a needs analysis, and subsequently allows for the development of system requirements in an orderly, rigorous fashion. In addition, in some cases, the Quality Function Deployment Process will be specified if enough information does not exist in the internal measurement system to fully develop the system requirements. In either case, requirements for the system will be specified by user needs. Since the requirements will be derived from user needs, all performance measures will be linked to user needs. Then, at the time of selection, all users should opt for relatively similar alternatives because the Systems Engineering Process has allowed only for the creation of alternatives that closely parallel user needs. Therefore, the resulting tax will be low since most users will agree to the selection of a specific alternative. Thus, we have minimized the effects caused by information incentives when few users exist for a system.
5.5.2.2 Mutual Participant Benefit

Mutual participant benefit is closely linked to information effects. The same cure offered for income effects will be offered here. The elements of the Systems Engineering Process chosen will provide alternatives that closely parallels user needs. In fact, the Systems Engineering Process will not be used at all if user needs do not require it. It then follows that if user needs do not require use of the Systems Engineering Process, then the Demand-Revealing Process will not be enacted. Thus, most participants will benefit from enactment of the Demand-Revealing Process, since it will only be enacted when the internal information system or information gained informally indicates that a new system must be provided or that the existing system is not sufficient for user needs. Since the Quality Function Deployment Process may be used to determine the most beneficial areas for improvement, if no improvement is indicated by the Quality Function Deployment Process, then work on improvements would stop. In this way, mutual participant benefit will be virtually ensured since the Central Agency will know that a problem either does or does not exist prior to enacting the Systems Engineering Process. If the Quality Function Deployment Process indicates that a problem exists, then work with the Systems Engineering Process will proceed.

To ensure mutual participant benefit, the information obtained during implementation of the Systems Engineering Process will allow the Central Agency to determine which users will benefit from each alternative, and thus, how costs for the new system or improvement should be allocated. This
approach then will ensure that all users of the system benefit to some degree (although it is noted that some users may benefit more than others).

5.5.2.3 Coalitions

The likelihood of coalitions forming when the number of constituents is low is fairly high (Mueller, 1979). At first, it does not seem that the requirements development process within the Systems Engineering Process will alleviate this problem because "...incentives exist to gather information about not only one's preferences, but also those of others who may be potential coalition members (Mueller, 1979)."

However, it must be remembered that this condition exists when the good in question is public, and all users are paying the same fees. In the case domain considered by this thesis, users will pay variable rates for goods consumed depending upon how much is consumed. Unfortunately, we are still left with having to collect enough revenue to ensure sufficient funds available to cover a fixed cost\(^{12}\). Even though the fee assessed users depends upon their rate of consumption, inherent within the fee is a fixed cost (e.g., design, development, construction, and overhead costs that must be paid over time). Therefore, users who do not frequently use the system may incur greater overhead costs than they feel they should.

This condition may lead to two coalitions forming: (1) one composed of those who place heavy demands upon the system, and (2) those who use the system

\footnote{12. Note: The mechanism considered by Vickrey would operate with a deficit here. We want to avoid this, so we allocate all costs to the users, plus any deficit.}
infrequently. Again, though the tax burden placed on the most frequent users may be so great that they will settle for lesser performance along with lower fixed costs in a specific system alternative. Also, during the requirements development step (either relying on the internal measurement system or the Quality Function Deployment Process), it should be brought to light that this great disparity exists in system use. At this point, it may be decided to obtain two systems, and thus eliminate this dichotomous need that exists for various system performance. In this case, we may choose to break the single group into two or more groups, if feasible, and treat them separately. The information necessary to separate these groups will be revealed by the Systems Engineering Process or a combination of the Systems Engineering Process and the Quality Function Deployment Process.

However, it should be noted that, for some alternatives, it may not be feasible to divide the users into two or more groups because of excessively high initial system costs. For example, a system of satellites may have an excessive initial cost. If users form coalitions, some for inception of the satellite alternative, and some against, it may not be feasible to satisfy both groups at the same time. If the users against inception of service were in the minority, and they would benefit from the inception of services, then the group should stay as one.

In any case, the Central Agency is made aware that these coalitions exist because of the information provided by the internal measurement system, or from implementation of the Quality Function Deployment Process. Therefore, the problem of coalitions forming is either mitigated (e.g., knowledge that groups
exist) or avoided (e.g., break groups into two or more seemingly homogeneous units).

5.5.2.4 Monetary Valuations

The requirements process within Systems Engineering should identify all desirable system attributes. These attributes may be composed of cost components, but it is certainly expected that some will consider system performance characteristics. The implementation of the Demand-Revealing Process though will require that users state their preferences in dollars. Since the Central Agency will inform the users of their share of the costs, this is not so unrealistic an expectation.\(^{13}\)

It has been stated that wealthier individuals have more bargaining power under the Demand-Revealing Process than do poor individuals. By including the Systems Engineering Process, and Quality Function Deployment Process if necessary, equitable allocation of system costs can be developed. Thus, the problem of money valuations is somewhat mitigated since wealthier individuals may have to pay more if their expected usage is higher. However, if the wealthier individual desires the same level of service as a poorer individual and each is paying the same amount, then the wealthier individual will have more bargaining power by virtue of their higher wealth.

It should, however, be noted that the purpose of Demand-Revealing mechanisms are not to equitably distribute resources, and as such may be manipulated by

13. It should be noted that utility analysis deals with non-monetary issues, but in the end, aggregation of benefits may reflect a dollar preference for an alternative.
starting wealth position. So, when two individuals are paying the same rate and one individual possesses more wealth than the other, we cannot control the monetary effects.

5.6 Overview of Integrated Decision Approach

The Integrated Decision Approach will work by applying the Systems Engineering Process and the Quality Function Deployment Process to stage two of the decision process (Figure 5.4). Stage three of the decision process will be enabled by the Demand-Revealing Process. Actual implementation of stage two of the decision process will depend upon the way in which information was received in stage one. If sufficient information exists in the internal measurement system to develop all system requirements, then the Quality Function Deployment Process will not be used during the requirements development step within the Systems Engineering Process. If sufficient information does not exist internally, then the Quality Function Deployment Process will be used during the requirements development step within the Systems Engineering Process. In either case, output from the Systems Engineering Process will be a set of mutually exclusive (or at least independent) alternatives. The Demand-Revealing Process will then be enacted to facilitate selection of the best alternative.

An approach combining the Demand-Revealing Process, the Quality Function Deployment Process and elements of the Systems Engineering Process has been developed, and it has been shown that this approach mitigates or eliminates the deficiencies inherent in the Demand-Revealing Process for the decision types treated herein. Since the deficiencies have been eliminated, it can now be said
Figure 5.4 The Integrated Decision Approach
that the Demand-Revealing Process may yield results that are as good as results
that could be obtained by utility mechanisms. Further, since the Demand-
Revealing Process does not require that utility be made explicit, it can also be
said that the Demand-Revealing Process may require: (1) less time to conduct,
(2) less personnel, and (3) result in a lower cost than if utility function
mechanisms were employed. This is because of the large number of utility
functions that would have to be created.

However, since the Demand-Revealing Process may impose a tax on a user, and
the tax is proportional to the quality of the analysis that precedes enactment of
the Demand-Revealing Process, it is imperative that requirements be developed
correctly. This will result in a minimal tax being levied on the users. As was
demonstrated, the Quality Function Deployment Process, and elements of the
Systems Engineering Process, if employed correctly, will greatly reduce the tax
paid by any user. It follows then that the human element plays a great role in
the implementation of the decision process. If the humans involved perform
poorly, or simply make mistakes, then the Demand-Revealing Process may place
a high tax burden on system users. If this occurs, then the alternative selection
may be inefficient.
VI. HYPOTHETICAL EXAMPLE

6.1 Background

6.1.1 Spaceflight Tracking and Data Network

This hypothetical example is derived from a satellite communications system developed and operated by the National Aeronautics and Space Administration. The system background is as follows: The Missions Operations and Data Systems Directorate, located at Goddard Space Flight Center in Greenbelt, Maryland, "is responsible for program planning, development, and operation of the National Aeronautics and Space Administration's near-Earth network of space and ground-tracking and data communications facilities and systems (Network Division Systems Development Activities, 1989)." The Missions Operations and Data Systems Directorate is responsible for the systems and services provided by the Spaceflight Tracking and Data Network. The Spaceflight Tracking and Data Network provides tracking and data acquisition services to a diverse group of space flight projects. The Missions Operations and Data Systems Directorate is currently concerned with: (1) evolving space flight project requirements, (2) the need to reduce maintenance and operations costs, (3) the need to increase efficiency, (4) replacement of obsolete systems, (5) the need to improve systems reliability and network availability, and (6) the expected increase in users vying for network services.

6.1.2 Space Network

The Space Network (SN), a component of the Space Tracking and Data Network "...was developed to provide a set of standard Tracking and Data
Acquisition services to low-Earth orbiting satellites operating in the S- and Ku- and frequency ranges (Network Division Systems Development Activities, 1989)." The Space Network uses geostationary tracking and data relay satellites to provide coverage to low-Earth orbiting satellites, and manned spacecraft.

6.1.3 Network Control Center

The Network Control Center (NCC) is responsible for scheduling resources available on the Space Network. Resources currently available include: (1) ground links, (2) bandwidth, and (3) antennas. Antennas provide "...both forward and return links for multiple access (SSA), and K-band single access (KSA) services as well as tracking service using one-way Doppler and MA [multiple access] and SA [single access] two-way range and Doppler (Gill and Paul, 1991)."

6.1.4 History of the SN

After deployment of the first tracking and data relay satellite in 1988, it became readily apparent that tracking and data relay satellites would "...dramatically increase [the coverage available to low-Earth orbiting satellites] beyond that previously afforded through ground-based tracking stations (Network Systems Development Activities, 1989)." In 1988, the Missions Operations and Data Systems Directorate determined that the Spaceflight Tracking and Data Network operations concepts should be modified to reflect the evolving demands expected to be placed upon the network. The concepts were divided into six phases, with completion of the sixth to occur in 1994. These changes,
however, do not reflect changes to be made to the network when the space station comes on line in 1997.

6.2 Changes in the NCC

6.2.1 NCC Automation

In the 1970's, the Network Control Center relied on UNIVAC computer systems. By the early 80's, a new computer system (VAX) was selected and installed to provide real-time functions, while the UNIVAC's were retained to provide non-real-time functions. The changeover from UNIVAC's to VAX's took 18 months. During changeover, it was determined that "UNIVAC applications and software was not suitable for the VAX environment, so the decision was made to convert the software to the VAX (Network Control Center Block II Project History Report, 1990)."

6.2.2 New Directions

At this time, the Network Control Center is attempting to adhere to the tasks specified under the Spaceflight Tracking and Data Network operations concepts. Tasks include developing a new system, the Space Network Control Center (SNCC), by 1997 to meet expected demands resulting from the deployment of the space station. Currently, the Network Control Center is attempting to: (1) develop top-level performance requirements for the SN, (2) gain knowledge and experience by simulating the existing Space Network, and (3) develop algorithms to schedule resources on the Space Network.
6.3 The Hypothetical Example

6.3.1 Assumptions Made

The following hypothetical example, drawn from the Space Network, is constructed to demonstrate that the Integrated Decision Approach will work one time, and on all possible paths in the conceptual model. Since the Space Network is so complex, an example must be developed which is relatively simple, and will also impart understanding of the Integrated Decision Approach. Therefore, none of the events or data are real in this hypothetical example.

It will be assumed that there exists one Tracking and Data Relay Satellite that is in constant contact with a single ground-based antenna on Earth, and all users (in this case users are space flight projects) can communicate with their spacecraft through this tracking and data relay satellite at any time. Further, it is assumed that the Space Network only provides communication services, not tracking information. It will be further assumed that the Space Network operates on a first-come-first-served-basis (FCFS), and users may gain access to the ground-based antenna system through a central network processor located at the Network Control Center. Finally, it will be assumed that there are fourteen space flight projects vying for service on this system and that they are paying for all operation and maintenance (O&M) costs incurred by the system. If expansion of the system becomes necessary, then the users must pay all expansion costs.  

14. It should be noted that the stated assumptions are not possible on the Space Network.
To show how the Integrated Decision Approach will work, an example problem will be constructed around this simplified Space Network. This simplified problem may then be solved using the Integrated Decision Approach since the following conditions are satisfied:

1) A definite number of users exists, and they can be identified - In this case fourteen users vie for service on the Space Network. In addition, the individual users percentage of total service time is known. Because the percentage of service time is known, all costs can be allocated equitably.

2) The users are paying for all costs of the system - At this point only O&M are assessed, but users will pay for all expansion costs if expansion becomes necessary.

3) The users may use no other system - In this case, because the cost of a single system is prohibitive, and thus, only one system of this type exists. Further, because of the high initial cost, the marginal cost of time on the system will decrease as the system utilization increases.

6.3.2 Synopsis of the Example

To illustrate how the Integrated Decision Approach may be applied, this hypothetical example starts with the baseline Space Network in 1989 and tracks changes made to the Space Network through 1991. During this time, the Demand-Revealing Process, the Quality Function Deployment Process, and elements of the Systems Engineering Process are employed to solve a system capacity problem; in this example, how many jobs can be processed per hour. In addition, specific system performance measures are developed by the use of the Quality Function Deployment Process. The internal information system is then modified to measure this new information and subsequently used to detect a
system capacity problem. At this point, two independent configurations are
developed using the Systems Engineering Process. These independent
configurations are partitioned into four mutually exclusive alternative
configurations. Of these four mutually exclusive alternatives, two are ruled out
because of their failure to meet minimum expected performance requirements.
Finally, the selection of the best mutually exclusive alternative is facilitated by
the Demand-Revealing Process. Problems with the Demand-Revealing Process
are reviewed and it is shown how these problems were mitigated or eliminated
for the situation in this example. The example problem is as follows:

6.4 Status of the Space Network in January 1989

6.4.1 Performance Measures Employed

The Central Agency relied on three system performance measures in 1989. They
were: (1) reliability, (2) time to repair, and (3) utilization. The cost per minute of
Space Network time is based upon network utilization. The Space Network,
began operation in January of 1989 and will terminate operation at the end of
December of 1998. It can therefore be concluded that the Space Network has a
mission life of 10 years (87,600 hours).

6.4.2 Reliability

Requirements for the baseline Space Network specified that the system have an
overall Mean Time Between Failure (MTBFy) of no less than 2,500 hours in any
given year y. Therefore, overall system reliability had to be R_s = 6.055E-16,
where the failures were exponentially distributed (Figure 6.1).
OVERALL SYSTEM RELIABILITY

\[ R_S = 0.9997 \times 2.461 \times 10^{-8} \times 2.461 \times 10^{-8} = 6.055 \times 10^{-16} \]

\[ L = \ln(6.056 \times 10^{-16}) / -87,600 = 4.000 \times 10^{-4} \]

\[ MTBF = 1/4.000 \times 10^{-4} = 2,500 \text{ Hours} \]

\[ A = 2,500 / (2,500 + 0.5) = 0.9998 \]

Figure 6.1 The Top-Level Reliability Block Diagram - 1989
System reliability $R_s$ can be derived from the specified MTBF as follows:

$$R_s = e^{-87,600/\text{MTBF}_y}$$

where 87,600 is the mission life in hours. It was noted that specifications required that the satellite must have a reliability $R_{\text{sat}} = 0.9997$ since the satellite, once deployed, cannot be repaired (Figure 6.2). To achieve this level of reliability, it was necessary to provide several redundant components. Therefore, the satellite has 3 antennas, 3 receivers, 4 transmitters, and 1 power supply. To achieve a reliability of $R_{\text{ps}} = 0.9998$ for the power supply, it was necessary to provide three solar panels and four batteries (Figure 6.3). The MTBF$_{1989}$ for this baseline system is 2,500 hours.

### 6.4.3 Time to Repair

The original specifications for the baseline Space Network specified that the system have an availability of $A_y = 0.9998$ in each year, where the availability is:

$$A_y = \frac{\text{MTBF}_y}{(\text{MTBF}_y + \text{MTTR}_y)} \quad \text{for all } y = 1989, 1990, ..., 1998$$

and where $\text{MTTR}_y$ was the mean time to repair the system in any given year $y$. Since the MTBF$_{1989}$ was equal to 2,500 hours, it follows that substitution into the availability equation yielded:

$$\text{MTTR}_{1989} = \frac{2,500}{0.9998} - 2,500$$

Thus, the $\text{MTTR}_y$ for the system had to be less than or equal to 0.5 hours to fall within the specified limits. Assume, for this system, the MTTR$_{1989}$ was exactly 0.5 hours.
Figure 6.2: The Reliability Block Diagram for the Satellite
Figure 6.3 The Reliability Block Diagram for the Power Supply
6.4.4 SN Utilization

The Space Network utilization $U_y$ in any given year was defined to be the amount of time in minutes that the network was used (i.e., actual processing time) in one year $UT_y$ divided by the amount of available processing time $AT_y$ in minutes on the network in the same year. $AT_y$ was derived from the availability equation. The Space Network operated 24 hours per day per year (525,600 minutes per year) at an availability $A_y = 0.9998$. Therefore, $AT_{1989}$ was given by:

$$AT_{1989} = (525,600 \text{ minutes/year})(0.99998)$$

It follows then that $AT_{1989} = 525,495$ minutes. This means that it was expected that for 105 minutes in 1989, the Space Network would not be operating. During this 105 minutes, repairs would be conducted.

Estimates of the total amount of time to be used $UT_{1989}$ on the Space Network in 1989 was 350,400 minutes. The equation for $UT_y$ at the end of any year was given by:

$$UT_y = \sum_{i=1}^{N} J_{yi} \quad \text{for all } i = 1,2,\ldots,n$$
$$\quad \text{for all } y = 1989,1990,\ldots,1998$$

where $N$ is the total number of users and $J_{yi}$ is the total amount of system time used by a single user. For the Space Network, $N$ will always remain at 14 users. In addition, the percentage of system time $P_{yi}$ used by an individual user in any year was given by:

$$P_{yi} = J_{yi}/UT_y \quad \text{for all } i = 1,2,\ldots,n$$
$$\quad \text{for all } y = 1989,1990,\ldots,1991$$
In the case of the Space Network, $P_{yi}$ was a constant. Therefore, increases in $J_{yi}$ were expected to be proportional to increases in $UT_y$.

The utilization of the Space Network in 1989 was estimated as:

$$ U_y = \frac{UT_y}{AT_y} \quad \text{for all } y = 1989, 1990, ..., 1991 $$

where $UT_{1989} = 350,400$ minutes and $AT_{1989} = 525,495$ minutes. Accordingly, it was estimated that $U_{1989} = 0.6668$ or $66.68\%$.

6.4.5 Cost Per Minute

The cost per minute of processing time on the system was based upon the payment of all operation and maintenance (O&M) costs for the year. O&M costs were expected to be $10,000,000 per year in constant dollars (i.e., inflation free dollars). The cost per minute for any year was calculated based upon the total O&M costs incurred in the last year divided by the total minutes of processing time used for the last year. Since the system had just started operation, the total system processing time $UT_y$ had to be estimated for 1989. This time was given as 350,400 minutes. In addition, the charge per minute $CM_y$ of processing time in a certain year was be given by:

$$ CM_y = \frac{O&M_y}{UT_y} $$

The charge per minute $CM_{1989}$ in 1989 was given by:

$$ CM_{1989} = \frac{10,000,000}{350,400} $$

It follows than that $CM_{1989}$ was set at $28.54$ per minute.
It was noted that charging for processing time in this way could generate either a deficit $D_y$ or a surplus $S_y$ of funds within the Central Agency. This is because if $U_T y$ was less than anticipated, then the a deficit would result. However, if $U_T y$ was greater than anticipated, then a surplus of funds would result. To handle either of these conditions a policy was enacted that stated that (1) if a deficit were incurred, then users would be charged a percentage of the deficit equal to their percentage of use of the system $CD_y = (D_y)(P_{yi})$, and (2) if a surplus occurred, then users would be repaid a percentage of the surplus equal to their percentage of use of the system equal to $CS_y = (S_y)(P_{yi})$. The time interval for this calculation of surplus or deficit would extend over one year where a year is considered to begin on January 1 and end on December 31.

6.5 Status of the Space Network in December 1989

6.5.1 The 1989 Annual Performance Review Meeting

In early December of 1989, a meeting was held to discuss the first year of operation of the Space Network. At the meeting, the Director of the Space Network (SN Director) was surprised when he was told by his superiors that several system users were dissatisfied with the level of service provided by the Network. It was revealed by the superiors that directors of these user agencies had contacted them to inform them that they were dissatisfied with the performance of the Space Network. The users did not reveal exactly why they were dissatisfied. Most users did, however, declare that they felt that it took too long to process their jobs.
At this point, the SN Director decided to call some of his staff to discuss information provided by the Space Network internal measurement system. After review of the information provided by the internal measurement system, it was found that all predictions of system reliability, utilization, and maintenance made in January 1989 were valid. In fact, the total number of minutes used (UT$_{1989}$) was estimated to be 350,400. This estimation was made for UT$_{1989}$ using the first 11 months of data from 1989, and estimating the demand in December of 1989. The availability (A$_{1989}$) was similarly determined to be 0.9998. Further, the utilization was estimated to be 66.68%.

It was concluded at the meeting that the internal measurement system was not providing sufficient information to make decisions concerning Space Network operations. It was decided that the Quality Function Deployment Process (via the House of Quality) would be enacted to discover user concerns, and to determine how the Space Network's performance could be improved. In addition, the information provided by the Quality Function Deployment Process would be incorporated within the existing measurement system so that it could be used in the future as a better means of assessing Space Network performance from a user perspective.

6.5.2 Implementation of the Quality Function Deployment Process

The Quality Function Deployment Process was started two days later when the SN Director assigned an engineer to develop customer attributes and their relative importance. Since there were only fourteen users for the system, the engineer decided to visit directors and workers from each of the user agencies and question them directly as to what attributes of the Space Network they felt
contributed to its success or failure to meet their expectations. After questioning
directors and workers at all fourteen user agencies, the engineer developed a list
of customer attributes and their relative importance to Space Network success or
failure. These attributes and their respective weights provide the initial entries
into the House of Quality for the Space Network (Figure 6.4).

6.5.3 The Development of Performance Measures

After reviewing the list of customer attributes developed by the engineer, the SN
director assigned a team of engineers to develop performance measures that,
when combined, could be used to monitor all of the customer attributes. The
specific performance measures identified by the engineering team were (1) cost
per minute, (2) yearly refund, (3) residual error rate, (4) reliability, (5) MTTR,
(6) utilization, (7) mean interarrival time, and (8) mean service time15.

After development of the performance measures, the relationships that exist
between the performance measures themselves were developed. These
relationships are located on the top of the House of Quality (Figure 6.4).
Subsequently, the relationships that exist between the customer attributes and
the performance measures were developed. These relationships are located in
the middle section of the House of Quality.

6.5.4 The Calculation of Performance Measures

The SN Director next assigned the same team of engineers the task of
determining how to calculate these measures of Space Network performance

15. Note: Some of these measures for computer networks were contained in an article by Grubb
and Cotton, 1975.
Figure 6.4 The House of Quality for the Space Network
and then to determine the level of performance of the existing system. The first task was to determine how to calculate the cost per minute for each year. This was already known, and was given by:

\[ CM_y = \frac{O&M}{UT_y} \]

Further, \( CM_{1989} \) was shown to be $28.54.

Next, the refund per year \( RE_y \) was calculated as:

\[ RE_y = CM_y \times UT_y - O&M_y \]

where \( UT_y \) is the actual number of minutes used in one year. Since \( UT_{1989} \) was estimated to be 350,400 minutes, \( CM_{1989} = 28.54 \), and \( O&M_{1989} = 10,000,000 \), it follows that \( RE_{1989} = 416 \).

The residual error rate \( RER_y \) of the system was then defined. It is given by:

\[ RER_y = \frac{(C_{ye} + C_{yu} + C_{yd})}{C_{yt}} \]

where,

\( C_{ye} \) = Number of erroneous information characters accepted by the satellite.

\( C_{yu} \) = Information characters transmitted, but not delivered to the satellite.

\( C_{yd} \) = Information characters accepted in duplicate by the satellite, though they were not intended for duplication.

\( C_{yt} \) = Information characters contained in the data supposed to be transmitted.
It was then decided that $\text{RER}_y$ should be employed on a yearly basis. Since data available for the first 11 months of 1989 was available, this was used as a basis for calculating $\text{RER}_{1989}$. In the first 11 months of 1989 the measures are as follows:

$$C_{1989e} = 18,300; C_{1989u} = 69,300; C_{1989d} = 12,300; C_{1989t} = 1\text{E}11$$

$\text{RER}_{1989}$ may be calculated as:

$$\text{RER}_{1989} = (18,300 + 69,400 + 12,300)/1\text{E}11$$

So, it follows that $\text{RER}_{1989}$ was equal to $1\text{E}-06$ or 0.0001%.

The next measure calculated was reliability. This measure was developed prior to 1989 and was known. It is $R_s = 6.055\text{E}-16$, and $\text{MTBF}_y = 2,500$ hours. In addition to reliability, the $\text{MTTR}_y$ was known to be 0.5 hours.

The utilization for the system $\text{U}_y$ was also determined using the first 11 months of data in 1989, and estimating usage in December. $\text{UT}_{1989}$ was estimated to be 350,400 hours. Since $\text{AT}_{1989}$ was equal to 525,495 minutes, $\text{U}_{1989}$ was equal to 66.68%.

The mean interarrival time and the mean service time were determined by collecting several day's worth of data from the Space Network. After reviewing the data, the engineers decided that the interarrival times and services times were exponentially distributed. This was shown for both interarrival and service times by constructing a Chi-Square goodness of fit test. It was concluded that the interarrival time could be described by an exponential distribution with a mean of 7.5 minutes. Further, the engineers concluded that the service times
could be described by an exponential distribution with a mean of 10 minutes. Therefore, it follows that the mean number of jobs arriving per hour $L$ is:

$$L = \frac{60 \text{ minutes/hour}}{7.5 \text{ minutes/job}} = 8 \text{ jobs per hour.}$$

The mean number of jobs processed $M$ can be similarly calculated. It is:

$$M = \frac{60 \text{ minutes/hour}}{10 \text{ minutes/job}} = 6 \text{ jobs per hour.}$$

After conducting this analysis, the engineers noted that queueing theory principles\textsuperscript{16} could not be further applied to this problem. This is because queueing theory assumes that jobs are continuously arriving, and at some time, the system will reach an equilibrium state. For equilibrium to occur, the mean number of jobs that can be processed per hour must be greater than the number of jobs arriving per hour. In this case, there are more jobs arriving per hour ($L = 8$) than can be processed per hour ($M = 6$).

It was noted, however, that the jobs may not be arriving continually. In fact, as Figure 6.5 shows, jobs arrive only between 8 AM Eastern Standard Time and 8 PM Eastern Standard Time. The actual processing of jobs however starts at 8 AM and terminates after 8 PM. It was concluded that the later a job request was submitted in the day, the more time it would take to be processed. Further, it was concluded that the jobs were arriving in a probabilistic, non-steady state manner. Therefore, queueing theory would not be further applied to this problem.

\textsuperscript{16} Note: Queueing principles discussion detailed from presentation on queueing theory contained in Introduction to Operations Research by Hillier and Lieberman, 1990.
Figure 6.5 Space Network Utilization Profile - 1989
6.5.5 Completion of the House of Quality

After the calculations of engineering performance measures were completed, they were entered into the House of Quality. As Figure 6.4 shows, the baseline performance was entered on the line corresponding to the existing system. At this point, the SN Director assembled the team of engineers in a meeting to finish the House of Quality. First on the agenda in the meeting was to determine the technical difficulty associated with eliciting a positive change in a performance measure\(^\text{17}\). Technical difficulty of each measure was placed on a five point ranking scale. As can be seen in Figure 6.4, the easiest to change was the yearly refund. Yearly refund was easiest to change because the calculations required are minimal, and the accuracy should be fairly close. On the other hand, the hardest to change was the mean service time. Mean service time was the hardest to change because all jobs sizes submitted by users were relatively similar. The only way to decrease this measure was to either add capacity (e.g., add another similar satellite system), or modify the existing system (e.g., increase the MTBF or decrease the MTTR).

The imputed percentage of importance of each performance measure was the next agenda item. As Figure 6.4 shows, the most important measures were: (1) cost per minute [13%], (2) reliability [19%], (3) utilization [18%], and (4) mean interarrival time [19%].

\(^{17}\) By positive change, it is meant that the change will improve system performance. So, if system cost were lowered, the change would be considered positive.
Next, an estimated percentage of cost to change was developed for each of the performance measures. The least costly was linked to certain performance measures. They were (1) cost per minute, (2) yearly refund, and (3) utilization.

As the last step in the meeting, the SN Director consulted the team to develop targets for system changes. It was felt at the time that the existing system provided yearly refunds, residual error rates, an MTBF, an MTTR, utilization, and mean service times that were acceptable. It was felt, though that the mean interarrival time was too low. As Figure 6.5 revealed, the users were submitting jobs only during the period 8 AM EST until 8 PM EST; half of the operation time of the Space Network. The engineers felt that more jobs should be submitted during the period from 8 PM EST until 8 AM EST. They felt if this were to occur, some of the loading during the 8 AM EST till 8 PM EST would be reduced.

6.5.6 Establishment of the Improved Demand Rate

After much discussion, the engineers developed the utilization profile as depicted in Figure 6.6. They felt that since some jobs could be run as batch (i.e., unattended), it would not present an undue hardship for users to submit some of their jobs during the hours 8 PM EST until 8 AM EST. After some calculation, it was decided that an improved mix of jobs would occur when 27% of the jobs were submitted and run during what is now termed off-peak time (i.e., 8 PM EST until 8 AM EST). The utilization during the off-peak time period was represented by \( U_{OY} \) and the utilization during peak time was given as \( U_P \), where

\[
U_Y = U_P + U_{OY}
\]
Figure 6.6 Improved Utilization Profile for the Space Network
Further, the minutes run per year during off-peak time were represented by \( \text{UTO}_y \). From the queueing study, the team of engineers predicted that an improved mix of jobs in 1990 would occur when \( \text{UO}_{1990} = 0.27 \). It follows then that, \( \text{UTO}_{1990} \) is given by:

\[
\text{UTO}_{1990} = \text{UO}_{1990} \times \text{UT}_{1990}
\]

where \( \text{UT}_{1990} = 350,400 \) minutes was the predicted Space Network usage in 1990. From this, it follows that \( \text{UTO}_{1990} \) was predicted to be 94,608 minutes.

The team of engineers noted that to get users to submit jobs during this off-peak time some type of off-peak rate had to be charged that would be less than the peak rate. This off-peak rate would have to be set such that the users would have sufficient incentive to run jobs in a batch fashion. After some calculation and deliberation, it was agreed that a suitable rate for off-peak time \( \text{CMO}_y \) would be $17 per minute. Since all O&M costs still had to be paid for by users, this meant that the peak rate would be higher than the rate in 1989 (assuming demand did not change). The peak rate was calculated as:

\[
\text{CMP}_y = [\text{O&M}_y - \text{UTO}_y \times \text{CMO}_y]/(\text{UT}_y - \text{UTO}_y)
\]

Thus, the charge per minute of peak time in 1990 was set at \( \text{CMP}_{1990} = 32.83 \). It was also felt that at this rate, utilization of the system would remain constant (i.e., demand would remain the same). It was noted at that time that the O&M costs would not change in 1990, (i.e., the O&M cost would be $10,000,000 in 1990 dollars).
6.5.7 Updating the Information System

After the meeting, the SN Director decided to implement this variable rate policy. As can be seen in the House of Quality, the targets for cost per minute and mean interarrival time were set with this new policy. The cost target had been met and it was assumed that this would reduce some of the load during peak-periods of demand. It remained to be seen, however, if the mean interarrival time target would be met in 1990. However, as a final step, the SN Director assigned a team to update the internal measurement system so it would be measuring the eight performance measures developed during the Quality Function Deployment Process.

As a final note, it was determined that setting the variable rate policy was the least costly way to achieve higher performance levels from the Space Network. This can be readily corroborated by looking at the House of Quality. In Figure 6.4 on the line "Estimated Percentage of Cost" it can be seen that two of the least costly measures (cost per minute at 0.5% and mean interarrival time at 1.25%) had been manipulated so as to improve system performance.

6.6 Status of the Space Network in December 1990

6.6.1 Results of the 1990 Annual Performance Review Meeting

In early December of 1990, a meeting was held to discuss the second year of operation of the Space Network. At the meeting, the SN Director revealed that the internal measurement system has shown that the rate policy put in place in the beginning of 1990 did initially result in lessening demand during peak hours, but it was later found that users also increased their total demand level in
November to 39,412 minutes out of an available 43,791 minutes (Figure 6.7). This meant that the system was operating at a 90% utilization level in November.

6.6.2 New Demand Profiles for the Space Network

After analyzing the data for the first 11 months of 1990, it was projected that the utilization in December would increase to 93%. Thus, it was expected that users would consume 40,726 minutes of available system time ($AT_{1990}$) in 1990. At this increasing rate of demand, it was projected that overall utilization in 1990 would be $U_{1990} = 80\%$, with the total minutes consumed in 1990 $UT_{1990} = 420,480$. It was further estimated that of the 420,480 minutes consumed in 1990, 35\% would be on the off-peak rate. Therefore, while $UO_{1990}$ was estimated to be 27\% in December of 1989, it was found in December of 1990 that it would more likely be 35\%. Further, $UP_{1990}$ was estimated to be 73\% in December of 1989. It was found in December of 1990, however, that $UP_{1990}$ would more likely be 65\%.

6.6.3 Refund Schedule Development

A projected refund schedule was developed at this point (Table 6.1). As can be seen, at the rate of demand estimated, the rates established in 1989 (i.e., $CMP_{1990} = 32.84/\text{min}$ and $CMO_{1990} = 17/\text{min}$) resulted in a surplus of funds equal to $1,474,691$. As stated before, the fourteen users exhibit a constant percentage of total system use equal to:

$$P_y = J_{yi}/UT_y \text{ for } i = 1, 2, \ldots, 14$$
130 Jobs Received in 24 Hours. Utilization = 90%

Figure 6.7 Space Network Utilization Profile - November 1990
<table>
<thead>
<tr>
<th>USER</th>
<th>% USED IN 1990</th>
<th>MINUTES USED IN 1990</th>
<th>AMOUNT PAID IN 1990</th>
<th>REFUND IN 1990</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>OFF-PEAK TIME</td>
<td>PEAK TIME</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>16,819</td>
<td>$100,073</td>
<td>$358,909</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>46,253</td>
<td>275,205</td>
<td>987,016</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>29,434</td>
<td>175,132</td>
<td>628,107</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>25,229</td>
<td>150,113</td>
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<td>6.5</td>
<td>27,331</td>
<td>162,619</td>
<td>583,230</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>84,096</td>
<td>500,371</td>
<td>1,794,567</td>
</tr>
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<td>7</td>
<td>2</td>
<td>8,410</td>
<td>50,040</td>
<td>179,465</td>
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<tr>
<td>8</td>
<td>9</td>
<td>37,843</td>
<td>225,166</td>
<td>807,551</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>33,638</td>
<td>200,146</td>
<td>717,818</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>2,102</td>
<td>12,507</td>
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<td>11</td>
<td>3</td>
<td>12,614</td>
<td>75,053</td>
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<td>17</td>
<td>71,482</td>
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<td>1</td>
<td>4,205</td>
<td>25,020</td>
<td>89,733</td>
</tr>
</tbody>
</table>

TOTALS 100 420,480 2,501,856 8,972,835 1,474,691
where $J_{yi}$ is the total amount of processing time used by the $i_{th}$ user in one year. The percentage of total time used for all fourteen users is given in the second column in Table 6.1. It was noted at the time that the percent use of off-peak time for an individual user was generally equal to $UO_{y}$. Therefore, estimated individual user refunds are calculated using $UO_{1990} = 0.35$ and $UP_{1990} = 0.65$.

6.6.4 Conclusions Reached and Decisions Made

Using these data, it was concluded in the meeting that (1) the demand was shifting too far in favor of off-peak access, and (2) overall use of the system was increasing at an alarming rate. From these conclusions, two decisions were reached. First, the off-peak rate in 1991 would have to be higher than in 1990 to slow the rate of increase of use of the total system. In addition, no matter what the off-peak rate was in 1991, it was observed that the system would be operating at 100 percent capacity in 1992, with $UP_{1992} = 0.5$ and $UO_{1992} = 0.5$.

The second decision reached was that since the internal measurement system indicated that demand was increasing so rapidly, it was expected that users would require more available service time in the future. Since all users would be required to pay for all costs of improvements in addition to O&M costs, it was decided that the Demand-Revealing Process would be employed to reveal the users' true preferences for any system improvement alternatives. It was further decided that enough information existed internally to develop system alternatives. From this, it was concluded that the Quality Function Deployment Process would not have to be employed again. Finally, the systems improvement alternatives would be developed using the Systems Engineering Process.
6.6.5 Determination of Rates for 1991 and 1992

After the meeting concluded, the SN Director decided to raise the off-peak CMO, from $17 per minute in 1990 to CMO$_{1991}$ = $18 per minute in 1991. It was estimated at this rate, the utilization U$_y$ would remain constant in 1991.

The utilization for off-peak in 1991 was estimated to be UO$_{1991}$ = 0.35, and utilization of peak time in 1991 was estimated to be UP$_{1991}$ = 0.65. In addition, total usage in minutes in 1991 UT$_{1991}$ was estimated to be 420,480. The minutes used in 1991 for off-peak time were estimated to be:

\[
UTO_{1991} = UO_{1991} \times UT_{1991}
\]

It follows then that UTO$_{1991}$ = 147,168 minutes. The cost per minute of peak time was then given by:

\[
\]

Substitution into this equation lead to a CMP$_{1991}$ = $26.90 per minute. Note that this is lower than in 1990. This is because the O&M cost was the same, the off-peak and on peak utilization had remained constant, and the off-peak rate had been marginally increased. It was expected that this increase in the off-peak rate would slow the increase in total demand for the system. Table 6.2 presents the estimated annual charges for each of the fourteen users in 1991. It should be noted that even though the off-peak rate had been raised, the system users would pay no more in total for service in 1991 then they did in 1990, and would
Table 6.2 Projected Annual User Charges in 1991

<table>
<thead>
<tr>
<th>USER</th>
<th>% USED IN 1990</th>
<th>MINUTES USED IN 1990</th>
<th>ESTIMATED CHARGES FOR 1991</th>
<th>TOTAL CHARGES PER USER IN 1991</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>OFF-PEAK TIME</td>
<td>PEAK TIME</td>
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<tr>
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<td>16,819</td>
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<td>20</td>
<td>84,096</td>
<td>529,805</td>
<td>1,470,419</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>8,410</td>
<td>52,983</td>
<td>147,049</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>37,843</td>
<td>238,411</td>
<td>661,685</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>33,638</td>
<td>211,919</td>
<td>588,160</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>2,102</td>
<td>13,243</td>
<td>36,754</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>12,614</td>
<td>79,468</td>
<td>220,556</td>
</tr>
<tr>
<td>12</td>
<td>17</td>
<td>71,482</td>
<td>450,337</td>
<td>1,249,863</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>21,024</td>
<td>132,451</td>
<td>367,605</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>4,205</td>
<td>26,492</td>
<td>73,524</td>
</tr>
<tr>
<td>TOTALS</td>
<td>100</td>
<td>420,480</td>
<td>2,649,025</td>
<td>7,352,095</td>
</tr>
</tbody>
</table>
receive the same amount of service during the off-peak hours they did in 1990. This is because $P_{yi}$ is a constant.

### 6.6.6 Development of Charge Schedule

After determining the expected charges for 1991, the engineering team developed an expected charge schedule for 1992. Table 6.3 presents the estimated charges per user in 1992. Since the total hours expected to be used in 1992 $UT_{1992}$ was equal to the available hours in 1992 (i.e., $AT_{1992} = 525,495$), the Central Agency decided to lower the cost of off-peak time to $CMO_{1992} = \$12$. Since $UO_{1992}$ was estimated to be 0.5, it follows that $UP_{1992}$ equaled 0.5. With $UO_{1992} = 0.5$ and $UT_{1992} = 525,495$, $UTO_{1992} = 262,748$ minutes. With this information, the engineers calculated the expected peak rate $CMP_y$ for 1992. It is as follows:

$$CMP_{1992} = \frac{[O&M_{1992} - UTO_{1992} \times CMO_{1992}]}{(UT_{1992} - UTO_{1992})}$$

So, $CMP_{1992}$ was estimated to be $\$26.06$ per minute.

### 6.6.7 Output from the Systems Engineering Process

To meet the requirements of the second decision, the engineers used the Systems Engineering Process. The output from the implementation of the Systems Engineering Process is included in Appendix A. The Systems Engineering Process was conducting by use of RDD-100, a computer based SE tool marketed by Ascent Logic Corporation. Output from RDD-100 was two independent alternative configurations. Configurations are the make-up of the
Table 6.3 Projected Annual User Charges in 1992

<table>
<thead>
<tr>
<th>USER</th>
<th>% USED IN 1991</th>
<th>MINUTES USED IN 1991</th>
<th>ESTIMATED CHARGES FOR 1992</th>
<th>TOTAL CHARGES PER USER IN 1992</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>OFF-PEAK TIME</td>
<td>PEAK TIME</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>21,020</td>
<td>$126,119</td>
<td>$273,888</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>57,804</td>
<td>346,827</td>
<td>753,192</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>36,785</td>
<td>220,708</td>
<td>479,304</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>31,530</td>
<td>189,178</td>
<td>410,832</td>
</tr>
<tr>
<td>5</td>
<td>6.5</td>
<td>34,157</td>
<td>204,943</td>
<td>445,068</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>105,099</td>
<td>630,594</td>
<td>1,369,440</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>10,510</td>
<td>63,059</td>
<td>136,944</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>47,295</td>
<td>283,767</td>
<td>616,248</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>42,040</td>
<td>252,238</td>
<td>547,776</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>2,627</td>
<td>15,765</td>
<td>34,236</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>15,755</td>
<td>94,589</td>
<td>205,416</td>
</tr>
<tr>
<td>12</td>
<td>17</td>
<td>89,334</td>
<td>536,005</td>
<td>1,164,024</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>26,275</td>
<td>157,649</td>
<td>342,360</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>5,255</td>
<td>31,530</td>
<td>68,472</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>100</strong></td>
<td><strong>525,495</strong></td>
<td><strong>3,152,970</strong></td>
<td><strong>6,847,200</strong></td>
</tr>
</tbody>
</table>
system (e.g., the number of satellites, ground antennas, and processors available).

The implementation of the Systems Engineering Process generated two independent configurations that could be employed to gain improvement of performance within the SpaceNetwork (Table 6.4). Configuration 1, developed in Section A.1, consisted of modification to the Space Network, with the expectation that the performance would improve. Modifications would be made to the existing ground antenna and processor to improve their reliability. As shown in Figure 6.8, the reliability of the Space Network would be $R_s = 1.060E-07$ with an MTBF = 5,455 hours. These modifications to the system would result in 57 more minutes of processing time being available per year (i.e., an $AT_y = 525,552$), and would occur at a LCCC(0%) = $18,000,000$. It follows that the total system life-cycle cost at zero percent interest would increase to $98,000,000.

The second independent configuration, developed in Section A.2, consisted of installing a second satellite system (i.e., both the existing system and the new system would be operated simultaneously). The satellite system would feature an improved ground antenna and processor such that the reliability of the Space Network when the new satellite system was added would be $R_s = 1.284E-22$, and with an MTBF = 1,738 hours (Figure 6.9). Adding an additional satellite would result in an additional LCCC(0%) = $118,000,000$. The effect on the Space Network would be a LCCC(0%) = $194,000,000$. If the satellite system were added, then the total available time $AT_y$ would increase to 1,050,882 minutes per year.
Table 6.4 Performance Gains Expected from Two Independent Projects

<table>
<thead>
<tr>
<th>PERFORMANCE CHARACTERISTICS</th>
<th>PROJECT 1: MODIFY EXISTING SYSTEM</th>
<th>PROJECT 2: INSTALL NEW SATELLITE SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROJECT LIFE</td>
<td>8 Years</td>
<td>8 Years</td>
</tr>
<tr>
<td>LCCC AT 0%</td>
<td>$98,000,000</td>
<td>$194,000,000</td>
</tr>
<tr>
<td>MTBF</td>
<td>5,455 Hours</td>
<td>1,738 Hours</td>
</tr>
<tr>
<td>EXPECTED UTILIZATION</td>
<td>100%</td>
<td>80%</td>
</tr>
<tr>
<td>PROCESSING HOURS AVAILABLE</td>
<td>525,552</td>
<td>1,050,882</td>
</tr>
<tr>
<td>PERCENT OF TIME ON PEAK RATE</td>
<td>50%</td>
<td>69%</td>
</tr>
<tr>
<td>PERCENT OF TIME ON OFF-PEAK RATE</td>
<td>50%</td>
<td>31%</td>
</tr>
<tr>
<td>AVAILABILITY</td>
<td>0.9999</td>
<td>0.9997</td>
</tr>
</tbody>
</table>
OVERALL SYSTEM RELIABILITY

\[ R_S = (0.9997) \times (6.755E-04) \times (1.569E-04) = 1.060E-07 \]

\[ L_S = \ln(1.060E-07)/ -87,600 = 1.833E-04 \]

MTBF \[ = 1/1.833E-04 = 5,455 \text{ Hours} \]

\[ A = 5,455/(5,455 + 0.5) = 0.9999 \]

Figure 6.8 Top-Level Reliability Block Diagram for the Space Network if Modifications Are Made to the Existing System
OVERALL SYSTEM RELIABILITY

\[ R_S = (0.9997)^2 \times (2.461 \times 10^{-8})^2 \times (1.569 \times 10^{-4}) \times (6.755 \times 10^{-4}) = 1.284 \times 10^{-22} \]

\[ L = \ln(1.284 \times 10^{-22}) - 87,600 = 5.754 \times 10^{-4} \]

\[ MTBF = 1/5.754 \times 10^{-4} = 1,738 \text{ HOURS} \]

\[ A = 1,738/(1,738 + 0.5) = 0.9997 \]
6.6.8 The Development of Mutually Exclusive Alternatives

Since the Demand-Revealing Process requires that alternatives put up for a vote be mutually exclusive, the two independent configurations had to be partitioned into four mutually exclusive alternatives. Table 6.5 shows this partitioning. As can be seen, there are four mutually exclusive alternatives (1) Do Nothing, Modify System, (3) Add Satellite, and (4) Add Satellite and Modify System (Add and Modify).

After carefully reviewing the mutually exclusive alternatives, the engineering team felt that the Modify the existing system and the Add Satellite alternatives could be ruled out immediately. In the case of the Modify System alternative, it was felt that the additional life-cycle cost of $18,000,000 was too high for the 57 minutes of extra processing time expected to be gained per year. In addition, the Add Satellite alternative was ruled out because the MTBF of 1,738 hours was significantly lower than the required system MTBF of 2,500 hours. It should be noted here that even though the Add Satellite alternative essentially doubled Space Network capacity in minutes per year, the failure rate is calculated by the number of failures per year. If the Add Satellite alternative system fails, then because it is a sequential system, double the amount of available system time will be lost.

If the Add and Modify alternative was selected, then it was expected that the user charges would be the same as in Table 6.2, but would also include the $100,000,000 initial cost of the alternative. Table 6.6 shows the estimated charges that users would incur in 1991 if the add and modify alternative was selected. It was also estimated that user charges in 1992 for the Do Nothing and
Table 6.5 Formulation of Four Mutually Exclusive Alternatives

<table>
<thead>
<tr>
<th>PERFORMANCE CHARACTERISTICS</th>
<th>MUTUALLY EXCLUSIVE ALTERNATIVES</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Do Nothing</td>
<td>Mod. System</td>
<td>Add Satellite</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td>----------------------------</td>
<td>---------------------------------</td>
<td>-------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>PROJECT LIFE</td>
<td>8 Years</td>
<td>8 Years</td>
<td>8 Years</td>
<td>8 Years</td>
</tr>
<tr>
<td>LOCAT 0%</td>
<td>$160,000,000</td>
<td>$288,000,000</td>
<td>$194,000,000</td>
<td>$212,000,000</td>
</tr>
<tr>
<td>MTBF</td>
<td>2,300 Hours</td>
<td>3,300 Hours</td>
<td>1,758 Hours</td>
<td>2,727 Hours</td>
</tr>
<tr>
<td>EXPECTED UTILIZATION</td>
<td>100%</td>
<td>100%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>PROCESSING HOURS AVAILABLE</td>
<td>321,920</td>
<td>321,922</td>
<td>1,030,882</td>
<td>1,030,890</td>
</tr>
<tr>
<td>PERCENT OF TIME ON PEAK RATE</td>
<td>30%</td>
<td>30%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>PERCENT OF TIME ON OFF-PEAK RATE</td>
<td>20%</td>
<td>30%</td>
<td>31%</td>
<td>31%</td>
</tr>
<tr>
<td>AVAILABILITY</td>
<td>0.9999</td>
<td>0.9999</td>
<td>0.9997</td>
<td>0.9998</td>
</tr>
</tbody>
</table>
Table 6.6 Projected Annual User Charges for 1991 if the Add and Modify Alternative is Selected

<table>
<thead>
<tr>
<th>USER</th>
<th>% USED IN 1990</th>
<th>MINUTES USED IN 1990</th>
<th>ESTIMATED COSTS FOR 1991</th>
<th>TOTAL CHARGES PER USER IN 1991</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>16,819</td>
<td>$4,000,000</td>
<td>$4,400,040</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>46,253</td>
<td>11,000,000</td>
<td>12,100,128</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>29,434</td>
<td>7,000,000</td>
<td>7,700,088</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>25,229</td>
<td>6,000,000</td>
<td>6,600,072</td>
</tr>
<tr>
<td>5</td>
<td>6.5</td>
<td>27,331</td>
<td>6,500,000</td>
<td>7,150,068</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>84,096</td>
<td>20,000,000</td>
<td>22,000,224</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>8,410</td>
<td>2,000,000</td>
<td>2,200,032</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>37,843</td>
<td>9,000,000</td>
<td>9,900,096</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>33,638</td>
<td>8,000,000</td>
<td>8,800,079</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>2,102</td>
<td>500,000</td>
<td>549,997</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>12,614</td>
<td>3,000,000</td>
<td>3,300,024</td>
</tr>
<tr>
<td>12</td>
<td>17</td>
<td>71,482</td>
<td>17,000,000</td>
<td>18,700,200</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>21,024</td>
<td>5,000,000</td>
<td>5,500,056</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>4,205</td>
<td>1,000,000</td>
<td>1,100,016</td>
</tr>
</tbody>
</table>

TOTALS 100 420,480 100,000,000 10,001,120 110,001,120
the Add and Modify alternatives would be the same as those given in Table 6.3. This is because the changes to the system would not take effect until January 1993 if the Add and Modify alternative was selected. Finally, the reliability for the Add and Modify alternative yields an $R_s = 1.123E-14$ and an MTBF = 2,727 hours (Figure 6.10).

The engineers noted that the expected demand for the Space Network if the Do Nothing alternative was selected would follow the profile given in Figure 6.11. As can be seen, it was expected that the demand would rise until 1992, and then remain constant until 1998. It should be noted that the demand from the beginning of 1992 through 1998 would be exactly the time available on the Space Network. In addition, it was projected that as minutes used per year $U_T$ rose to be equal to $A_T$ in 1992, the utilization during off-peak and peak would be $U_{O1992} = 0.5$ and $U_{P1992} = 0.5$ respectively. Further, it was predicted that

$$U_{Oy} = 0.5 \text{ for } y = 1993, 1994, ..., 1998$$

and

$$U_{Py} = 0.5 \text{ for } y = 1993, 1994, ..., 1998$$

if the Do Nothing alternative was selected.

The estimated annual user charges for 1993 if the Add and Modify alternative was selected are presented in Table 6.7. Since the O&M costs would increase to $O&M_{1993} = $14,000,000 per year and the expected $U_P$ and $U_O$ would change if the Add and Modify alternative was selected, it became necessary to
OVERALL SYSTEM RELIABILITY

\[ R_s = (0.9997)^2 \times (6.755E-04)^2 \times (1.569E-04)^2 = 1.123E-14 \]
\[ L = \ln(1.123E-14)/-87,500 = 3.663E-04 \]
\[ MTBF = 1/3.663E-04 = 2,727 \text{ Hours} \]
\[ A = 2,727/(2,727 + 0.5) = 0.9998 \]

Figure 6.10 Top-Level Reliability Block Diagram for the Add and Modify Alternative
Figure 6.11  Projected Space Network Utilization if the Do Nothing Alternative is Selected
Table 6.7 Projected Annual User Charges in 1993 if the Add and Modify Alternative is Selected

<table>
<thead>
<tr>
<th>USER</th>
<th>% USED IN 1993</th>
<th>MINUTES USED IN 1993</th>
<th>ESTIMATED CHARGES FOR 1993</th>
<th>TOTAL CHARGES PER USER IN 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>21,024</td>
<td>$83,255</td>
<td>$559,966</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>57,816</td>
<td>228,951</td>
<td>1,539,906</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>36,792</td>
<td>145,696</td>
<td>979,940</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>31,536</td>
<td>124,883</td>
<td>839,949</td>
</tr>
<tr>
<td>5</td>
<td>6.5</td>
<td>34,164</td>
<td>135,289</td>
<td>909,944</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>105,120</td>
<td>416,275</td>
<td>2,799,829</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>10,512</td>
<td>41,626</td>
<td>279,981</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>47,304</td>
<td>187,324</td>
<td>1,259,923</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>42,048</td>
<td>166,510</td>
<td>1,119,932</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>2,628</td>
<td>10,409</td>
<td>69,998</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>15,768</td>
<td>62,441</td>
<td>419,974</td>
</tr>
<tr>
<td>12</td>
<td>17</td>
<td>89,352</td>
<td>353,834</td>
<td>2,379,855</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>26,280</td>
<td>104,069</td>
<td>699,958</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>5,256</td>
<td>20,814</td>
<td>139,992</td>
</tr>
</tbody>
</table>

**TOTALS** 100 525,600 2,081,376 11,917,771 13,999,147
determine the expected charges per minute CMO\textsubscript{y} and CMP\textsubscript{y} in 1993. It was estimated that the minutes used in 1993 UT\textsubscript{1993} would be equal to 525,600.

An off-peak rate of CMO\textsubscript{1993} = $18/min was chosen to establish the rates. At CMO\textsubscript{1993} = $18/min, it was expected that the percent of time on off-peak rates UO\textsubscript{1993} would be 22%. From these estimates, it was determined that the total off-peak minutes consumed in 1993 would be:

\[ UTO_{1993} = UO_{1993} \times UT_{1993} \]

Thus, UTO\textsubscript{1993} was expected to be 115,632. The peak rate CMP\textsubscript{y} for 1993 was then determined as follows:

\[ CMP_{1993} = \frac{[O&M_{1993} - UTO_{1993} \times CMO_{1993}]}{(UT_{1993} - UTO_{1993})} \]

Substitution into the equation yielded CMP\textsubscript{1993} = $29.07/min.

The engineers also noted that if the Add and Modify alternative was selected, then the demand would rise at a decreasing rate until 1998. As Figure 6.12 shows, the demand would rise through 1992 (as in the Do Nothing alternative) but after 1992, more service time would be available to fulfill user demand. Essentially, by 1998, the users would have doubled their current consumption of service time. The projected demand rate for the Add and Modify alternative was determined to be an increasing function with a decreasing rate.

To model this phenomenon, an estimate of the projected minutes used UT\textsubscript{y} in 1993 and 1998 were required. Best estimates of these were UT\textsubscript{1993} = 525,600 and UT\textsubscript{1998} = 840,960.
Figure 6.12 Projected Space Network Utilization if the Add and Modify Alternative is Selected
A function of the form

\[ UT_y = (UT_{1998} + UT_{y-1})/2 \] for \( y = 1994,1995,\ldots,1997 \)

was then chosen to model the increasing function with a decreasing rate. It was also noted that as \( UT_y \) increased, so too would \( UO_y \). It was expected that \( UO_{1993} = 0.22, UO_{1994} = 0.22, UO_{1995} = 0.25, UO_{1996} = 0.30, UO_{1997} = 0.35 \), and \( UO_{1998} = 0.35 \). From this it follows that \( UP_{1993} = 0.78, UP_{1994} = 0.78, UP_{1995} = 0.75, UP_{1996} = 0.70, UP_{1997} = 0.65 \), and \( UP_{1998} = 0.65 \).

6.6.9 The Determination of a User's Preference

After completing the estimates of charges, utilization, and performance for the two mutually exclusive alternatives, the agency provided each user with the projected charges for each mutually exclusive alternative. All information developed to this point was given to users so that they could evaluate each alternative, and report their preference for a specific alternative.

As an example of the development of user preferences, consider the process taken by User One. User One decided to use life-cycle cost analysis to evaluate the net benefits they expected to receive from each alternative. Since the costs given by the Central Agency were in constant dollars, an inflation free interest rate \( i' \) was chosen. The calculation of \( i' \) requires estimates of the average inflation rate \( f \) from 1991 through 1998 and an MARR. The relationship is:

\[ i' = \left( \frac{1 + MARR}{1 + f} \right) - 1 \]

Since the inflation rate was estimated to be \( f = 4.8\% \) and the Federal Government's cost of money is roughly 10\%, it was determined that \( i' = 5\% \).
User One next chose a benefit in dollars per minute that they expected to receive during off-peak and peak time. These benefits were expressed in constant dollars. User One determined that their benefit during peak time was $35/min while the benefit during off-peak time was $23/min. User One next determined their total benefits per year for peak and off-peak time. This was done by using the estimated percentage use per year $\text{Py}_1 = 0.04$, and the estimates of $\text{UO}_y$, $\text{UP}_y$, and $\text{UT}_y$ provided by the Central Agency. The expected benefits for the Do Nothing alternative are shown in Table 6.8, while the expected benefits for the Add and Modify alternative are shown in Table 6.9. From Table 6.8, it can be seen that the total expected life-cycle benefits at $i = 0\%$ for the Do Nothing Alternative were $2,957,582$ during peak times and $1,827,503$ during off-peak time. Similarly, Table 6.9 shows that the expected life-cycle benefits at $i = 0\%$ for the Add and Modify alternative were $5,203,089$ during peak time and $1,563,386$ during off-peak time.

After determining the benefits expected to be received per year, User One used the cost and utilization information provided by the Central Agency to determine his/her annual cost for each alternative. These expected costs are shown in Tables 6.8 and 6.9. From Table 6.8, it can be seen that the expected total life-cycle cost at $i = 0\%$ for the Do Nothing alternative was $3,200,047$. In Table 6.9 it can be seen that the total life-cycle cost at $i = 0\%$ for the Add and Modify alternative was $8,160,013$.

At this point, User One determined their net life-cycle benefits for each alternative. This was done by subtracting the total cost in each year from the benefits expected to be received in that year. At this point, the net benefits per
Table 6.8 Expected Benefits and Costs for User One if the Do Nothing Alternative is Selected

<table>
<thead>
<tr>
<th>YEAR</th>
<th>MINUTES USED</th>
<th>PERCENT USE</th>
<th>EXPECTED BENEFITS</th>
<th>EXPECTED COSTS</th>
<th>NET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PEAK</td>
<td>OFF PEAK</td>
<td>PEAK</td>
<td>OFF PEAK</td>
</tr>
<tr>
<td>1991</td>
<td>16,819</td>
<td>65</td>
<td>35</td>
<td>$382,632</td>
<td>$135,393</td>
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<tr>
<td>1992</td>
<td>21,020</td>
<td>50</td>
<td>50</td>
<td>367,850</td>
<td>241,730</td>
</tr>
<tr>
<td>1993</td>
<td>21,020</td>
<td>50</td>
<td>50</td>
<td>367,850</td>
<td>241,730</td>
</tr>
<tr>
<td>1994</td>
<td>21,020</td>
<td>50</td>
<td>50</td>
<td>367,850</td>
<td>241,730</td>
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<tr>
<td>1995</td>
<td>21,020</td>
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<td>50</td>
<td>367,850</td>
<td>241,730</td>
</tr>
<tr>
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<td>21,020</td>
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<td>367,850</td>
<td>241,730</td>
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<tr>
<td>1997</td>
<td>21,020</td>
<td>50</td>
<td>50</td>
<td>367,850</td>
<td>241,730</td>
</tr>
<tr>
<td>1998</td>
<td>21,020</td>
<td>50</td>
<td>50</td>
<td>367,850</td>
<td>241,730</td>
</tr>
<tr>
<td>TOTALS</td>
<td>163,959</td>
<td></td>
<td></td>
<td>2,957,582</td>
<td>1,827,503</td>
</tr>
</tbody>
</table>
Table 6.9 Expected Benefits and Costs for User One if the Add and Modify Alternative is Selected

<table>
<thead>
<tr>
<th>YEAR</th>
<th>MINUTES USED</th>
<th>PERCENT USE</th>
<th>EXPECTED BENEFITS</th>
<th>EXPECTED COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PEAK</td>
<td>OFF PEAK</td>
<td>PEAK</td>
</tr>
<tr>
<td>1991</td>
<td>16,819</td>
<td>65</td>
<td>35</td>
<td>$382,682</td>
</tr>
<tr>
<td>1992</td>
<td>21,020</td>
<td>50</td>
<td>50</td>
<td>367,920</td>
</tr>
<tr>
<td>1993</td>
<td>21,024</td>
<td>78</td>
<td>22</td>
<td>573,955</td>
</tr>
<tr>
<td>1994</td>
<td>27,504</td>
<td>78</td>
<td>22</td>
<td>750,859</td>
</tr>
<tr>
<td>1995</td>
<td>30,744</td>
<td>75</td>
<td>25</td>
<td>807,030</td>
</tr>
<tr>
<td>1996</td>
<td>32,364</td>
<td>70</td>
<td>30</td>
<td>792,918</td>
</tr>
<tr>
<td>1997</td>
<td>33,174</td>
<td>65</td>
<td>35</td>
<td>754,709</td>
</tr>
<tr>
<td>1998</td>
<td>33,984</td>
<td>65</td>
<td>35</td>
<td>773,136</td>
</tr>
</tbody>
</table>

216,630  \hspace{1cm} 5,203,159  \hspace{1cm} 1,563,432  \hspace{1cm} 8,160,013  \hspace{1cm} -1,393,538
year were summed to provide a net benefit (i.e., the life-cycle benefit) for each alternative at an interest rate equal to zero. In Table 6.8, it can be seen that the expected net benefit for the Do Nothing Alternative was $1,585,038. From Table 6.9 it can be seen that the expected net benefit for the Add and Modify alternative was -$1,393,538. Thus, at an interest rate equal to zero, the Do Nothing alternative was providing more benefits than the Add and Modify Alternative.

Since User One is using an inflation free discount rate equal to 5%, calculations were performed to determine the present equivalent (PE) value of each of the alternatives. It was found that PE_{DN}(5\%) = $1,330,687, while the PE_{A&M}(5\%) = -$1,891,271. It was noted at that time that PE_{A&M}(0\%) = -$1,393,538 was greater than PE_{A&M}(5\%) since the first money flow of the Add and Modify alternative was negative and all other subsequent cash flows were positive. Thus, the net benefits received in the years 1992 and 1994 through 1998, while much greater than the net benefits received for the Do Nothing alternative in the same years, were not at least equivalent to the cost incurred in 1991 at any positive interest rate.

With this information, User One decided that he/she preferred the Do Nothing alternative to the Add and Modify alternative. Further, they determined that their preference for the Do Nothing alternative was $1,330,687; the present equivalent value of the alternative. This preference number was chosen because

18. It also follows that since all net benefits in any year are positive for the Do Nothing alternative and the total net benefit at i = 0 and the first money flow for the Add and Modify alternative is negative, then at any positive interest rate the Do Nothing Alternative would be preferred to the Add and Modify alternative.
the User One did not want to overstate or understate their preference for the Do Nothing alternative. Since the maximum tax imposed by the Demand-Revealing Process on a user if their vote is instrumental in alternative selection is equal to the user's stated preference, User One was careful not to overstate their preference. Further, User One chose their preference to be the present equivalent value of the Do Nothing alternative because, in this way, the tax imposed could never exceed the benefits they expected to receive from the alternative\(^\text{19}\). In addition, a present equivalent preference was used because the tax would be imposed in 1991 while the benefits were expected to accrue through 1998. Therefore, if User One had stated their preference to be the expected net benefits \(\text{PE}_{\text{DN}}(0\%) = 1,585,038\), then they may pay more in taxes than they will accrue in net benefits at their discount rate.

6.6.10 Implementation of the Demand-Revealing Process

After preference for an alternative is determined, the user reports the preference to the Central Agency. After all fourteen users preferences were collected, the Central Agency conducted the Clarke Tax calculation procedure. Table 6.10 shows the results of the Demand-Revealing Process. From the table, it can be seen that the Add and Modify alternative was preferred to the Do 

\(^{19}\) It should be noted here that there is no right or wrong way to determine a preference. While the approach presented for User One is logical, it may be that a certain user, when faced with the same costs and benefits as User One, will report a higher preference for the Do Nothing alternative to avoid the loss in net benefits if the Add and Modify alternative was selected. Similarly, another user may not wish to give up all of the benefits they expect to receive from an alternative. In this case, they may report a preference which is lower than that reported by User One. In all three cases however, the reported preference will be subject to the imposition of a tax. This tax may be as high as the reported preference. Therefore, whatever approach the user takes to establish their preference, they must be careful not to overstate it. Further, if the user understates their preference, they may run the risk of their preferred alternative being the loser.
Table 6.10 Results of the Demand-Revealing Process

<table>
<thead>
<tr>
<th>USER</th>
<th>REPORTED PREFERENCES FOR TWO ALTERNATIVES</th>
<th>CLARKE TAX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALTERNATIVE 0: DO NOTHING</td>
<td>ALTERNATIVE 3: MODIFY EXISTING SYSTEM, AND ADD CAPACITY</td>
</tr>
<tr>
<td>1</td>
<td>$1,330,687</td>
<td>$0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3,261,184</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2,075,299</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1,778,828</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1,927,061</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>5,929,425</td>
</tr>
<tr>
<td>7</td>
<td>592,943</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>2,668,241</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>2,371,770</td>
</tr>
<tr>
<td>10</td>
<td>148,236</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>889,414</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>5,040,011</td>
</tr>
<tr>
<td>13</td>
<td>1,482,356</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>296,471</td>
<td>0</td>
</tr>
</tbody>
</table>

4,740,107 | 25,051,819 | 0
Nothing alternative. Specifically, the Add and Modify alternative had reported preferences of $25,051,819 while the Do Nothing alternative had reported preferences of $4,740,107. Consequently, the Clarke Tax imposed was zero since the removal of any of the preferences for the Add and Modify alternative will still result in the Add and Modify alternative being selected. Since the Clarke Tax was zero, it was concluded that the quality of the analysis was such that the user's true preference was known prior to implementation of the Demand-Revealing Process. It should be noted that the analysis was so good that the preferences for the Do Nothing alternative could increase by 400% and the Add and Modify alternative would still be preferred with no tax imposed.

6.6.11 Some Observations Regarding this Hypothetical Example

It can be argued through this example that the problems inherent with the Demand-Revealing Process are mitigated or eliminated when the Quality Function Deployment Process and elements of the Systems Engineering Process are applied prior to implementation of the Demand-Revealing Process. Consider first the problem of information incentives. As was shown in Chapter Five, the tax would be proportional to the quality of the analysis performed to develop the mutually exclusive alternatives. Therefore, users would have a very high incentive to receive and provide accurate information. By first applying the Quality Function Deployment Process, modifying the information system, and then employing elements of the Systems Engineering Process, alternatives were arrived at that in general, satisfied user requirements. Hence, the overwhelming preference for the Add and Modify alternative.
Next, consider the problem of mutual participant benefit. By using appropriate measures, partially developed through the Quality Function Deployment Process and then installed in the internal measurement system, the Central Agency was able to determine with a fair degree of certainty that most users would benefit from an increase in system capacity. When the internal measurement system indicated the dramatic increase in demand in December of 1990, it was also known that all users had increased their usage of the system. Hence, the Central Agency could infer that all users would increase their demand for time on the Space Network if more time could be made available at a reasonable cost.

The next problem to be considered is that arising from coalitions. It should be noted that the desire of the Demand-Revealing Process is to achieve allocation efficiency. This sometimes comes at the expense of equitable distribution. In this example, a minority of users stated preferences for the Do Nothing alternative, while a majority stated preferences for the Add and Modify alternative. It seems unlikely, given these circumstances, that coalitions would be formed by the users who chose the Add and Modify alternative since they are in the majority. However, the users who form the minority may well have attempted to form a coalition to prevent the Add and Modify alternative form being selected. If they were to do this however, they would need to raise their aggregate preferences by more than 400%. In this case, it seems unlikely that they would do that because they would run the risk of incurring a tax burden that was substantially larger than the benefit they would receive by being in the coalition. This information points to the conclusion that the quality of the analysis prior to enactment of the Demand-Revealing Process provided
alternatives that were preferred by the majority of the users, and further, by a substantial margin.

In some cases, it may be beneficial to partition coalitions, if they exist. However, in this case, the initial system cost is prohibitive. In addition, the O&M costs are fixed annually. If user groups were partitioned into coalition groups and allowed to use different systems, then the marginal cost of each system would be higher than the marginal cost if all coalitions used the same system.

The next problem to be considered is monetary valuations. Money valuations affect the selection of an alternative since users are allocated initial costs on a percentage of use basis. It is assumed that the users requiring more service time per year also have larger budgets. Therefore, the annual costs for each user may be viewed as a percentage of their wealth. By viewing the problem in this way, we can show that the costs were fairly allocated to users, and further that money valuation effects should be mitigated. Costs were fairly allocated to users since they are paying for exactly the amount of service they use and no more. Second, money valuations are reduced because users will incur a charge per year that is proportional to their budget. Therefore, users requiring more service will have to pay more annually than user requiring less service. It follows then that their wealth levels are identically proportional to the amount of service required. Therefore, the user with the larger total wealth will not be able to dominate the user with less wealth. Hence, income valuations have been mitigated.

The other four problems identified with Demand-Revealing Processes, (1) income effects, (2) cycling, (3) bankruptcy, and (4) inordinate amount of proposals were negated. First, income effects were not evident in this example
problem since only two mutually exclusive alternatives were voted upon. If more than two alternatives were to be voted upon, then the Central Agency could have either restricted preference reports to be each alternative against the do nothing alternative, or a measure to combat cycling could have been enacted. For the problem of bankruptcy, it is quite likely that the Central Agency would make certain that the expected allocated costs for each user could be paid out of their budgets, i.e., no deficit would result. The problem of an inordinate number of proposals is not likely to result in this case domain since there exist a limited number of users who share a limited amount of resources.

As a final observation, it may be noted that if a decision mechanism employing utility functions were used, then 112 utility functions would have to be developed\(^{20}\). Further, each of the mutually exclusive alternatives would need to be compared using these 112 utility functions. Comparison would be made using an additive or multiplicative function designed to aggregate all utility functions. By using the Demand-Revealing Process, the Central Agency has avoided the necessity of developing these utility functions and, further, has achieved decision selection that is just as good as would have resulted from a decision mechanism employing utility functions. In addition, the Demand-Revealing Process may require less cost in time, manpower, and dollars than utility analysis.

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\(^{20}\) Since there are 8 performance measures and 14 users, there will be \(8 \times 14 = 112\) utility functions. Also, the real Space Network has hundreds of performance measures and a large amount of users. Since the number of utility functions required to capture each user's preferences would be extremely high, it would be most likely that a Supra-User's utility function would be used. The Supra-User would most likely be the person responsible for design and development of the Space Network. It should be noted that if a Supra-User's utility function is used in lieu of all user's utility functions, then all user's preferences are not likely to be represented. Hence, it can be concluded that as the number of performance measures and users increase, the Demand-
VII. APPLICABILITY OF THE INTEGRATED DECISION APPROACH

7.1 Effects of Violations of the Three Necessary Conditions

The Integrated Decision Approach relies on decentralized decision making, and thus, is completely applicable to groups that meet the three conditions stated in Section 1.3. It is important that the three conditions be binding at all times during the system life-cycle. Reasons for this are as follow. If the first condition, a definite number of users exists, is violated, then there would exist an indefinite number of users. If an indefinite number of users exist, then it would not be possible to identify all of them. This first violation, however, would not be likely to occur in practice, so it can be considered to be a minor problem. However, it does point to the fact that as the number of users increases (and their attributes are known), it may be more difficult to identify all users. Further, as was shown, the incentive to provide information decreases.

Violations of the second constraint will always be more serious than the first. This is because the Demand-Revealing Process is eliciting preference based upon users stated demand schedules. If the users incurred no cost for the system, they may have a tendency to overstate their demand (i.e., will exhibit an inelastic demand schedule that will shift outwards). Overstated demand occurs because the only cost that would be imposed upon a user would be Clarke Tax. In the situation considered by public choice researchers, the cost and the tax may be low. Cost and tax are low because, in the environment the Demand-

Revealing Process is more favorable than centralized decision mechanisms relying on utility functions.
Revealing Process is being applied, a large number of users exist (a 100,000 or more is not uncommon). Users are, however, told their marginal cost for an alternative and asked to develop a demand schedule (i.e., reflect of preference and utility for an alternative). In the domain being considered here, the number of users is much lower than is considered by public choice researchers, and the cost per user will be much higher. If all costs are not incurred (particularly initial costs) by the users, then demand may be highly inelastic. Thus, preferences may be overstated.

Violations of the third condition, users may use no alternate system once operation begins, may have the most serious consequences on system operation. This violation is the most severe since all charges including initial cost, O&M, and phase-out have been calculated based upon a certain number of users. If one user were to depart, then the costs incurred by all other users would be increased marginally. Since the Demand-Revealing Process was run with certain cost expectations being made explicit to users, the preferences of all remaining users after a user had withdrawn may be different. That is, they may receive less benefits then had originally been intended. Of course, some users may benefit by others withdrawing since more system capacity may be available. In this case, the users preferences would have been understated when the Demand-Revealing Process was run if they voted for the alternative that was selected, or, if they voted for another alternative, they may have reached decision reversal when faced with the information that more capacity was available. In either case, the results provided by the Demand-Revealing Process would no longer be valid after a user has departed. This lack of validity is especially true when the number of users is low.
7.2 Problems that this Integrated Decision Approach may Solve

This approach may be applied to a wide range of problems that meet the necessary conditions. If the necessary conditions are not initially met, then it may be possible to change the system under study so they are met. This approach may be used to solve problems that range in complexity from simple to extremely difficult. Some examples of simple problems are: (1) selection of a copier that is shared, and (2) selection of a shared micro or mini computer system. Examples of problems with medium difficulty are: (1) selection of a building where functional organizations must share and pay for space, and (2) selection of a shared mainframe computer system. Some examples of problems with extreme difficulty are: (1) development of a system of satellites for a set of users with heterogeneous demands, (2) selection of a site for an airport, and (3) the development of a power plant for a community.

As was shown, these types of problems may also be addressed by centralized decision mechanisms, but there is no need to do this since the results should be the same. Further, the results will be obtained faster, and at less cost.
VIII. SUMMARY, CONCLUSIONS, AND EXTENSIONS

8.1 Summary

The objective of this research was to provide an approach that could be used to make decisions when the three conditions stated in Section 1.3 are binding. As the first step to meet this objective, decision mechanisms were compared. It was shown that decision mechanisms may be classified as either centralized or decentralized. It was further shown that centralized decision mechanisms that rely on utility analysis provide the best results (i.e., reveal user preferences better than other centralized mechanisms). Next, it was shown that the Demand-Revealing Process, a decentralized decision mechanism, may also reveal user preferences as well as utility mechanisms. However, it was shown that the Demand-Revealing Process has several inherent deficiencies that had to be corrected before it could yield satisfactory results as a decision mechanism.

At this point, it was postulated that the Quality Function Deployment Process and elements of the Systems Engineering Process could be used to alleviate these deficiencies if they were employed prior to implementation of the Demand-Revealing Process. As was shown, the decision process consists of three stages. The first stage is enabled either by the formal information system or by informal information. After the first stage of the decision process is enabled, it was shown that the Systems Engineering Process could be used during stage two of the decision process to generate system design alternatives. The Systems Engineering Process begins with the identification of a specific need (or needs) for a system and ends when detailed design and development activities are completed. The Systems Engineering Process occurs during the
early phases of a system's life-cycle, but must account for all activities within all phases of the system's life-cycle. However, the emphasis in this research was to determine how the Systems Engineering Process could be used with the Demand-Revealing Process to make early design decisions. Therefore, it was shown that the third stage of the Systems Engineering Process, detail design and development, would not occur until the Demand-Revealing Process was completed. This order of implementation was logical since the objective was to develop an approach that could be used to make early design decisions, and thus, result in resources being committed as early as possible to designs that would truly fulfill user expectations. In addition, it was shown that the Demand-Revealing Process would be applied after alternative trade-off and optimization, but before system synthesis and definition and the preliminary design review. As such, detail design and development activities were not considered.

In addition, since use of the Systems Engineering Process necessitates the development of requirements, a process to enable this was studied. The process studied was the Quality Function Deployment Process. It was further shown that the Quality Function Deployment Process only need be applied when enough information does not exist in the formal measurement system to develop all requirements. Finally, the resulting approach included all activities that would be conducted through the selection of a specific candidate system to be implemented.

A hypothetical example was constructed to show how the Integrated Decision Approach works. A real-world system was selected as the basis of the problem, but several assumptions had to be made to make the problem workable. The
example began in 1989 with the baseline system, and performance measures that were being applied at that time. It was then shown that system users were dissatisfied with the service they were receiving from the system. Since the internal measurement system did not provide enough information to develop the complete set of user concerns, the Quality Function Deployment Process was enacted. Quality Function Deployment output was a complete set of performance measures that accurately reflected user attributes. At this point, a variable rate policy was enacted to alleviate congestion during peak hours, and the internal measurement system was modified to reflect these measures.

In the following year it was shown that demand was increasing. Since the internal measurement system provided all necessary information to make changes, the Quality Function Deployment Process was not applied again. Instead, user requirement's were developed directly from the internal measurement system, and constituted the initial entry into the Systems Engineering Process. Implementation of the elements of the Systems Engineering Process resulted in four mutually exclusive alternatives. Two of these alternatives were immediately ruled out. The Demand-Revealing Process was then enacted as a means of selection between the two remaining alternatives. As was shown, the quality of the analysis that preceded the Demand-Revealing Process was such that no tax was charged. It was concluded that the Integrated Decision Approach mitigated or eliminated the inherent deficiencies of the Demand-Revealing Process. Because of this, it was shown that the Integrated Decision Approach could be employed to implement the decision process when the three conditions are binding.
8.2 Conclusions

An approach has been postulated which addresses a class of public sector decision problems. As was shown, solutions to this class of problems typically consume large amounts of resources (both time and money). Because of the inefficiency of currently used approaches, it was demonstrated that an alternative approach should be developed with the purpose of being more efficient than currently employed approaches. The Integrated Decision Approach was developed in response to the need for these better approaches.

Second, this research has shown that an Integrated Decision Approach can be developed that makes operational a three-step decision process. The approach is applicable to decisions which meet the conditions described in Section 1.3 and may provide selection which is as good as could be obtained by utility function approaches. Near the end of the research, it was found that Herbert Simon (1960) postulated a three-step decision process. Since this author developed the three-step decision process without being aware of Simon's model, this lead to the conclusion that the three-step process or model may be a good representation of the steps taken to make a decision.

Third, the Integrated Decision Approach is face valid because an hypothetical example was constructed which demonstrated that each path within the Integrated Decision Approach would work in this instance. Therefore, it was shown that the Integrated Decision Approach will work at least once.

Finally, Demand-Revealing Processes were not widely accepted in the past. This was mainly because of the deficiencies which were inherent within the processes
themselves. This research has demonstrated, through an hypothetical example, that the Demand-Revealing Processes will provide better results if they are used as a component within the Integrated Decision Approach. Therefore, many of the objections to Demand-Revealing Processes will be overcome when the Integrated Decision Approach is employed.

8.3 Extensions

During this research, it was stated that the Integrated Decision Approach may be compared to utility analysis. It was shown that the results obtained from this approach may be as good as results that could be obtained from decision mechanisms that rely on utility functions for the three necessary decision conditions stated.

It is recommended that further research be done in this area to establish empirical evidence to determine if the results obtained from the Integrated Decision Approach would be as good as those that could be obtained from utility functions. It is therefore recommended that the Integrated Decision Approach and a decision mechanism that relies on utility functions be applied simultaneously to the same decision problem after the completion of Systems Engineering and Quality Function Deployment, if necessary. This application should be applied to an organizational decision that meets the conditions stated in Section 1.3. Some bias may be removed by applying Systems Engineering and Quality Function Deployment prior to enactment of the two decision mechanisms.
VIII. REFERENCES

8.1 References Cited


Groves, Theodore and John O. Ledyard, "Reply to Comments by Tideman and Tullock and Greenberg, Mackay and Tideman on some Limitations of Demand Revealing Processes." (Spring-1977) 29, 2: 140-143.


Network Control Center Block II Project History Report, Greenbelt, Maryland: National Aeronautics and Space Administration - Goddard Space Flight Center, 1990.


8.2 Additional Works Consulted


Moulin, Hervé and Scott Shanked, "Serial Cost Sharing." Paper prepared for Discussion within Economic Department at Virginia Polytechnic Institute and State University.


APPENDIX

As noted in Chapter 6, RDD-100 (Requirements Driven Development), a computer-based Systems Engineering development tool, was used to develop the two independent configurations. The output from RDD is exhibited in its original form herein. The process was initiated with the input of requirements and terminated with the allocation of inputs and outputs to interfaces.

The RDD-100 tool is a large, interactive data-base which allows systems engineers to input requirements, and determine constraints. A Behavior Diagram is then created by the systems engineer. The Behavior Diagram is actually an input/output analysis coupled to a functional analysis. After this is complete, various system configurations are developed, each which must fulfill the requirements, constraints, and enable the Behavior Diagram. Performance indexes are created off-line. These indexes reflect how well the chosen architecture will fulfill certain performance metrics and measures. Finally, a schematic of the system architecture is developed. All inputs, outputs, and functions are linked to the architecture components or the interfaces between components. The information resulting can then be used to determine the preferred alternative. In this case, the output will form input into the Demand-Revealing Process.
This section contains the output from RDD-100 for the first configuration. During the process, performance measures (termed performance indexes in RDD) were created for the system. These were established by parametric estimation.
1 System Top-Level Description

Modifications to Existing System

Purpose:
This system consists of the Space Network after modifications have been done to increase the reliability of the ground antenna and processor facilities. Consequently, this is the first of the independent projects.

1 - Space Network with modifications

Built From Sub-Components:
Subsystem: 1.1 Satellite
Subsystem: 1.2 Ground antenna
Subsystem: 1.3 Central processor

2 - Maintenance components

Built From Sub-Components:
Facility: 2.1 Fault detection center
Human: 2.1 Maintenance crew

External Interfaces:
Subsystem: 1.3 Central processor
Subsystem: 1.1 Satellite
ExternalSystem User computing facility
ExternalSystem User space vehicle

Performs Top-Level Function: Space Network

Description of System Mission(s):
This function, Space Network, facilitates the Space Network's mission statement. This function is further decomposed to show how various elements of the Space Network combine to fulfill the mission statement.

System-Level "Originating" Requirements:
1 - Mission

Design Constraints:
Availability
MTBF
MTTR
O&M

Source Document:
Space Network Meeting Results - December, 1990.

First-Level System Functions:
Space Network
TimeFunction 1.1 Receive user request
TimeFunction 1.2 Transmit user request
TimeFunction 1.3 Wait for acknowledgement
TimeFunction 1.4 Bring down information from user space vehicle
TimeFunction 1.5 Terminate job request
TimeFunction 1.6 Provide information to user
TimeFunction 1.7 Detect fault
TimeFunction 1.8 Dispatch maintenance crew
TimeFunction 1.9 Repair fault
2 System-Level ("Originating") Requirements

1 Mission

Description:
The Space Network was developed to allow Spaceflight Projects (users) to communicate with their respective space vehicles. The Space Network as it stands now is composed of one satellite, one ground antenna, and one central processor. The system was developed to allow users to contact their respective vehicles 24 hours per day, 365 days per year. The Space Network began operation in January of 1989 and is scheduled to complete operation in December of 1998. Since demand for the system has increased significantly in 1990, it has been determined that the system users may benefit from an increase in capacity. Capacity should be in the form of an increase in available time on the Space Network.

Incorporates System Requirement(s):
1.1 - Cost Per Minute
1.2 - Yearly Refund
1.3 - Residual Error Rate
1.4 - Reliability
1.5 - Mean Time to Repair
1.6 - Utilization
1.7 - Mean interarrival time
1.8 - Mean Service Time
1.9 - Availability

Trace To:
TimeFunction: 1 - Space Network

Source Document:
Space Network Meeting Results - December, 1990.

1.1 Cost Per Minute

Description:
The cost per minute is the amount charged users per minute of time used on the Space Network. Further, cost per minute can be divided into cost per minute during peak time, and cost per minute during off-peak time.

1.2 Yearly Refund

Description:
The yearly refund is the total amount of money refunded to users at the end of a year.

1.3 Residual Error Rate

Description:
The Residual Error Rate is used to determine how much error will be tolerated per year. In this case, the maximum error is 0.001%.

1.4 Reliability

Description:
The reliability of the Space Network shall be such that the MTBF in any year is no less than 2,500 hours. Since the satellite cannot be repaired, the reliability of this component should be at least 0.99998.
1.5 Mean Time to Repair

Description:
The mean time to repair (MTTR) for the Space Network is 0.5 hours. Since the satellite cannot be repaired, the MTTR applies only to the ground antenna and the central processor.

1.6 Utilization

Description:
Utilization for the Space Network is calculated monthly and yearly. Utilization can be further classified as utilization during peak hours and utilization during off-peak hours.

1.7 Mean interarrival time

Description:
Mean interarrival times are exponentially distributed, and reflect the time elapsed between job arrivals. The mean interarrival time in January of 1990 was 15 minutes.

1.8 Mean Service Time

Description:
Mean service times on the Space Network are exponentially distributed. The mean service time in December of 1990 was expected to be 10 minutes. Mean service time will not decrease unless faster processing of jobs is made available.

1.9 Availability

Description:
The availability for the Space Network should be 0.9998 in any year, and is defined by MTBF/(MTBF + MTTR).
3 Design Constraints

1.1 Availability

Description:
The availability for the Space Network must be at least 0.99998.

Constraints:
TimeFunction 1  Space Network

1.2 MTBF

Description:
The MTBF for the Space Network must be at least 2,500 hours.

Constraints:
TimeFunction 1  Space Network

1.3 MTTR

Description:
The mean time to repair can be at most 30 minutes.

Constraints:
TimeFunction 1  Space Network

1.4 O&M

Description:
The O&M costs should be at most $15,000,000 per year in constant dollars.

Constraints:
TimeFunction 1  Space Network
5 Hierarchical Function List

1.1 Receive user request
1.2 Transmit user request
1.3 Wait for acknowledgement
1.4 Bring down information from user space vehicle
1.5 Terminate job request
1.6 Provide information to user
6 System Functional Behavior Description

Behavior Model for "Space Network"
1.1 Receive user request

Description:
User enters job request on FCF5 queue. Includes all code required to establish linkage between user space vehicle and space network. This package will include location of user vehicle, desired transmission frequency, code to gather required data/information, and location to send desired information.

Inputs:
- Fault repaired
  - source: Human: 2.1 Maintenance crew
  - Job request

Outputs:
- Fault detected
  - destination: Facility: 2.1 Fault detection center
  - Job request package
    - destination: 1.2 - Transmit user request

1.2 Transmit user request

Description:
Establish linkage between user space craft and Space Network elements.

Inputs:
- Job request package
  - source: 1.1 - Receive user request

Outputs:
- Job processing requirements
  - destination: 1.3 - Wait for acknowledgement

1.3 Wait for acknowledgement

Description:
Wait for start transmission signal from user space vehicle.

Inputs:
- Job processing requirements
  - source: 1.2 - Transmit user request
  - Proceed with transmission

Outputs:
- Specific job package
  - destination: 1.4 - Bring down information from user space vehicle

1.4 Bring down information from user space vehicle

Description:
Receive information from the user space craft. Will hold information in a temporary buffer (this is because some user's cannot process information as fast as the Space Network can deliver it).

Inputs:
- Specific job package
  - source: 1.3 - Wait for acknowledgement

Outputs:
- Job completed
  - destination: 1.5 - Terminate job request
- Requested information
  - destination: 1.6 - Provide information to user
1.5 Terminate job request

Description:
Tear-down linkage between Space Network and user space vehicle.

Inputs:
Job completed
  source: 1.4 - Bring down information from user space vehicle

1.6 Provide information to user

Description:
Take information stored in Space Network and transmit to users.

Inputs:
Requested information
  source: 1.4 - Bring down information from user space vehicle

Outputs:
Information from the space vehicle

1.7 Detect fault

Description:
Determine that system is inoperable or will soon be inoperable. May be either solid or intermittent fault.

Inputs:
Fault detected
  source: 1.1 - Receive user request

1.8 Dispatch maintenance crew

Description:
Give maintenance crew location of fault area.

1.9 Repair fault

Description:
Determine cause of fault and repair.

Outputs:
Fault repaired
  destination: 1.1 - Receive user request
7 Performance Indices

1 Modify Space Network estimated performance

Description:
The performance of the Space Network after Modify Project is selected can be estimated. The following
measures are used to describe network performance, and thus, show how this prospective change will affect
users.

Category:
Top-level performance

Value:
0.0

Units:
No standard units

Exhibited By:
Component: 1 - Space Network with modifications

1.1 Project life

Description:
The project should last 8 years. Detail design will begin after alternative selection. If the modify project is
selected, then it is expected modifications will be completed by the end of 1991. The Space Network will
then end operation at the end of 1998.

Category:
Life-length

Value:
8.0

Units:
Years

1.2 LCCC at 0%

Description:
It is expected that the design, development, implementation, and operation of the modify project will result
in a LCCC at 0% of $8,000,000. Therefore, the LCCC of the Space Network at 0% from BOY 1991
through EOY 1998 is expected to be $98,000,000.

Category:
System Cost

Value:
9.8e7

Units:
Discounted dollars
1.3 MTBF

Description:
The MTBF for the Space Network if the modify project is accepted is expected to be 5,455 hours.

Category:
Dependability

Value:
5455.0

Units:
Hours

1.4 Expected Utilization

Description:
It is expected that the Space Network will experience 100% utilization from BOY 1991 through EOY 1998 if the modify project is accepted.

Category:
Timeliness

Value:
100.0

Units:
Percent available hours used

1.5 Processing hours available

Description:
If the modify project is selected, then there will be 525,495 hours available on the Space Network in 1991 and 525,552 hours available per year from BOY 1992 through EOY 1998.

Category:
Timeliness

Value:
525552.0

Units:
Hours

1.6 Percent of time on peak rate

Description:
If the modify project is selected, then it is expected that the percent of peak time used will be 100%. Thus, out of the total time used, 50% will be consumed during peak hours.

Category:
Timeliness

Value:
50.0

Units:
Percent of total job requests that will be run during peak hours.
1.7 Percent of time on off-peak rate

Description:
If the modify project is selected, then it is expected that of the total time used, 50% will be during off-peak hours.

Category:
Timeliness

Value:
50.0

Units:
Percent of total job requests that will be run during off-peak hours.

1.8 Availability

Description:
Availability for the Space Network is estimated to be 0.9999, and is defined by MTBF/(MTBF + MTTR).

Category:
Timeliness

Value:
0.9999

Units:
Percent of time that the system is available.

1.9 Mean time to repair

Description:
The mean time to repair for the modify alternative is 30 minutes.

Category:
Dependability

Value:
0.5

Units:
Hours

1.10 Residual error rate

Description:
Residual error rate is used to determine the percent of error bits versus bits that are not in error.

Category:
Dependability

Value:
1.0e-4

Units:
Percent of error bits
8 Item Dictionary

1. A Job request

Input To:
  TimeFunction 1.1 Receive user request

1. B Job request package

Output From:
  TimeFunction 1.1 Receive user request

Input To:
  TimeFunction 1.2 Transmit user request

1. C Job processing requirements

Output From:
  TimeFunction 1.2 Transmit user request

Input To:
  TimeFunction 1.3 Wait for acknowledgement

1. D Proceed with transmission

Input To:
  TimeFunction 1.3 Wait for acknowledgement

1. E Specific job package

Output From:
  TimeFunction 1.3 Wait for acknowledgement

Input To:
  TimeFunction 1.4 Bring down information from user space vehicle

1. F Requested information

Output From:
  TimeFunction 1.4 Bring down information from user space vehicle

Input To:
  TimeFunction 1.6 Provide information to user
1.6 Job completed

Output From:
  TimeFunction 1.4 Bring down information from user space vehicle

Input To:
  TimeFunction 1.5 Terminate job request

1.7 Fault detected

Output From:
  TimeFunction 1.1 Receive user request

Input To:
  Facility: 2.1 Fault detection center

1.8 Fault repaired

Output From:
  Human: 2.1 Maintenance crew

Input To:
  TimeFunction 1.1 Receive user request

1.9 Information from the space vehicle

Output From:
  TimeFunction 1.6 Provide information to user
9 Components

1 Space Network with modifications
   Component Type:

   Description:
   The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

   Built From Components:
   Subsystem: 1.1 Satellite
   Subsystem: 1.2 Ground antenna
   Subsystem: 1.3 Central processor

   Component-Level Performance Requirements:
   Modify Space Network estimated performance

1.1 Satellite
   Component Type: Subsystem

   Description:
   The Space Network with modifications has one satellite whose purpose is to link user space vehicles to the ground antenna.

   Builds Higher-Level Component/System:
   Component 1 Space Network with modifications

1.2 Ground antenna
   Component Type: Subsystem

   Description:
   The ground antenna, located in New Mexico, serves the purpose of linking the central processor to the satellite.

   Builds Higher-Level Component/System:
   Component 1 Space Network with modifications

1.3 Central processor
   Component Type: Subsystem

   Description:
   The central processor, located in Maryland, serves the purpose of linking the ground antenna to the users' computer systems.

   Builds Higher-Level Component/System:
   Component 1 Space Network with modifications

2 Maintenance components
   Component Type:

   Description:
   The Space Network has two maintenance components. They are the Fault Detection Center, and the Maintenance Crews.

   Built From Components:
   Facility: 2.1 Fault detection center
   Human: 2.1 Maintenance crew
2.1 Fault detection center  
Component Type: Facility

Description:
The Fault Detection Center has the responsibility of detecting and isolating faults in all components of the Space Network. After detection and isolation, the Fault Detection Center dispatches maintenance crews at the appropriate locations. If failure occurs in the satellite, then automatic back-up (i.e., redundant systems) are to automatically resume operation.

Builds Higher-Level Component/System:
Component 2  Maintenance components

2.1 Maintenance crew  
Component Type: Human

Description:
Two maintenance crews will be available. One crew will reside at the ground antenna location, and one crew will reside at the central processor location. These crews will be available 24 hours per day. Training will be specific to each type of component worked on, i.e., ground antenna or central processor. These crews will also be available to perform maintenance on other systems operated by NASA. Hence, having them available 24 hours per day will not seriously affect the O&M costs.

Builds Higher-Level Component/System:
Component 2  Maintenance components
10 Interfaces Between Components

Derived Interfaces

Database Interface Elements

1.1 Satellite-user vehicle interface

Description:
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

Connects to:
System Modifications to Existing System
External System User space vehicle
Subsystem: 1.1 Satellite

Comprised of Link: Space vehicle information
Comprised of Link: User job request

1.2 Satellite tracking interface

Description:
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

Connects to:
Subsystem: 1.1 Satellite
Subsystem: 1.2 Ground antenna

Comprised of Link: Job request package
Comprised of Link: Specific job package

1.3 Ground link-processor interface

Description:
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

Connects to:
Subsystem: 1.2 Ground antenna
Subsystem: 1.3 Central processor

Comprised of Link: Job request package
Comprised of Link: Requested info.
1.4 Central processor-user processor interface

*Description:*
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

*Connects to:*
- System: Modifications to Existing System
- ExternalSystem: User computing facility
- Subsystem: 1.3 Central processor

Comprised of Link: Job completed

Comprised of Link: Job request

Comprised of Link: Requested information

2.1 Fault detection-satellite interface

*Description:*
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

*Connects to:*
- Subsystem: 1.1 Satellite
- Facility: 2.1 Fault detection center

Comprised of Link: Fault monitoring of satellite

2.2 Fault detection-ground antenna interface

*Description:*
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

*Connects to:*
- Subsystem: 1.2 Ground antenna
- Facility: 2.1 Fault detection center

Comprised of Link: Fault monitoring of ground antenna

2.3 Fault detection-central processor interface

*Description:*
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

*Connects to:*
- Subsystem: 1.3 Central processor
- Facility: 2.1 Fault detection center

Comprised of Link: Fault monitoring of central processor
2.4 Fault detection-maintenance crew interface

Description:
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

Connects to:
Facility: 2.1 Fault detection center
Human: 2.1 Maintenance crew

Comprised of Link: Maintenance instructions
This section contains the output from RDD-100 for the second independent configuration. During the process, performance measures (termed performance indexes in RDD) were created for the system. These were established by parametric estimation.
1 System Top-Level Description

Install Additional Satellite System

Purpose:
This system consists of the Space Network after the new satellite system has been added to increase the amount of time available on the Space Network in a given year. Consequently, this is the second of the independent projects.

1 - Space Network with additional satellite system
   Built From Sub-Components:
   Subsystem: 1.2 Ground antenna
   Subsystem: 1.3 Central processor

Subsystem: 1.1 - Satellites
   Built From Sub-Components:
   Subsystem: 1.1.1 Satellite 1
   Subsystem: 1.1.2 Satellite 2

Subsystem: 1.2 - Ground antenna
   Built From Sub-Components:
   Subsystem: 1.2.1 Ground antenna 1
   System Segment: 1.2.2 Ground antenna 2

Subsystem: 1.3 - Central processor
   Built From Sub-Components:
   Subsystem: 1.3.1 Central Processor 1
   Subsystem: 1.3.2 Central Processor 2

2 - Maintenance components
   Built From Sub-Components:
   Facility: 2.1 Fault detection center
   Human: 2.1 Maintenance crew

External Interfaces:
   Subsystem: 1.3 Central processor
   Subsystem: 1.1 Satellites
   ExternalSystem User computing facility
   ExternalSystem User space vehicle

Performs Top-Level Function: Space Network

Description of System Mission(s):
This function, Space Network, facilitates the Space Network’s mission statement. This function is further decomposed to show how various elements of the Space Network combine to fulfill the mission statement.

System-Level “Originating” Requirements:
1 - Mission

Design Constraints:
Availability
MTBF
MTTR
O&M
First-Level System Functions:
Space Network
  TimeFunction 1.1 Receive user request
  TimeFunction 1.2 Transmit user request
  TimeFunction 1.3 Wait for acknowledgement
  TimeFunction 1.4 Bring down information from user space vehicle
  TimeFunction 1.5 Terminate job request
  TimeFunction 1.6 Provide information to user
  TimeFunction 1.7 Detect fault
  TimeFunction 1.8 Dispatch maintenance crew
  TimeFunction 1.9 Repair fault
2 System-Level ("Originating") Requirements

1 Mission

Description:
The Space Network was developed to allow Spacelight Projects (users) to communicate with their respective space vehicles. The Space Network as it stands now is composed of one satellite, one ground antenna, and one central processor. The system was developed to allow users to contact their respective vehicles 24 hours per day, 365 days per year. The Space Network began operation in January of 1989 and is scheduled to complete operation in December of 1998. Since demand for the system has increased significantly in 1990, it has been determined that the system users may benefit from an increase in capacity. Capacity should be in the form of an increase in available time on the Space Network.

Incorporates System Requirements(s):
1.1 - Cost Per Minute
1.2 - Yearly Refund
1.3 - Residual Error Rate
1.4 - Reliability
1.5 - Mean Time to Repair
1.6 - Utilization
1.7 - Mean interarrival time
1.8 - Mean Service Time
1.9 - Availability

Traces To:
TimeFunction: 1 - Space Network

Source Documents:
Space Network Meeting Results - December, 1990.

1.1 Cost Per Minute

Description:
The cost per minute is the amount charged users per minute of time used on the Space Network. Further, cost per minute can be divided into cost per minute during peak time, and cost per minute during off-peak time.

1.2 Yearly Refund

Description:
The yearly refund is the total amount of money refunded to users at the end of a year.

1.3 Residual Error Rate

Description:
The Residual Error Rate is used to determine how much error will be tolerated per year. In this case, the maximum error is 0.0001%.

1.4 Reliability

Description:
The reliability of the Space Network shall be such that the MTBF in any year is no less than 2500 hours. Since the satellite cannot be repaired, the reliability of this component should be at least 0.9998.
1.5 Mean Time to Repair

Description:
The mean time to repair (MTTR) for the Space Network is 0.5 hours. Since satellites cannot be repaired, the MTTR applies only to the ground antenna and the central processor.

1.6 Utilization

Description:
Utilization for the Space Network is calculated monthly and yearly. Utilization can be further classified as utilization during peak hours and utilization during off-peak hours.

1.7 Mean interarrival time

Description:
Mean interarrival times are exponentially distributed, and reflect the time elapsed between job arrivals. The mean interarrival time in January of 1990 was 15 minutes.

1.8 Mean Service Time

Description:
Mean service times on the Space Network are exponentially distributed. The mean service time in December of 1990 was expected to be 10 minutes. Mean service time will not decrease unless faster processing of jobs is made available.

1.9 Availability

Description:
The availability for the Space Network should be 0.9998 in any year, and is defined by MTBF/MTBF + MTTR).
3 Design Constraints

1.1 Availability

Description:
The availability for the Space Network must be at least 0.9998.

Constraints:
TimeFunction 1 Space Network

1.2 MTBF

Description:
The MTBF for the Space Network must be at least 2,500 hours.

Constraints:
TimeFunction 1 Space Network

1.3 MTTR

Description:
The mean time to repair can be at most 30 minutes.

Constraints:
TimeFunction 1 Space Network

1.4 O&M

Description:
The O&M costs should be at most 15,000,000 per year in constant dollars.

Constraints:
TimeFunction 1 Space Network
5 Hierarchical Function List

1.1 Receive user request
1.2 Transmit user request
1.3 Wait for acknowledgement
1.4 Bring down information from user space vehicle
1.5 Terminate job request
1.6 Provide information to user
6 System Functional Behavior Description

Behavior Model for "Space Network"
1.1 Receive user request

Description:
User enters job request on FCFS queue. Includes all code required to establish linkage between user space vehicle and space network. This package will include location of user vehicle, desired transmission frequency, code to gather required data/information, and location to send desired information.

Inputs:
Fault repaired
source: Human 2.1 Maintenance crew
Job request

Outputs:
Fault detected
destination: Facility 2.1 Fault detection center
Job request package
destination: 1.2 - Transmit user request

1.2 Transmit user request

Description:
Establish linkage between user space craft and Space Network elements.

Inputs:
Job request package
source: 1.1 - Receive user request

Outputs:
Job processing requirements
destination: 1.3 - Wait for acknowledgement

1.3 Wait for acknowledgement

Description:
Wait for start transmission signal from user space vehicle.

Inputs:
Job processing requirements
source: 1.2 - Transmit user request
Proceed with transmission

Outputs:
Specific job package
destination: 1.4 - Bring down information from user space vehicle

1.4 Bring down information from user space vehicle

Description:
Receive information from the user space craft. Will hold information in a temporary buffer (this is because some user's cannot process information as fast as the Space Network can deliver it).

Inputs:
Specific job package
source: 1.3 - Wait for acknowledgement

Outputs:
Job completed
destination: 1.5 - Terminate job request
Requested information
destination: 1.6 - Provide information to user
1.5 Terminate job request

Description:
Tear-down linkage between Space Network and user space vehicle.

Inputs:
Job completed
  source: 1.4 - Bring down information from user space vehicle

1.6 Provide information to user

Description:
Take information stored in Space Network and transmit to users.

Inputs:
Requested information
  source: 1.4 - Bring down information from user space vehicle

Outputs:
Information from the space vehicle

1.7 Detect fault

Description:
Determine that system is inoperable or will soon be inoperable. May be either solid or intermittent fault.

Inputs:
Fault detected
  source: 1.1 - Receive user request

1.8 Dispatch maintenance crew

Description:
Give maintenance crew location of fault area.

1.9 Repair fault

Description:
Determine cause of fault and repair.

Outputs:
Fault repaired
  destination: 1.1 - Receive user request
7 Performance Indices

1 Install additional satellite system

Description:
The performance of the Space Network after Install Additional Satellite System is selected can be estimated. The following measures are used to describe network performance, and thus, show how this prospective change will affect users.

Category:
Top-level performance

Value:
0.0

Units:
No standard units

Exhibited By:
Component: 1 - Space Network with additional satellite system

1.1 Project life

Description:
The project should last 8 years. Detail design will begin after alternative selection. If the Install Additional Satellite Project is selected, then it is expected modifications will be completed by the end of 1992. The Space Network will then end operation at the end of 1998.

Category:
Life-length

Value:
8.0

Units:
Years

1.2 LCCC at 0%

Description:
It is expected that the design, development, implementation, and operation of the Install Additional Satellite Project will result in a LCCC at 0% of $114,000,000. Therefore, the LCCC of the Space Network at 0% from BOY 1991 through EOY 1998 is expected to be $194,000,000.

Category:
System Cost

Value:
1.94e8

Units:
Discounted dollars
1.3 MTBF

Description:
The MTBF for the Space Network if the Install Additional Satellite Project is accepted is expected to be 1,738 hours.

Category:
Dependability

Value:
1738.0

Units:
Hours

1.4 Expected Utilization

Description:
It is expected that the Space Network will experience 100% utilization from BOY1991 through EOY 1992 and then 22% off-peak in 1993 increasing to 35% off-peak in 1998 if the Install Additional Satellite Project is accepted.

Category:
Timeliness

Value:
81.0

Units:
Percent of available hours used in 1998

1.5 Processing hours available

Description:
If the Install Additional Satellite Project is selected, then there will be 525,495 hours available on the Space Network in 1991 and 192, and 1,050,882 hours available per year from EOY 1992 through EOY 1998.

Category:
Timeliness

Value:
1.05088e6

Units:
Hours available in 1993 through 1998

1.6 Percent of time on peak rate

Description:
If the Install Additional Satellite Project is selected, then it is expected that the percent of peak time used will be 100% in 1991 and 1992. After 1992, peak time used will markedly increase and then drop slightly through 1998.

Category:
Timeliness
1.7 Percent of time on off-peak rate

**Description:**
If the Install Additional Satellite Project is selected, then it is expected that of the total time used, 50% will be during off-peak hours in 1991 and 1992.

**Category:**
Timeliness

**Value:**
65.0

**Units:**
Percent of total job requests that will be run during off-peak hours in 1998.

1.8 Availability

**Description:**
Availability for the Space Network if the Install Additional Satellite Project is selected is estimated to be 0.99997, and is defined by MTBF/(MTBF + MTTR).

**Category:**
Timeliness

**Value:**
0.9997

**Units:**
Percent of time that the system is available.

1.9 Mean time to repair

**Description:**
The mean time to repair for the Install Additional Satellite Project is 30 minutes.

**Category:**
Dependability

**Value:**
0.5

**Units:**
Hours

1.10 Residual error rate

**Description:**
Residual error rate is used to determine the percent of error bits versus bits that are not in error.

**Category:**
Dependability

**Value:**
1.0e-4

**Units:**
Percent of error bits
1.A Job request

Input To:
TimeFunction 1.1 Receive user request

Carried by interface link:
Job request

1.B Job request package

Output From:
TimeFunction 1.1 Receive user request

Input To:
TimeFunction 1.2 Transmit user request

Carried by interface link:
Job request package

1.C Job processing requirements

Output From:
TimeFunction 1.2 Transmit user request

Input To:
TimeFunction 1.3 Wait for acknowledgement

1.D Proceed with transmission

Input To:
TimeFunction 1.3 Wait for acknowledgement

Carried by interface link:
Space vehicle information

1.E Specific job package

Output From:
TimeFunction 1.3 Wait for acknowledgement

Input To:
TimeFunction 1.4 Bring down information from user space vehicle
1.F Requested information

Output From:
  TimeFunction 1.4 Bring down information from user space vehicle

Input To:
  TimeFunction 1.6 Provide information to user

Carried by interface link:
  Job request
  Requested info.
  Requested information
  User job request

1.G Job completed

Output From:
  TimeFunction 1.4 Bring down information from user space vehicle

Input To:
  TimeFunction 1.5 Terminate job request

Carried by interface link:
  Job completed

1.H Fault detected

Output From:
  TimeFunction 1.1 Receive user request

Input To:
  Facility: 2.1 Fault detection center

Carried by interface link:
  Fault monitoring of central processor
  Fault monitoring of ground antenna
  Fault monitoring of satellite

1.I Fault repaired

Output From:
  Human: 2.1 Maintenance crew

Input To:
  TimeFunction 1.1 Receive user request

Carried by interface link:
  Fault monitoring of central processor
  Fault monitoring of ground antenna
  Fault monitoring of satellite

1.J Information from the space vehicle

Output From:
  TimeFunction 1.6 Provide information to user

Carried by interface link:
  Specific job package
9 Components

1 Space Network with additional satellite system

Component Type:

Description:
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

Built From Components:
Subsystem: 1.2 Ground antenna
Subsystem: 1.3 Central processor

Component-Level Performance Requirements:
Install additional satellite system

1.1 Satellites

Component Type: Subsystem

Description:
The Space Network will have two satellites if the Install Additional Satellite Project is selected.

Built From Components:
Subsystem: 1.1.1 Satellite 1
Subsystem: 1.1.2 Satellite 2

1.1.1 Satellite 1

Component Type: Subsystem

Description:
The Space Network has two satellites whose purpose is to link user space vehicles to the ground antenna. This first satellite is the original satellite, and has the same reliability as the new satellite.

Builds Higher-Level Component/System:
Component 1.1 Satellites

1.1.2 Satellite 2

Component Type: Subsystem

Description:
Satellite 2 is the new satellite, and has the same reliability as satellite 1.

Builds Higher-Level Component/System:
Component 1.1 Satellites

1.2 Ground antenna

Component Type: Subsystem

Description:
The Space Network after the Install Additional Satellite Project is implemented will have two ground antennas, located in New Mexico, which serve the purpose of linking the central processors to the satellites.
Builds Higher-Level Component/System:
  Component 1  Space Network with additional satellite system

Builds From Components:
  Subsystem: 1.2.1  Ground antenna 1
  System Segment: 1.2.2  Ground antenna 2

1.2.1  Ground antenna 1
  Component Type: Subsystem
  Description:
  Ground antenna is the original antenna, and has a lower reliability than the newer ground antenna.

Builds Higher-Level Component/System:
  Component 1.2  Ground antenna

1.2.2  Ground antenna 2
  Component Type: System Segment
  Description:
  The newer ground antenna will have a reliability that is higher than the older ground antenna.

Builds Higher-Level Component/System:
  Component 1.2  Ground antenna

1.3  Central processor
  Component Type: Subsystem
  Description:
  The central processor, located in Maryland, serves the purpose of linking the ground antennas to the users' computer systems.

Builds Higher-Level Component/System:
  Component 1  Space Network with additional satellite system

Builds From Components:
  Subsystem: 1.3.1  Central Processor 1
  Subsystem: 1.3.2  Central Processor 2

1.3.1  Central Processor 1
  Component Type: Subsystem
  Description:
  This processor is the original processor and has a lower reliability than the newer central processor.

Builds Higher-Level Component/System:
  Component 1.3  Central processor

1.3.2  Central Processor 2
  Component Type: Subsystem
  Description:
  This newer central processor has a reliability which is higher than the older central processor.

Builds Higher-Level Component/System:
  Component 1.3  Central processor
2 Maintenance components

Component Type:

Description:
The Space Network has two maintenance components. They are the Fault Detection Center, and the Maintenance Crews.

Built From Components:
Facility: 2.1 Fault detection center
Human: 2.1 Maintenance crew

2.1 Fault detection center

Component Type: Facility

Description:
The Fault Detection Center has the responsibility of detecting and isolating faults in all components of the Space Network. After detection and isolation, the Fault Detection Center dispatches maintenance crews at the appropriate locations. If failure occurs in the satellite, then automatic back-up (i.e., redundant systems) are to automatically resume operation.

Builds Higher-Level Component/System:
Component 2 Maintenance components

2.1 Maintenance crew

Component Type: Human

Description:
Two maintenance crews will be available. One crew will reside at the ground antenna location, and one crew will reside at the central processor location. These crews will be available 24 hours per day. Training will be specific to each type of component worked on, i.e., ground antenna or central processor. These crews will also be available to perform maintenance on other systems operated by NASA. Hence, having them available 24 hours per day will not seriously affect the O&M costs.

Builds Higher-Level Component/System:
Component 2 Maintenance components
10 Interfaces Between Components

Derived Interfaces

Database Interface Elements

1.1 Satellite-user vehicle interface

Description:
The Space Network with modifications can be decomposed by three components. They are: (1) Satellite, (2) ground antenna, and (3) central processor.

Connects to:
- System InsAll Additional Satellite System
- ExternalSystem User space vehicle
- Subsystem: 1.1 Satellites

Comprised of Link: Space vehicle information

Carries:
- 1.D Proceed with transmission

Input To:
- TimeFunction 1.3 Wait for acknowledgement

Comprised of Link: User job request

Carries:
- 1.F Requested information

Output From:
- TimeFunction 1.4 Bring down information from user space vehicle

Input To:
- TimeFunction 1.6 Provide information to user

1.2 Satellite tracking interface

Connects to:
- Subsystem: 1.1 Satellites
- Subsystem: 1.2 Ground antenna

Comprised of Link: Job request package

Carries:
- 1.B Job request package

Output From:
- TimeFunction 1.1 Receive user request

Input To:
- TimeFunction 1.2 Transmit user request
Comprised of Link: Specific job package

Carries:
    1.J Information from the space vehicle

Output From:
    TimeFunction 1.6 Provide information to user

1.3 Ground link-processor interface

Connects to:
    Subsystem: 1.2 Ground antenna
    Subsystem: 1.3 Central processor

Comprised of Link: Job request package

Carries:
    1.B Job request package

Output From:
    TimeFunction 1.1 Receive user request

Input To:
    TimeFunction 1.2 Transmit user request

Comprised of Link: Requested info.

Carries:
    1.F Requested information

Output From:
    TimeFunction 1.4 Bring down information from user space vehicle

Input To:
    TimeFunction 1.6 Provide information to user

1.4 Central processor-user processor interface

Connects to:
    System Install Additional Satellite System
    ExternalSystem User computing facility
    Subsystem: 1.3 Central processor

Comprised of Link: Job completed

Carries:
    1.G Job completed

Output From:
    TimeFunction 1.4 Bring down information from user space vehicle

Input To:
    TimeFunction 1.5 Terminate job request
Comprised of Link: Job request

Carries:
  1.A Job request

Input To:
  TimeFunction 1.1 Receive user request

Output From:
  TimeFunction 1.4 Bring down information from user space vehicle

Input To:
  TimeFunction 1.6 Provide information to user

Comprised of Link: Requested information

Carries:
  1.F Requested information

Output From:
  TimeFunction 1.4 Bring down information from user space vehicle

Input To:
  TimeFunction 1.6 Provide information to user

2.1 Fault detection-satellite interface

Connects to:
  Subsystem: 1.1 Satellites
  Facility: 2.1 Fault detection center

Comprised of Link: Fault monitoring of satellite

Carries:
  1.H Fault detected

Output From:
  TimeFunction 1.1 Receive user request

Input To:
  Facility: 2.1 Fault detection center

  1.1 Fault repaired

Output From:
  Human: 2.1 Maintenance crew

Input To:
  TimeFunction 1.1 Receive user request
2.2 Fault detection-ground antenna interface

Connects to:
Subsystem: 1.2 Ground antenna
Facility: 2.1 Fault detection center

Comprised of Link: Fault monitoring of ground antenna

Carries:
1.H Fault detected

Output From:
TimeFunction 1.1 Receive user request

Input To:
Facility: 2.1 Fault detection center
1.l Fault repaired

Output From:
Human: 2.1 Maintenance crew

Input To:
TimeFunction 1.1 Receive user request

2.3 Fault detection-central processor interface

Connects to:
Subsystem: 1.3 Central processor
Facility: 2.1 Fault detection center

Comprised of Link: Fault monitoring of central processor

Carries:
1.H Fault detected

Output From:
TimeFunction 1.1 Receive user request

Input To:
Facility: 2.1 Fault detection center
1.l Fault repaired

Output From:
Human: 2.1 Maintenance crew

Input To:
TimeFunction 1.1 Receive user request

2.4 Fault detection-maintenance crew interface

Connects to:
Facility: 2.1 Fault detection center
Human: 2.1 Maintenance crew

Comprised of Link: Maintenance instructions
VITA

William K. Hoehn was born in Huntington, New York on July 24, 1962. He graduated from Walt Whitman High School in Bethesda, Maryland in 1980. Mr. Hoehn then worked at various jobs during the day and attended college at night until 1986 at which point he returned to school full-time. He then obtained a Bachelor of Technology in Industrial Technology in 1988 from The State University of New York College of Technology in Utica, New York.

Upon graduation from SUNY, Mr. Hoehn worked for one year with the Chicago Pneumatic Tool Company in Utica, New York. Mr. Hoehn began studies at Virginia Tech in 1989, and wishes to obtain a Ph.D. in Industrial Engineering and Operations Research.