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Method for Optimizing Resource Allocation in a Government Organization

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METHOD FOR OPTIMIZING RESOURCE ALLOCATION IN A GOVERNMENT ORGANIZATION

Abstract

by

JAMES AFARIN

The managers in Federal agencies are challenged to control the extensive activities in government and still provide high-quality products and services to the American taxpayers. Considering today's complex social and economic environment and the $3.8 billion daily cost of operating the Federal Government, it is evident that there is a need to develop decision-making tools for accurate resource allocation and total quality management.

The goal of this thesis is to provide a methodical process that will aid managers in Federal Government to make budgetary decisions based on the cost of services, the agency's objectives, and the customers' perception of the agency's product.

A general resource allocation procedure was developed in this study that can be applied to any government organization. A government organization, hereafter the "organization," is assumed to be a multidivision enterprise. This procedure was applied to a small organization for the proof of the concept. This organization is the Technical Services Directorate (TSD) at the NASA Lewis Research Center in Cleveland, Ohio.

As a part of the procedure, a nonlinear programming model was developed to account for the resources of the organization, the outputs produced by the organization, the decision-makers views, and the customers' satisfaction with the organization.

The information on the resources of the organization was acquired from current budget levels of the organization and the human resources assigned to the divisions. The outputs of the organization were defined and measured by identifying metrics that assess the outputs, the most challenging task in this study.

The decision-maker's views are represented in the model as weights assigned to the various outputs and were quantified by using the analytic hierarchy process. The customers' opinions regarding the outputs of the organization were collected through questionnaires that were designed for each division individually. Following the philosophy of total quality management, information on customers' satisfaction is presented in the model as the quality of output.

The model is a nonlinear one whose objective is to maximize customers' satisfaction such that the total cost of operation does not exceed the organization's budget. This model represents a structured approach or policy mechanism, at the agency level, to make capital investment decisions based on the priorities of the agency and the quality of outputs. This procedure applied to TSD resulted in a resources allocation scheme that was reasonable and acceptable to the decision-makers and, as expected, dependent on the assumptions and accuracy of the data used in the model.

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Table of Contents

PART TWO

MODEL ESTIMATION

PART THREE

RESULTS AND CONCLUSIONS

PART ONE

INTRODUCTION AND MODEL FORMULATION

This part contains two chapters. In Chapter 1, before developing a mathematical model for optimum resource allocation, the need for this effort is justified. Next, the history of the budgeting system is considered and the contributions of the thesis are outlined. In Chapter 2 the mathematical model is introduced and a general problem formulation is developed. Next, a more specific model is introduced and all the assumptions are justified.

Chapter 1

Introduction and Background

In this chapter, the need for this study is justified. In Section 1.1, a background for the problem is offered and a foundation for the following chapters is presented. In Section 1.2, the historical background of the budgeting system is discussed, and in Section 1.3, the contributions of this work are highlighted.

1.1 Introduction

The national debt is over $4 trillion. It took more than 2 centuries, 1776–1981, to reach $1 trillion of debt and only 12 years to add $3 trillion. If this trend continues to the year 2000, the national debt will reach $13 trillion and 95% of all personal income taxes will be used to pay only the interest on the debt [Grace 1988].

A major contributor to the size of the deficit is government waste. Martin Gross identified 75 different areas where significant amounts of money are wasted [Gross 1992]. He argues that less spending, not higher taxes, is the best way to reduce the deficit [Grace 1989]. The Wall Street Journal in the November 24, 1992, issue reported that budget experts are urging President Clinton to reduce government waste to solve the nation's deficit problem [Wartzman 1992].

Presently, the decision-makers are not provided with the opportunity to examine the objectives of various programs. Interagency trade-offs are difficult to examine, and the link between cost and services is hard to discern. Cuts are imposed without recognizing their impact on various services. Agencies are frequently expected to absorb cuts and still maintain the current level of services.

A resource allocation procedure that examines the government's goals and measures the output of the organization will help managers to use resources in the most efficient manner possible, eliminate waste, and consequently reduce the deficit. Traditionally, the resources are allocated on the basis of incremental change to the categories of expenses known as line items. Each year at the beginning of the budget process, the previous year's budget is selected as the model for the present year's budget. Experts contend that this is a mistake because the previous year's budget is the result of thousands of errors that accumulated over prior years [Gross 1992]. During the course of history, several attempts have been made to reform the budget process in a manner that reflects government objectives and measures the production of government. Budgeting systems, such as performance budgeting (PB) in the 1940s, the planning, programming, and budgeting system (PPBS) in the 1960s, and zero-base budgeting (ZBB) in the 1970s, were introduced to change the incremental budget, but they were not successful (see Section 1.2).

The objective of this study was to develop a decision-making tool for optimizing the allocation of resources for the purpose of maximizing the customers' satisfaction. This tool is designed for all government organizations at agency and subagency levels regardless of their size. The objectives for developing a decision-making tool for managers in the Federal Government are (1) to assist decision-makers in making consistent decisions; (2) to provide decision-makers with information on the trade-offs and pitfalls of their decisions; (3) to provide decision-makers with a road map and systematic approach to arriving at a decision; and (4) to document the process of decision-making for future reference and to maintain consistency [Hobbs et al. 1992].

This thesis is unique because it borrows the notion of measuring productivity from PB, focusing on objectives from PPBS, and considering different alternatives from ZBB. Then, it employs optimization methods and customer perception in deciding the best resource allocation scheme. It also institutes a standard format for making decisions that follows the classical model of rational decision-making, requiring that managers identify objectives and alternatives, select criteria, and choose alternatives based on the criteria.

An actual application of the decision-making tool requires specific information about the organization under study. In this study, the mathematical model was developed for a typical organization, but assumptions and the model input, such as type of resources, parameters, and decision variables and their values, were specifically tailored for the Technical Services Directorate (TSD).

TSD is one of nine organizations called directorates that make up the NASA Lewis Research Center. These directorates have specific functions, and their efforts are concentrated and focused to satisfy the mission of Lewis, which is presented in Section 3.1. The directorate under consideration, TSD, provides engineering, technical, and environmental services to support both experimental research and facilities. A major portion of this study is dedicated to developing procedures for gathering data that will help decision-makers to make right assumptions in the various stages of model development.

The organization is not profit oriented and is not therefore controlled by the free market. At the same time, its very existence is dependent on the optimum use of its resources and the quality of the goods and services it provides to the taxpayers. The organization was created to fulfill a specific need of society and is bound by the regulations imposed by legislative bodies, such as Congress and state and local governments.

Optimum resource allocation means identifying and evaluating all the activities in an organization and then increasing resources only among those that, within the given fiscal constraints, laws, and executive orders, will maximize the effectiveness of the organization. Effectiveness is defined as the degree of success achieved in attaining predetermined goals or responding to the demand placed on the organization [Kinlaw 1987].

The textbook approach to this problem is to associate each activity with a measurable output. The tangible or intangible benefits accrued to the organization from a unit of output are balanced against the cost of producing the output. An overall measure of goodness is defined as the objective function, and the resource allocation is then continued so as to maximize the value of the objective function. For two or more objectives, a multiobjective ranking and optimization method must be used to make allocation decisions.

This technique is adequate if we are dealing with a manufacturing company that produces tangible output, such as automobiles, light bulbs, or doors. When we are faced with an organization in a large Federal research-and-development (R&D) establishment, such as NASA, the issues become fuzzy, and difficulties arise in measuring the output and determining the objective functions of the organization. For example, the output may be providing planning for satisfying the R&D facility's requirements or ensuring compliance with environmental laws and regulations. The objective function could be maximizing customer satisfaction or organization output.

The problem is fundamentally the same as analyzing a manufacturing firm that counts widgets to determine its level of output. But since we cannot optimize what we cannot measure, a critical element of optimization in this research is the ability to identify and measure the output of the organization. The complexity of the problem now becomes evident.

A system that only measures the output of an organization does not provide the total picture. The quality of the output is just as important as the level of the output. Therefore, we are also faced with accounting for quality in measuring the effectiveness of organization output. In the case of NASA, where the level of resources is fixed, the questions are as follows: What is the definition of quality? What is the cost of maintaining the level of quality and the quantity of the output? Should the quantity be reduced to improve quality? What level of quality is acceptable in our production?

For answers to some of these questions, we turn to total quality management (TQM). TQM is a comprehensive customer-focused system with seven major elements based on criteria of the President's Award for Quality [Lewis 1991]. These elements are top management leadership and support, strategic planning, focus on the customer, measurement and analysis, commitment to training and recognition, employee empowerment and teamwork, and quality assurance.

In the TQM context, the definition of quality is meeting customer requirements in developing a product or providing a service the first time and every time [Department of Commerce, 1989]. It is recognized that this definition is subjective and may vary from one customer to another. A great deal of communication is required to produce a specific definition of quality for an organization. To develop a model that will successfully display the level of quality obtained at any given time, a unit for measuring the quality should be created for every division of the organization. This measuring scale will enable the organization's managers to gauge their decisions on the basis of improving quality.

Although optimization of resource allocation is a classic problem and is analyzed in many publications [Lasdon 1970, Saaty 1982, Nagel and Long 1989], the development of a model is seldom investigated specifically when the subject is a Federal Government organization with a specific requirement for implementing TQM. The tool developed in this study consists of a mathematical model of the organization that includes all the activities, fiscal constraints, and limitations in a TQM framework. The concept of TQM will be reflected in all aspects of this research where appropriate. In other words, this model will be an amalgamation of mathematical optimization, resource allocation techniques, and the management system of TQM.

The cornerstone of this work will be the development of measuring sticks for quantifying the output and quality of every activity in the organization. These data, in mathematical form, will become the objective functions and decision variables for the optimization problem. The restriction on budget, manpower, and physical aspects of the organization will become part of the constraints of the problem. Constraints also define production functions, which convert resources into output. The final result is expected to be a flexible decision-making tool that will aid the director in allocating the resources of the organization in the best possible manner to maximize the quality and the quantity of the output.

1.2 Public Budgeting Systems

A study on fiscal federalism reveals that government collects more than 47 percent of all personal income. The Federal Government collects 27 percent, the states 8 percent, and local governments 12 percent [Advisory Commission 1990]. Federal Government spending is divided into controllable and uncontrollable programs. The entitlement programs are considered as uncontrollable. Under these programs, those who meet the statutory standards are legally entitled to receive certain benefits regardless of the budget circumstances. Unless the entitlement laws are changed, the Federal budget makers must look at the controllable portion of the budget to implement fiscal policies. Therefore, organizations such as the Department of Defense, the Department of State, and NASA are under tighter budget constraints in performing their missions.

Excluding the entitlement programs, budgetary decisions are made at macro- and microlevels. The macrolevel decisions are made in the Office of Management and Budget and in the Congress, where legislators are concerned with the size of the Government's budget, spending levels, and how much taxing should be imposed [LeLoup 1988]. For example, Congress decides the portion of the budget that is appropriated to the Department of Defense. Also, it decides how much taxes should be increased or how big a deficit it is willing to accept to support the appropriation. These decisions are based on political issues, the mood of the nation, and international circumstances.

With the exception of the Department of Defense, which partially employs the planning, programming, and budgeting system (explained later), the agency and subagency budgeting process is in practice incremental, not comprehensive [Posner 1993]. An agency's budget is almost never reviewed as a whole every year. Instead, it is based on last year's budget with attention focused on a range of increases or decreases. This concept of incrementalism was first published by Simon [1958] in his classic study, Administrative Behavior, and then by several other researchers (Lindblom [1961,1966] and Davis et al. [1966]).

Resource allocation is one of the most important decision-making processes in government organizations. Although Congress is charged with making these decisions at a macrolevel, agencies and organizations are responsible for using the appropriated funds in the most effective manner possible. Public budgeting consists of the techniques that decision-makers at all levels of government can use to justify and allocate their resources. Through the course of history, many budgeting systems were invented and implemented. In the following paragraphs, a brief explanation of the various budgeting systems is presented.

There was no formal budgetary procedure until the Budget and Accounting Act of 1921 [Howard 1973]. Before this time, Federal agencies would submit budget requests to the Congress directly without Presidential influence. After World War I, President Wilson initiated the idea of executive control on the budget mechanism but met strong resistance from Congress, which feared that this would give the President too much authority. Finally, by 1921, the Budget and Accounting Act was enacted, establishing the Bureau of the Budget (renamed the Office of Management and Budget in 1970), an arm of the executive branch that controls the budgeting process. The Budget and Accounting Act also established the General Accounting Office, which reports directly to Congress [Hyde 1992].

The 1920s was an era of fiscal control and responsibility. By the 1930s, the budget system was refined, and the line-item budget system was born [Babunakis 1976]. This refinement was the result of a concentrated effort by the budget bureaus on the spending process rather than on planning or developing programs.

In 1940, V.O. Key, Jr., wrote the famous article, "The Lack of Budgetary Theory." It asked the question, "On what basis shall it be decided to allocate X dollars to activity A instead of activity B?" Key wrote,

> The budget-maker never has enough revenue to meet the request of all spending agencies and he must decide how scarce means shall be allocated to alternative uses [Key 1940].

During the 1940s and 1950s, a change from fiscal control budgeting to management control budgeting occurred. In 1949, by recommendation of the Hoover Commission, the National Security Act Amendment law was signed, and performance budgeting emerged as a new budgeting system. The focus of this scheme was on the activities of the government rather than on the objectives or expenditures. This change in emphasis was a budgetary turning point where management gained control from the accounting officials in developing the budget [Grossbard 1971].

The performance budget failed in the 1950s because it was purely mechanical and replaced clarity with complexity [Schick 1971]. The main concern of the performance budget was with efficiency; the justification for the activity was ignored. Its goal was to maintain efficiency rather than to serve the needs of taxpayers [Knezevich 1973]. Because of this, it did not receive the necessary support from the lawmakers and administrators.

In the 1960s, government activities increased, and the emphasis was on identifying major objectives and programs to support these objectives [Novick 1968]. In 1960, the RAND Corporation published The Economics of Defense in the Nuclear Age [Hitch and McKean 1960]. The Kennedy administration reviewed this document, and as a result, the planning, programming, and budgeting system (PPBS) was adopted by the Department of Defense in 1961 under Robert McNamara [Knezevich 1973].

PPBS had two major objectives: (1) developing the objectives of the organization and (2) devising a system for achieving those objectives [Schultze 1968]. PPBS was concerned with clarifying the objectives of government programs and monitoring the relationship between the output of the program and its objective. Another objective of PPBS was to establish the total cost of the program in the future. This was particularly important, since PPBS searched for the most effective alternative of obtaining the program's objectives.

Although President Johnson claimed that PPBS was "a very new and revolutionary system" [Bureau of the Budget, 1968], the history of the PPBS in the Federal Government dates back to wartime control systems introduced by the War Production Board in 1942. In the private sector, it can be traced to 1920, when it was introduced in General Motors and perhaps even earlier in Dupont [Novick 1970]. A former assistant of the Bureau of the Budget testified that "every element of procedure and organization in PPBS can be found here and there within the Executive Branch prior to August 1965" [Comptroller General 1969]. This is the closest budgeting system to this research. The difference is that PPBS used cost-benefit analysis based on assumptions of future cost rather than using decision-maker's value to rank alternatives. PPBS did not input the decision-maker's judgment and did not account for the quality of output. Also, PPBS transferred the decision-making function to the production personnel and away from the managers.

PPBS may have been the optimal method for the Department of Defense, but it was not workable for the entire Federal Government because the Congress refused to use it. The executive branch had required agencies to prepare two separate budgets: the line-item budget, and the PPBS budget. Congress only considered the line-item budget. The agencies were then forced to cross-reference the approved line items back to the PPBS budget [Rabin

1988]. Owing to the inherent complications of dual budget systems, the PPBS was finally abandoned by the Nixon administration.

Budget reforms in the 1970s resulted from competition between the legislative and executive branches over controlling budgets and spending. Also, at this time, resources were diminishing because of the lack of both economic growth and support for tax increases [Hyde 1992].

By 1977, in the Carter administration, zero-based budgeting (ZBB) was launched. In this system, every expenditure must be justified from the beginning of every year like a new expenditure. Every agency was required to rationalize each government program, new or existing, in its entirety each time an annual budget was formulated [Executive Office 1977]. Every budget proposal justified the expenditure for all new and existing projects on the basis of reevaluated goals, methods, objectives, and resources [Merewitz and Sosnick 1971].

On April 19, 1977, the Office of Management and Budget (OMB) issued budget preparation instructions for ZBB. Under these rules, managers of Federal departments had to identify and rank decision packages at four funding levels for each program: (1) The minimum level, below which the program would not be viable; (2) the maintenance level, that which is required to continue the existing level of operation without changing policy; (3) the intermediate level, which is a point between the minimum and maintenance levels; and (4) the improvement level, which expands the current level of operation by requiring additional funding. In total, four budgets had to be prepared for every item every year [Axelrod 1988]. The ZBB implementation procedures significantly increased the workload of the agencies and overwhelmed government managers and were terminated by the Reagan administration.

The 1980s was a decade when process "Mickey Mouse." The media labeled submitted budgets "dead on arrival" because they were based on unrealistic economic assumptions [Hyde 1992]. The 1985 Budget and Emergency Deficit Control Act (also known as the Gramm-Rudman-Hollings Act) was created with the singular goal of reducing the deficit and was passed within 90 days without a hearing [Collender 1990].

1.3 Contributions and Organization of Thesis

The current budgeting system in the Federal Government considers resource allocation as a set of single-objective problems. The present budget system at agency level is in practice incremental, not comprehensive. No structured process exists that compares and ranks alternatives according to a set of criteria in a budgeting system.

The main contribution of this study is the development of a systematic process to appropriate resources to various alternatives on the basis of performance, quality, and decision-makers input. The state of the art in the budgeting process of a government organization is advanced by incorporating the customers' input and the organization's objectives and effectiveness into the allocation of resources. Among other contributions, the quantification of the organization's output and its customer satisfaction is the most important one. Although developing metrics and measuring output and customer satisfaction are difficult, it was the start of a new philosophy in the government organization which articulates that customers' opinions and the performance of the organization matter.

Other contributions are the use of mathematical programming techniques in order to consider all alternatives in a comprehensive and consistent manner and the use of optimization techniques to aid managers in making the allocation decisions. In this thesis, the performance of the organization, the views of the customers, the preference of the decision-makers, and the budget limitation are linked through a nonlinear mathematical model that allows managers to examine various resource allocation schemes before disbursing funds.

The remaining chapters of the thesis explain the different stages of the resource allocation process. In Chapter 2, the mathematical model of the organization is developed and all the parameters and variables are explained. Chapter 3 introduces the NASA mission and the TSD objective, which are used in the model. Chapter 4 defines the quality of the output and the method of assessing the quality. In Chapter 5, the boundaries of the outputs are acquired and the weights of the outputs are estimated.

In Chapter 6, the resource use functions are estimated, and in Chapter 7, the results of the TSD case study are presented. Conclusions are given in Chapter 8, followed by appendices and references. Appendix A introduces the quality dimensions that were used in developing the questionnaires for TSD. Appendix B describes the analytical hierarchy process, and Appendix C presents the results of implementing the model using TSD data. Appendix D displays the TSD functions and required resources, and Appendix E presents the questionnaires.

Chapter 2

Mathematical Modeling

In this chapter, the concept of mathematical modeling and its use in this thesis are defined. The parameters and variables are defined and methods for estimating parameters are discussed. This information is necessary for using any optimization technique. In Section 2.1, mathematical modeling is defined and the phases of creating the model are described. In Section 2.2, a general formulation for the mathematical model is introduced, and in Section 2.3, a specific formulation for the government organization is presented.

2.1 Introduction

Mathematical modeling is the procedure of representing the behavior of a real system by sets of mathematical relationships. Modeling is the first step in the optimization process and provides a powerful tool for synthesizing, analyzing, planning, and controlling a complex system. In optimization techniques, mathematical models are formulated to determine values of decision variables that produce an optimum measure of goodness [Gill et al. 1989].

Formulating the problem depends on the availability of reliable information and the ability to structure its relevant aspects. According to Singh and Titli [1978], the creation of a mathematical model has two phases: structure determination and parameter estimation. The first phase is to select a structure for the model on the basis of the physical features of the system and the desired level of accuracy. The second phase is to assign values to the decision variables in the model structure such that the chosen structure delineates the system under consideration.

2.2 General Problem Formulation

In this section, the problem is transformed into a mathematical format in order to be analyzed and the model is developed for a multidivision organization. This is an optimization model where the objective is to maximize customer satisfaction. A measure of customer satisfaction, as a function of the quality and quantity of the organization's output, is developed and maximized in the model.

The optimization program was developed for the entire organization and not for individual divisions. The output was measured by a precise definition of a measure that counts the product. Quality was determined by the customers' general opinions on the quality of divisions' outputs, which were acquired through a questionnaire. There are also constraints on resource use and levels of production.

Let X_{ijlt} be the amount of output j produced by division i at quality level l using technology t. Technology, here, means a process that combines a particular mix of inputs to produce an output of a given quality. In a general case, some of the output produced by division i may be an input for division m, and at the same time division i may receive input from division n. Without loss of generality, the formulation can be written for division i with vector $\underline{\mathbf{X}}_i = \{X_{ijlt}\}$.

Let $\underline{\mathbf{R}}_i(\underline{\mathbf{X}}_i) = \{R_{ijltk} \quad \forall k\}$ be the vector of resource type "k" that is used to produce $\underline{\mathbf{X}}_i$, and let $\underline{\mathbf{Y}}_{mi}(\mathbf{X}_i) = \{Y_{mij'l't'}(X_i)\}$ be the vector of output j′ from another division m at quality level l′ using the technology t′ that is used as input to division i, where i ≠ m. Let $\underline{\mathbf{Z}}_i = \{Z_{ijlt}\}$ be the output vector of division i that customers receive directly. Total output $\underline{\mathbf{X}}_i$ is divided into $\sum_m \underline{\mathbf{Y}}_{im}$ and $\underline{\mathbf{Z}}_i$. These concepts are shown in Figure 2.1.

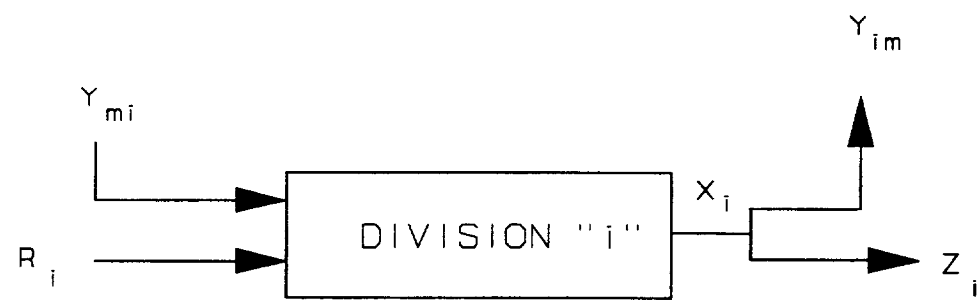

Figure 2.1 Division i Input and Output.

A general formulation is

$$\text{Max } F(\underline{\mathbf{Z}}_i \quad \forall i) \tag{2-1}$$

such that,

$$\sum_i \sum_j \sum_l \sum_t R_{ijltk}(X_{ijlt}) \le B_k \quad \forall k \tag{2-2}$$

$$\underline{\mathbf{X}}_i = \underline{\mathbf{Z}}_i + \sum_m \underline{\mathbf{Y}}_{im}(\mathbf{X}_m) \quad \forall i \tag{2-3}$$

All variables are nonnegative and bounded, where F( ) is the overall customer satisfaction as a function of quality and quantity. In the above formulation, it is assumed that the total resources that constitute the annual budget are fixed. Also, the allocation of resources within a division is the division chief's decision. Furthermore, resources are assumed to be segregated into k types. This assumption is reasonable because, per government regulations, some of the resources are not interchangeable. For instance, the institutional budget (utilities, maintenance, etc.) cannot interchange with the R&D budget.

A common implementation of equations (2-1) to (2-3) is to assume proportionality in all the functions. This assumption transforms them to

$$F(\underline{\mathbf{Z}}_i \quad \forall i) = \sum b_i \underline{\mathbf{Z}}_i \tag{2-4}$$

$$R_{ijltk}(X_{ijlt}) = \alpha_{ijltk} X_{ijlt} \tag{2-5}$$

$$Y_{mijlt}(X_m) = \Sigma_{j'l't'} \lambda_{mijj'll'tt'} X_{mj'l't'} \tag{2-6}$$

where b_i, α_{ijltk}, and $\lambda_{mijj'll'tt'}$ are the appropriate constants. This fixed-proportions approach is used frequently in economic input-output studies [Leontief 1966]. Leontief in his book <u>Input-Output Economics</u> used the same type of input-output analysis as equations (2-5) to (2-6) and argued that each economic sector requires inputs from other sectors that are assumed to be proportional to the first sector's output. He also cited, in Chapter 7 of his book, over 35 papers and articles that use the same proportionality concept to model allocation of resources for production of an economy's output. This work establishes a precedent for using the proportionality assumption for the input-output relations of a division.

2.3 Specific Problem Formulation

In this section, a specific model for this thesis based on the general model in the previous section is developed. Several assumptions were made to design a specific model that is practical and reliable for a government organization. I recognize that many of the assumptions are simplistic; but the purpose of the thesis is to demonstrate what can be learned from such a model. The thesis can then be a basis for developing a model that could be used for actual decisions. Such effort would require months of investigation, decision-makers commitment, and the scrutiny of affected parties inside and outside the agency. Below, I will describe and justify each assumption.

2.3.1 Resource Mix Assumption, Index t

The index t represents a technology that uses a unique mix of inputs for producing X_{ijlt} in the model. For example, it is possible that some of output j from division i at quality l was produced by using in-house resources (t = 1) and that some of it was purchased from a local vendor (t = 2) during the period when the model was executed (3 to 6 months). Alternatively, different values of t can represent different ratios of civil servants and student interns. For the sake of simplicity and demonstration, I assumed that each output j can only be produced by one mix of resources— i.e., resources cannot be substituted for each other. Therefore, I eliminated the index t from all variables X, Y, and Z.

2.3.2 Objective Function Assumption $F(Z_{ijl})$

The overall customer satisfaction F represents the customers' evaluation of the quality and quantity of an output. To illustrate my development of $F(Z_{ijl})$, assume that division i has five outputs that can be produced in three quantity levels (low, medium, and high). Assume five quality dimensions (see Section 4.3), such as communication, timeliness, and reliability, that can be measured on a scale of 1 to 5.

Now, I would have to develop a utility function for each output in division i that represents the customers' evaluation of different quantity levels (low, medium, and high) and every quality dimension (e.g., communication and timeliness) at all levels of quality (1 to 5). This task is difficult and time consuming and would require months of effort to obtain enough accurate information to create the utility function. Hence, to simplify the model further, I assumed that each division i produces its output j at a single quality level S_{ij}. With this assumption, the objective function $F(Z_{ijl} \quad \forall i)$ can be written as $F(Z_{ij}, S_{ij} \quad \forall i,j)$, where Z_{ij} represents the quantity and S_{ij} represents the quality of an output.

2.3.3 Additivity of Objective Function

It is obvious that if the amount and quality of every output of every division are maximized, all customers will be happy. But more than likely this strategy is cost prohibitive and not achievable under the existing resources. Therefore, trade-offs have to be made in which the merits of the outputs are compared.

I based this comparison on the impacts of outputs on the customers' satisfaction, which were introduced into the objective function as weights for the outputs.

Let W_{ij} be the weight that is assigned to the output X_{ij}. I assumed that the worth of each output does not depend on the levels of other outputs of the division. For example, in the Facilities Planning Office (FPO), the happiness of the customers with the construction-of-facilities budget request is assumed to be unrelated to their happiness with the energy management output of the office. This assumption simplifies the objective function and is a reasonable approximation for a first-cut model such as this one. In particular, I assumed that total customer satisfaction can be estimated by adding across divisions the customers' happiness with each individual division, which is a function of quality S_{ij} and quantity Z_{ij}. With these assumptions, the objective function becomes

$$F(Z_{ij},S_{ij} \quad \forall i,j) = \sum_{ij} W_{ij} F_{ij}(Z_{ij},S_{ij}) \qquad (2\text{-}7)$$

In equation (2-7), the attributes are assumed to be additive independent. Keeney and Raiffa [1976] described a three-step technique for verifying additive independence: (1) verify a property called utility independence; (2) verify a property called preferential independence; (3) if the previous properties are satisfied, determine if an additive or multiplicative functional form is appropriate. According to Keeney and Raiffa [1976], the attributes $F_{i''j''}$ and $F_{i'j'}$ (where $i'' \neq i'$ and $j'' \neq j'$) are additive independent if the paired preference comparison of any two lotteries defined by two joint probability distributions on $F_{i\bar{j}''}F_{i\bar{j}'}$ depends only on their marginal probability distribution. I have not performed the above steps owing to lack of time; however, I now describe how they might be undertaken.

To verify preferential independence and utility independence, the set of attributes F_{ij} is partitioned into two subsets $F_{i\bar{j}''}$ and $F_{i\bar{j}'}$. Each subset, in general, may have two or more attributes. First, utility independence between $F_{i\bar{j}'}$ and $F_{i\bar{j}''}$ could be verified by following an analogous procedure. The $F_{i\bar{j}''}$ is kept fixed at $f^{+}_{i\bar{j}''}$. Then, a comparison between a 50-50 lottery and either another 50-50 lottery or a single certainty consequence is performed. The consequences in the paired comparisons are described in the $F_{i\bar{j}'}$ attribute space while the $F_{i\bar{j}''}$ attributes are held fixed at $f^{+}_{i\bar{j}''}$. Next, the $F_{i\bar{j}''}$ is changed to another level $f^{+1}_{i\bar{j}''}$, and the process is repeated for several values of $f^{+}_{i\bar{j}''}$ covering the range of $F_{i\bar{j}''}$. If the decision-maker's preference between values of $F_{i\bar{j}''}$ does not depend on the value of $f^{+}_{i\bar{j}''}$, it can be concluded that $F_{i\bar{j}'}$ is utility independent of $F_{i\bar{j}''}$ [Keeney and Raiffa 1976]. In practice, this is normally done by defining $F_{i\bar{j}'}$ as a single attribute $X_{i\bar{j}'}$. The comparison are usually of the form shown in Figure 2.2. Here $X^{c}_{i\bar{j}'}$ is the certainty equivalent, $X^{o}_{i\bar{j}'}$ is the worst outcome, and $X^{*}_{i\bar{j}'}$ is the best possible outcome. If selecting the certainty equivalent $X^{c}_{i\bar{j}'}$ does not depend on $f^{+}_{i\bar{j}''}$, then $X_{i\bar{j}'}$ is utility independent of $F_{i\bar{j}''}$. This procedure is repeated for all $X_{i\bar{j}'}$.

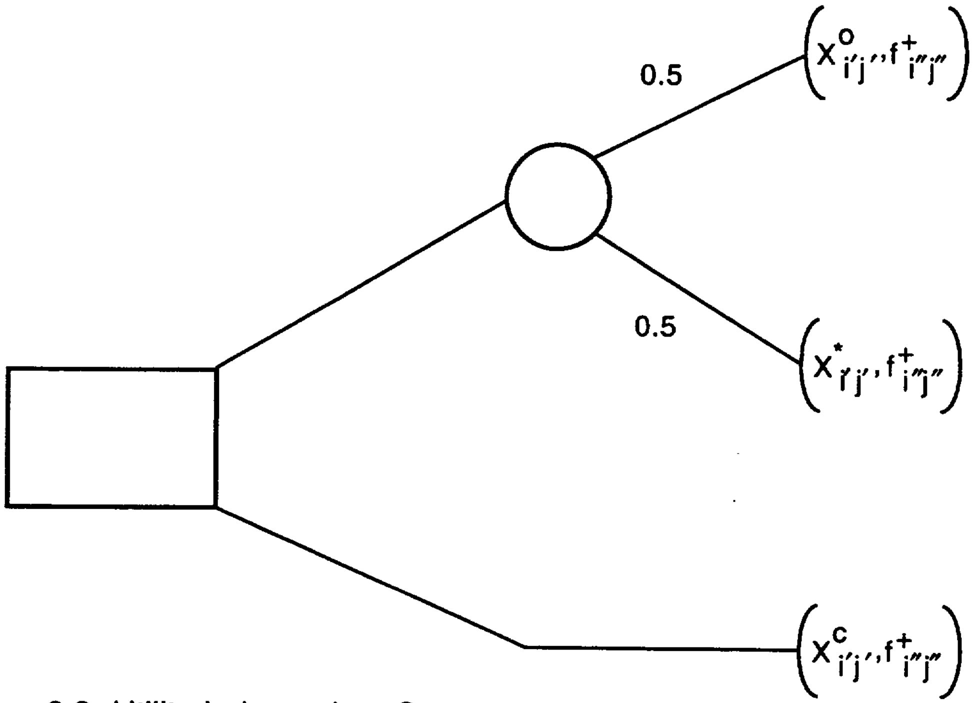

Figure 2.2 Utility-Independent Comparison.

Second, to verify whether partitioned-valued $F_{i'j'}$ is preferentially independent of $F_{i''j''}$, an $f^{-}_{i''j''}$ is chosen at an undesirable level of attributes. Then, distinct values $f'_{i'j'}$ and $f''_{i'j'}$ are chosen such that the decision-maker is indifferent between $(f'_{i'j'}, f^{-}_{i''j''})$ and $(f''_{i'j'}, f^{-}_{i''j''})$. The $f^{-}_{i''j''}$ is changed to a desirable level; if the decision-maker remains indifferent, $f'_{i'j'}$ is preferentially independent of $f'_{i''j''}$. Usually, $f_{i'j'}$ involves just two attributes. This procedure is repeated $n - 1$ times for $f_{i'j'} = (X_{ij}, X_{i'j'})$ for all $i'j' \neq ij$ when arbitrary ij is used as the basis of comparison.

Third, to determine if an additive or multiplicative functional form is appropriate, a lottery is constructed as shown in Figure 2.3,

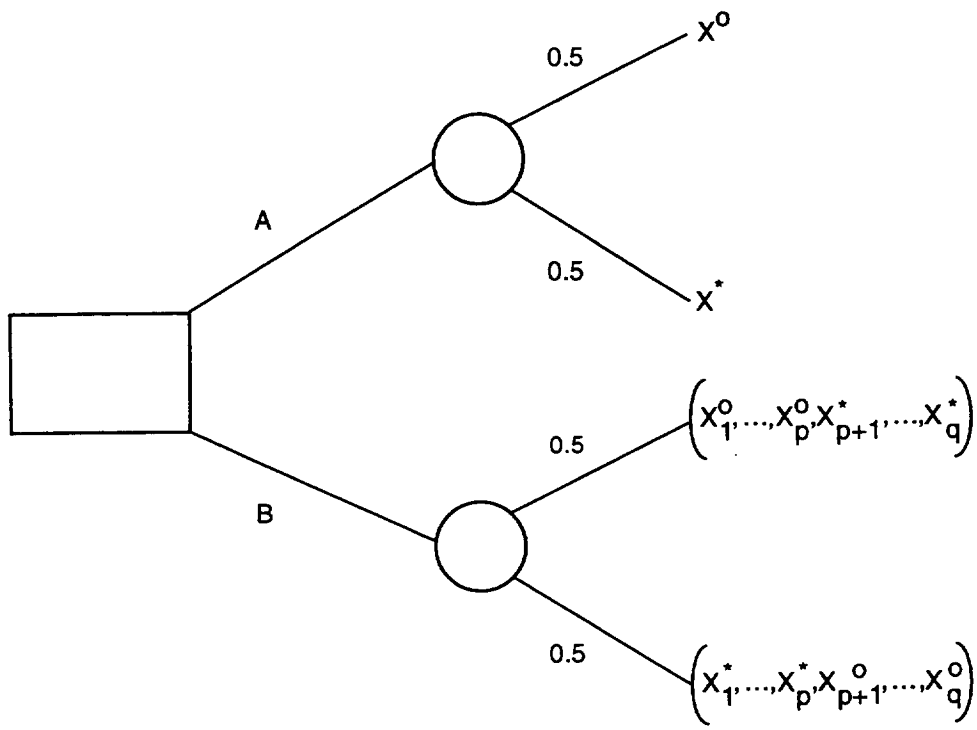

Figure 2.3 Additive and Multiplicative Comparison.

where in choice A all the elements are at either their best or worst values and in choice B some of the elements p are their best while the others are at their worst and vice versa. If the decision-maker is indifferent between A and B, the function is additive; otherwise it is multiplicative.

2.3.4 Quality of Output Versus Quality of Division

As defined earlier, quality is measured by assessing customer satisfaction. In particular, S_{ij} registers the customers' opinions of the quality of output j of division i. To determine S_{ij}, inquiries should be made on all the dimensions of quality (e.g., timeliness and communication; see Section 4.3) for all the outputs. For example, if an organization produces 50 outputs and 5 quality dimensions are considered, a total of 250 data points should be sought from customers in order to determine the S_{ij} for the X_{ij} produced during, say, one year. The enormity of this task for the investigator and for customers may result in poor data (see Section 4.4).

Furthermore, additional data are required to determine how resource allocation changes affect S_{ij}. To reduce the size of the problem, the quality of outputs is assumed to be the same for the entire division rather than for individual outputs. In this scheme, if the organization has 6 divisions, customers are asked for their opinions on the 6 divisions and 5 quality dimensions rather than on the 50 outputs and 5 quality dimensions. This simplification eliminates the need for the index j for S_i but may not be appropriate in an actual application and is made here just for convenience.

To determine an indicator of satisfaction with the quantity of a division's output, it is necessary to define an aggregate measure of an output by normalizing, weighing, and then adding all outputs of the division. Outputs Z_{ij} are normalized by dividing their value by their maximum value UZ_{ij} (maximum feasible value).

A function for $F_{ij}(Z_{ij},S_i)$ should be selected to characterize the reasonable assumption that satisfaction is zero if quantity is zero. A simple function that represents this characteristic is the multiplicative form, which was selected here. Therefore, the satisfaction of customers with a division can be estimated by

$$\text{Max} \sum_i S_i \sum_j W_{ij}[Z_{ij}/(UZ_{ij})] \tag{2-8}$$

Considering equation (2-8), the objective function's rate of change with respect to any variable is constant, given values of all other variables. For example, given S_i, the partial derivative of the objective with respect to X_{ij} is S_iW_{ij}/UX_{ij}, which is constant.

2.3.5 Customers As Only Recipients of Each Division's Output

As a further simplification, I assumed that all outputs produced by a division are received by customers and are not used as inputs to other divisions.

Future research should allow outputs of one division to be inputs to another. Some of the TSD products are actually combinations of outputs from several non-TSD divisions. But an assumption can be made that the customers are the recipients of all the outputs. If the outputs of two or more divisions are needed to complete a product, a customer could receive an output from one division and give it to another one to complete the product and so on. Caution must be taken in evaluating the final results of the model to ensure that the outputs that are required to complete the above product are available.

To clarify this point, imagine that the customer would like to bake a cake. The customer receives eggs from one of the divisions, flour from another one, and any other ingredients from other divisions. Finally, the customer gives all the necessary ingredients to a division in TSD to bake a cake. It is essential to ensure that all the ingredients, in the correct amount, are available to produce the cake.

This assumption allows us to eliminate variables Y_{mijlt} and Z_{ij} by setting $Z_{ij} = X_{ij}$. With the above assumptions the following mathematical model is presented:

$$\text{Max } Z = \sum_i S_i \sum_j W_{ij} X_{ij} / UX_{ij} \tag{2-9}$$

subject to

$$\sum_i RS_{ik}(S_i) + \sum_i \sum_j RX_{ijk}(X_{ij}) \leq B_k \quad \forall k \tag{2-10}$$

$$S_{min} \leq S_i \leq S_{max} \quad \forall i \tag{2-11}$$

$$LX_{ij} \leq X_{ij} \leq UX_{ij} \quad \forall i,j \tag{2-12}$$

and all variables are nonnegative.

The <u>decision variables</u> are

S_i General opinion of customers on the quality of division i outputs on a 1-to-5 scale

X_{ij} Units of output j produced by division i

The <u>parameters and functions</u> are

B_k Total resource of type k available to the organization

LX_{ij} Lower bound of X_{ij}

$RS_{ik}(S_i)$ Use of resource k as a function of S_i

$RX_{ijk}(X_{ij})$ Use of resource k as a function of X_{ij}

S_{max} Upper bound of S_i

S_{min} Lower bound of S_i

UX_{ij} Upper bound of X_{ij}

W_{ij} Weight of output j of division i

This model in its final format is presented in Section 6.4.

PART TWO

MODEL ESTIMATION

The second phase of modeling is assigning numerical values to the variables. These values are determined by examining the historical data, implementing engineering analysis, or using expert judgments that depend on the managers of the organization and the needs and attitudes of the customers. Next, procedures are presented to estimate the parameters of the model. Although the procedures are the same for various organizations, the numerical values of the parameters depend on the type of organization and its structure, goals, and mission.

Therefore, before estimating any parameters, a particular problem setting must be chosen. These methods are specifically applied to TSD to illustrate and further explain the procedures. Chapter 3 introduces the TSD, and Chapters 4 through 8 discuss the estimation of various parameters.

Chapter 3

Modeling Technical Services Directorate

In this chapter, the organization used as a case study in this thesis is defined, and the mission of the organization and its makeup are identified. This information is necessary for estimating the model parameters and executing the model in the following chapters. In Section 3.1, the mission of the NASA Lewis Research Center is described, and in Section 3.2, TSD and its mission and goals are explained. In Section 3.3, the execution of the TSD model is discussed, and in Section 3.4, the process of data collection is explained.

3.1 NASA Lewis Research Center Mission

Below is a quote from the NASA strategic plan for the 1990s [Challenging the Future 1992]. This important information is the basis for the TSD mission, which is explained in following section:

Our mission is to satisfy national needs through research, technology development, and systems development for aeronautical and space applications. We specialize in aero-propulsion, space propulsion, space power, certain aspects of space science and applications, and the related critical disciplines. NASA has designated Lewis as a Center of Excellence in the areas of aeronautical propulsion, space power, space communications, space nuclear propulsion systems, and space electric propulsion systems. This designation assigns the responsibility for producing research and technology advances in the given areas and for providing extended programmatic leadership, from research and technology to system development. Inherent in any Center-of-Excellence assignment is the requirement to form partnerships with participating centers and others having the expertise needed to contribute to the specific endeavor. Our role in the space chemical propulsion area is an example of such a partnership. In this area, we are a participating center. As such, we are expected to contribute both basic and focused technology in close collaboration with Marshall Space Flight Center (for large chemical systems) and with Johnson Space Center (for small chemical systems). These are the designated Centers of Excellence and future developers of the flight systems that will require this technology. We are NASA's designated Center of Excellence in the microgravity science disciplines of fluid physics, combustion science, and materials science. In the space science program, this designation assigns responsibilities that include the "principal investigator" function, experiment design, development, and operation, and publication of results. Finally, we are also responsible for delivering intermediate and large class expendable launch vehicle services for assigned missions.

3.2 Technical Services Directorate (TSD)

The organization under consideration, TSD, is managed by a director who leads the activities of four divisions and two offices, which will be referred to as a total of six divisions. Each division is headed by a division chief and is divided into several branches, the number depending on its size, that are controlled by branch chiefs. The work force in each branch reports directly to the branch chief, who reports to his or her division chief, who reports to the director. TSD employs over 700 civil servants and has an annual operating budget of approximately $50 million.

The director of TSD makes decisions on the amount of resources allocated and the responsibility assigned to each division. Divisions are competing for eight different categories of resources, which are considered the inputs of the divisions and will be explained in later sections. The output of TSD is to fulfill its mission in the best way possible.

Each division plays a specific role in meeting the directorate's responsibilities and has a set of unique constraints that are not shared by other divisions. The only definite linkage among all of the directorate activities is that the total resources of the divisions, manpower or funds, must not exceed the directorate budget allocation. They may also be outputs of some divisions that other divisions require as input. The mathematical formulation of the model can best be determined by examining the physical nature of the problem. In the Table 3.1, the division's name, organization code, and index in the mathematical model are listed. The organizations and some examples of their outputs are then described briefly.

Table 3.1 Divisions of Technical Services Directorate

NAME	ORG. CODE	INDEX "i"
FACILITIES PLANNING OFFICE (FPO)	7010	1
OFFICE OF ENVIRONMENTAL PROGRAMS (OEP)	7020	2
TEST INSTALLATIONS DIVISION (TID)	7200	3
FACILITIES OPERATIONS DIVISION (FOD)	7300	4
FABRICATION SUPPORT DIVISION (FSD)	7400	5
FACILITIES ENGINEERING DIVISION (FED)	7600	6

The Facilities Planning Office (FPO) provides the focal point for strategic planning of the construction-of-facilities activities to meet the Center's programmatic and institutional facility needs. FPO manages and coordinates the advocacy of the Center's Construction-of-Facilities (CoF) Program for rehabilitation, modification, or construction of research, research support, and institutional facilities. The division performs or directs studies of specific plans and support capabilities, including analyzing various courses of action and recommending a preferred approach to management for new or improved research facilities, maintenance of the integrity of the physical plant, or improvements in productivity of the research facilities. FPO manages the Center's Energy Conservation Program and serves as staff to the Facilities Review Board. FPO recommends facility plans that integrate requirements from all users. The division coordinates planning for non-CoF and maintenance-funded facility requirements.

FPO manages the facility utilization and space management programs to ensure the most efficient use of the Center's buildings and technical facilities. It allocates building space to meet research and institutional needs, manages the Center's off-site office leasing activities, and prepares and maintains the Center's facility utilization and real property reports.

FPO also manages the facilities operations and testing support services contract to provide contract personnel for support to research, fabrication, and operations.

The Office of Environmental Programs (OEP) is responsible for providing guidance and support to Lewis in five areas: industrial hygiene, environmental compliance, hazardous chemicals, health physics, and chemical sampling and analysis. OEP serves as a consultant to the Center staff in these areas. Occupational health and environmental hazards associated with the use of chemicals, radioactive materials, potable water, industrial waste, air and water pollution, and hazardous waste disposal are evaluated in accordance with all pertinent National Research Council (NRC), Environmental Protection Agency (EPA), and Occupational Safety and Health Administration (OSHA) regulations. OEP implements policies that have been formulated by the Environmental Pollution Control Board. Area safety committees are apprised of environmental, industrial hygiene, and radiation issues through the safety permit review process. Medical surveillance programs are developed in coordination with the medical officer. In addition to supporting the office, analytical chemistry assistance is provided to the Center's research programs and process systems technical support groups.

The Test Installations Division (TID) comprises eight branches and provides mechanical, electrical, and electronic support services necessary for the installation, maintenance, modification, operations, and repair of the Center's research apparatus and test facilities. These facilities include supersonic, subsonic, and icing research wind tunnels, high-altitude test chambers, space simulation chambers, zero-gravity drop facilities, shaker facilities, environmental test equipment, rocket and air-breathing engine test stands, and an aircraft that is used as flying test bed. The same services are supplied for the support of research on materials (composites, refractories, polymers, superalloys, etc.), electric propulsion, space power systems, and many other fields related to propulsion and power.

The Facilities Operations Division (FOD) provides engineering and technical support for operation, modification, maintenance, installation, and repair of research and institutional facilities throughout the Center. FOD schedules and operates the large prime movers (exhausters and compressors) of the central process air systems, supersonic tunnel drives, and the high-voltage electrical distribution network. The division manages the contracts to provide engineering and trade skills (millwrights, welders, etc.), research installation, major equipment, and systems maintenance.

Services also include maintenance and repair of the central research systems, utilities systems, buildings, roads, and grounds. FOD manages technical services and maintenance support service contracts and provides functional management of the Center's maintenance, custodial, buildings and grounds maintenance, and utilities (including heating, ventilating, and air-conditioning (HVAC)) budgets. FOD provides 24-hour services in support of fire protection and system alarms and administers a comprehensive security program concerned with identifying the need for and developing, implementing, and maintaining procedural and physical means for the protection and security of personnel, information, and property. FOD develops energy forecasts that provide technical and engineering support for the operation, modification, maintenance, installation, and repair of research support facilities, institutional facilities, and various systems. The division's outputs are divided into institutional and R&D categories. The institutional products are facilities maintenance, ground maintenance, custodial services, security, and fire protection. The products supporting R&D activities are control and operation of combustion air, exhaust air, atmospheric air, the variable-frequency drive, wind tunnels, and cooling towers.

The Fabrication Support Division (FSD) provides information and hardware required by engineering, research, and service organizations at the Center. FSD evaluates, develops, and applies advanced technology in metallurgy, metal forming and joining, machining, wood model-making, instrumenting, inspecting, and nondestructive testing. These efforts cover wind tunnel models, aircraft modifications, cryogenic components, numerous test mockups, and spaceflight assemblies. FSD provides support and controls the application of equipment and technologies required to fabricate, instrument, and inspect hardware procured through outside sources. It provides metallurgical consultation and material selection services to engineering, technical services, and research divisions.

The Facilities Engineering Division (FED) serves as engineering authority for construction of research and institutional facilities and systems. It establishes and maintains design and construction standards and drawings and records of facilities. FED analyzes designs of facilities, estimates costs and schedules, and provides construction inspection and contract management for facilities projects. It provides systems engineering and management, including operational and maintenance procedures, safety considerations, and systems configuration control and documentation for large, complex, centralized systems. FED also provides safety expertise through the Recertification of

Pressurized Systems Programs and the Building Life Safety Program and participates on Lewis safety committees and advisory panels.

At this point, specific information is required to formulate a mathematical model of the directorate. The next few paragraphs are dedicated to establishing the mission of the directorate and the inputs and outputs, goals, and limitations of each division.

TSD's mission is to provide technical services to support both experimental research and facilities. The experimental research support encompasses research hardware, fabrication, instrumentation, installation, and appropriate test support. Facility support includes construction-of-facilities planning, design, construction, operation, and maintenance and covers both research and institutional facilities. TSD plans for and directs engineering, technical, and trades personnel involved in providing functional support and provides the necessary facility coordination with other centers and appropriate government agencies.

TSD also directs the Center's environmental compliance, industrial hygiene, and energy management programs. In addition, TSD has overall responsibility for all construction performed for the Center. TSD fabricates the R&D hardware and installs the test rigs and necessary equipment [NASA Organization Manual 1990].

TSD's goal is to advance the Lewis mission by providing the best services possible to the other directorates at the Center. The objective of TSD, as it was developed through interviewing the division chiefs, is to become the best provider of services to other directorates. This means that the directorate should strive to maximize its customer satisfaction. TSD's customers could be internal or the other eight organizations that make up the Center. These directorates have specific functions and their efforts are concentrated and focused to satisfy the Lewis mission. TSD decision-makers should formulate quality improvement policies based on increasing customer satisfaction. TSD should anticipate customers' problems and seek solutions as if they were its own problems. This objective can be met only by focusing on customers' requirements and becoming a full partner in securing their goals.

3.3 TSD Model Implementation

For this study, a model for optimum resource allocation was applied to TSD to demonstrate the concept and identify the pitfalls and limitations of the procedure. The first task was to introduce the procedure to the decision-makers and seek their support. The best way of obtaining backing for any project in a hierarchical organization is to begin from the top of the hierarchy, where the director of the organization resides. To increase the chance of success in convincing the director on the merits of the process, the approval of my division chief, one of the decision-makers, was needed and obtained.

With the sponsorship of my division chief, a presentation of the resource allocation concept was made to the director of TSD and he accepted the project. With the director's blessing, the process was introduced to all division chiefs and implementation of the optimum resource allocation was instituted. The remainder of this chapter documents various procedures I employed in gathering information to gain insight into the operation of the organization and tailor the mathematical model to the directorate.

The mathematical model for TSD is based on the model developed in Chapter 2, where parameters and decision variables are uniquely developed for the directorate under consideration. Accurate development of the parameters requires specific information. A data collection process was developed and executed for gathering detailed information. These data are representative of the TSD mission, current resource allocation at the division level, and decision-makers' visions for the future of the directorate. Specific parameter estimation procedures are the subject of Chapters 4, 5, and 6.

3.4 TSD Internal Data Collection

Data gathering, in general, was accomplished by asking knowledgeable Lewis personnel either through face-to-face interviews or by questionnaire. Both techniques were used, as appropriate, in different parts of this study. The choice of data collection techniques and the types of questions depend on the type of data desired, the ease of implementation of one technique over the other, the number of informants, and the level of accuracy required.

After considering these criteria, the interviewing method was selected for obtaining information from decision-makers, and the questionnaire method was chosen for gathering information from customers, as explained in Chapter 4.

The group of decision-makers in this study consisted of the director of TSD and the six division chiefs, referred to as "the group" hereafter.

The interviewing method was used to capture the thought processes of the decision-makers and their opinions on alternatives, attributes, and priorities. The reasons for this selection are as follows: (1) the group of decision-makers was small, only seven people; (2) a reasonable amount of time was available for interviewing; (3) the margin of error in interviewing is much smaller than in the questionnaire method.

An interview is a flexible and interactive technique that produces up-to-date data. A direct contact in a personal interview enables the investigator to clarify any misinterpretation about the question. An interview can be structured or unstructured, formal or informal. According to Howard and Peters [1990], these types of interviews should be conducted in a structured and formal manner. At this stage, the researcher is faced with the problem of what questions to ask and in what format.

Two types of questions may be asked: an open question and a closed question. An open question is used when the researcher wants the interviewee to give his or her opinion on the subject and elaborate on the answer. A closed question, on the other hand, suggests an answer from predetermined alternatives and limits the response of the informant [Neter et al. 1978].

Before starting the dialog with the division chiefs and beginning to solicit information, it was essential to determine the expected outcome of the interviews. Therefore, a process for conducting the interviews and choosing the type of questions was developed and discussed with the director for his approval. The inputs from the director are boldfaced in the following process. The purpose of this process is to

- ESTABLISH THE OBJECTIVES OF THE DIRECTORATE.
- ***ESTABLISH THE DIVISIONS' FUNCTIONS.***
- ***ESTABLISH THE DIVISIONS' RESOURCES.***
- DEFINE THE OUTPUT OF THE DIVISIONS QUALITATIVELY.
- ESTABLISH THE MEASURING UNITS FOR THE OUTPUT.

The divisions' functions and resources were determined by taking an inventory of all their activities, which constitute over 150 functions, and their associated resources. The results of this investigation were presented to the group for accuracy and concurrence (see Appendix D). At this point, many functions have to be evaluated, a challenging and time-consuming task for the busy decision-makers.

One way to group these functions and reduce the size of this problem is to deal with the outputs of a division rather than its functions. For example, functions such as drafting and engineering have an output, which is a design. The product of several functions is classified as an output. The outputs that were identified, the resources that create the outputs, and specific questions that were asked to obtain this information are presented in Chapter 5.

Chapter 4

Present Quality of Division

In this and the next three chapters, I discuss the specific procedures used to estimate the parameters of the model. In this chapter the present quality of a division BS_i is determined. These data are essential for estimating the resource use function for the quality $RS_{ik}(S_i)$ of equation (2-10), which is discussed in Chapter 6.

In Section 4.1, the quality of output is defined, and in Section 4.2, the method of measuring the quality by using questionnaires is presented. The questionnaires are based on several quality dimensions that are explained in Section 4.3. In Section 4.4, creating an questionnaire that measures the quality of output is discussed, and in Section 4.5, the methods that examine the reliability and validity of a questionnaire are presented. In Section 4.6, the concepts introduced in this chapter are applied to TSD for illustration.

4.1 Quality of Output

The organization's production as measured through the quantifiable output may not give a true picture of its value if the quality of the output is not quantified. The link between quality of output and the success of an organization in private industry is well known and accepted. A study of more than 2500 businesses found that organizations with large market share and higher quality output earn profit margins five times greater than organizations with smaller market share and lower quality output [Buzzell and Gale 1987].

Steingraber [1991] reports that research by A.T. Kearney Inc. reveals that chief executive officers consider quality as a prerequisite for survival of their companies. Quality is defined as the extent to which the product meets the user's expectations [Muller 1991, Lewis and Mitchel 1990, Marr 1986, Montgomery 1985]. According to Strozier [1991], the goals of many successful service companies are defined in terms of results achieved for customers rather than service performance. This definition confirms the idea that the best judges of quality of output are the customers who receive the service.

In addition, government agencies are challenged to implement total quality management (TQM) principles, which require that organizations continue to improve the quality of their outputs. Hyde [1991] articulates that TQM relies heavily on direct feedback from recipients of products and services for assessment of quality. The best measure of quality is quantitative feedback from customers. This conclusion is recognized and successfully implemented by companies such as Xerox and IBM [Marr 1986].

It is also important to note that services usually go unnoticed when the customers are satisfied. Only when the customers experience problems do they pay attention to the quality of service [Levitt 1984, Leonard 1987]. This situation requires that organizations not only aim to maximize the service quality, but also be prepared to quickly eliminate any problems that are detected.

The definition of quality varies from company to company and from output to output. There are so many definitions that they are classified in five categories: transcendent, product based, manufacturing based, value based, and user based [Garvin 1988]. I explain each category in the following paragraphs.

The transcendent definition of quality is generally a level of excellence that is based on personal feeling [Tuchman 1980]. In other words, quality is a characteristic of a product or service that we know when we see it. The problem with this definition of quality is that it is vague and without practical guidance.

Product-based quality is defined as the amount of certain ingredients or attributes present in the product [Abbott 1955]. For example, a higher quality Persian carpet has more fiber knots per square inch. This approach associates the quality of a product with the amount of the desired attribute it possesses. There are two problems with this definition: (1) higher quality is achieved through higher cost and (2) quality is not acquired but assigned to a product on the basis of its component. In the case of TSD, this means that if the organization employs highly educated engineers, it can be assumed that they possess attributes such as communication, responsiveness, and timeliness and any other quality aspects of a service organization. This assumption is obviously not valid.

Manufacturing-based quality is basically conformance of the product specification to preestablished characteristics [Crosby 1979]. Under this definition, if an automobile is manufactured to its exact specification, it is a high-quality car regardless of the requirements. This means that a Cadillac made to its specification has the same quality as a Chevette made to its specification. This definition of quality may be appropriate for some of the divisions in TSD, such as Fabrication Support Division (FSD) and the Test Installations Division (TID), that have fabrication capability. As long as customers define the specification of the product and the part meets or exceeds those requirements, the divisions will have satisfied customers.

Value-based quality is defined in terms of cost and price. A product that performs to its specification is a quality product if it is offered at a reasonable price. Therefore, a $100,000 well-made and well-engineered car may not be a quality product because its price may not be reasonable [Broh 1982]. Although this definition of quality is becoming more and more popular, it is not suitable for this research.

User-based quality is directly related to the attitude of consumers toward the product. This concept seeks the exact combination of the product attributes that will satisfy the most customers. The more satisfied the users are, the higher is the quality of the product [Edwards 1968]. For example, in a service organization such as TSD, the quality of output is directly related to the level of customer satisfaction. The best judge of this type of quality are the customers who are the recipients of the service. Coppola [1991] noted that quality is ultimately defined by customers, and he warned against self-evaluation of quality, which can be disastrous for the organization. The user-based definition of quality is used in this thesis because its philosophy is parallel with the concept of TQM, which is used in the organization.

Because I defined quality as the degree of customer satisfaction, the next section is devoted to developing a system for measuring customer satisfaction.

4.2 Measuring Customer Satisfaction

The organization must identify the needs of customers and take appropriate actions to meet or exceed their needs and consequently maximize customer satisfaction. Customer satisfaction should be defined and measured quantitatively in order to be maximized. Customer satisfaction is defined as meeting customer requirements on quantity and quality of service and product. The measurement, in general, is assigning numbers to objects or events according to rules [Stevens 1951]. This definition is suitable for measuring tangibles, such as the number of widgets or drawings. For measuring intangibles, Blalock [1974] suggested that measurement can be viewed as a process of linking abstract concepts to empirical indicators. Because the quantity of the service or product is tangible, it can be determined by simple questions on the level of output. On the other hand, the quality of output is not easily articulated by the customer, and it is difficult to measure.

In this study, the attitudes of customers were measured by directly asking them about the quality of the organization's outputs. Specifically, customers were presented with a list of statements about the specific services provided by the organization and asked to agree or disagree with each statement. This procedure, which Nunnally [1978] called attitude scales, was conducted to determine how satisfied the customers are with the services provided by the organization. First, the dimensions of quality had to be identified, and then each had to be measured.

4.3 Identifying Quality Dimensions

Quality is a multidimensional entity. Garvin [1988] proposed to break it down into several dimensions, known as quality dimensions. These dimensions are representative of how the quality of a product or service is judged by customers. In a way, quality dimensions are customer satisfaction dimensions. There are two methods for developing quality dimensions: the quality dimension development approach and the critical incident approach [Hayes 1992]. Quality dimensions are developed specifically for each division even though some dimensions may be suitable for all the divisions.

The critical incident approach asks every customer to identify specific performance examples that illustrate the customer's perception of the quality [Flanagan 1954]. A critical incident is a specific example that the customer provides to demonstrate a positive or negative aspect of a product or service.

In examining many customers, the critical incident approach would not be a practical concept.

Quality dimension development involves the people who provide the service and understand its purpose and function [Hayes 1992]. These experts establish a set of quality dimensions that mostly pertain to their organization. For instance, in the case of TSD, experts are the division chiefs, who are most familiar with their products and can establish quality dimensions of their outputs. For example, the chief of the Test Installations Division (TID) selected 6 quality dimensions from a list of 21: availability, communication, responsiveness, reliability, flexibility, and competence. A list of the 21 quality dimensions with a brief explanation of each is given in Appendix A.

4.4 Measuring Quality

At the point where quality dimensions are identified, a measurement instrument should be developed to determine the attitude of the customers toward these quality dimensions. According to McNeal and Lamb [1979], customer satisfaction is most typically measured through surveys. A survey is a series of statements that are designed to gather specific data for developing policies or determining a course of action [Oppenheim 1966].

Although the contents of the surveys differ, the procedure for creating them is the same. The main point that must be considered in designing surveys is that completing a questionnaire is an imposition. Therefore, the number of questions should be kept to a minimum by requiring only precise information related to the objectives of the study.

The quality dimensions are the bases for designing questionnaires for customer satisfaction. The content of the questionnaire has certain characteristics: (1) the questions should be relevant to the objectives of the questionnaire; (2) the questions should be concise; (3) the questions should be unambiguous; (4) the questions should contain only one thought; (5) the questions should not contain double negatives.

The next important step after developing questions is selecting a procedure to quantify the response of the customers. Several response formats or scaling methods that are used to assign numbers to the customers' attitudes were considered: Thurstone's method of equal-appearing intervals [Thurstone 1927], Likert's scaling technique [Likert 1932], Guttman's scalogram approach [Guttman 1950], and item response theory (IRT) [Lord 1980].

The Likert scale was implemented here because of its simplicity and high reliability [Edwards and Kenney 1946]. Likert [1932] introduced a summative scale that is typically used to scale people with respect to their attitudes. The method asks customers to rate an attribute from excellent to unsatisfactory or from approved to disapproved or from strongly agree to strongly disagree by assigning a numerical value to their attitudes from a predetermined range. For example, a customer may be asked to evaluate the response time of maintenance calls from a continuous range of 1 to 5, where 1 represents unsatisfactory and 5 represents excellent (see Appendix E for various questionnaires). As Nunnally [1978] pointed out:

> Likert scales have a number of attractive advantages over all other methods: they (1) follow from an appealing model, (2) are rather easy to construct, (3) usually are highly reliable, (4) can be adapted to the measurement of many different kinds of attitudes, and (5) have produced meaningful results in many studies to date.

The quality dimensions and the method of measuring customer satisfaction have now been explained. In the next two sections the reliability and validity of this measurement technique are examined.

4.5 Reliability and Validity of Measurement

Like any type of measurement, there is error in measuring customer satisfaction by methods such as the Likert scale. Measurement error can be in the form of systematic error S or random error R. When a customer is asked about his or her opinion on a specific quality dimension, the answer is the level of the customer satisfaction with the product or service, which is known as a score for the question. However, this is not a true score T of satisfaction but an observed score X. In other words, there is error involved that distorts the observed scores away from the true scores [Carmines and Zeller 1979, Lord and Novick 1968, Nunnally 1978]. The source of error may be attributed to the following factors [Selltiz et al. 1976]: (1) the person's willingness to express his or her true feeling, (2) the person's mood, (3) the method of acquiring information, (4) the method of administering the interview or questionnaire, (5) the wording of the questionnaire, (6) an ambiguous statement in the questionnaire, (7) mechanical factors, such as circling the wrong number. Symbolically the relationship is

$$X = T + S + R \tag{4-1}$$

Two important issues must be addressed in any measurement: reliability and validity. Kerlinger [1973] equated reliability with dependability, stability, consistency, and predictability. Nunnally [1978] defined reliability as the extent to which measurements are repeatable. Reliability is directly related to the influence of random error on the measurement. If R = 0, the measure is perfectly reliable.

Validity is the degree to which the scale measures what it is supposed to measure. Referring to equation (4-1), a measurement is valid when X = T. There are three types of validity: content validity, criterion validity, and construct validity [Golden et al. 1984], which I discuss later in this chapter. Next, I review methods for assessing a questionnaire's reliability and validity.

4.5.1 Reliability

The reliability tests are based on the concept of correlation. Correlation is the strength of a relationship between two things. A correlation coefficient is the numerical index that expresses the linear relationship between two variables [Cohen et al. 1988]. The correlation coefficient ranges from −1 to +1. A coefficient of +1 or −1 implies a perfect linear relationship; a zero value for a correlation coefficient means no relationship between the two variables. A positive value for a correlation coefficient indicates that the two variables simultaneously increase or decrease together. A negative correlation generally means that if one variable increases, the other one will decrease.

There are four forms of reliability tests for a questionnaire: test and retest, alternative form, split-halves, and internal consistency. Test-retest is a reliability test that examines the correlation between the scores of the same questionnaire given twice to the same people. The alternative form method is similar to the test-retest method except that this technique searches for the correlation between the scores of two versions of the same questionnaire given to the same people. Nunnally [1978] recommended that the two questionnaires in either method be administered about two weeks apart. These methods were not suitable here because the customers were not willing to respond to two questionnaires about the same subject within a two-week period. Also, generating alternative forms of the questionnaire that have the same characteristics is difficult.

The split-halves reliability test follows the same concept as the alternative form reliability test with the exception that it is developed by dividing the questionnaire into two halves. It tests for the degree of consistency across items of the questionnaire. The advantage of this test is its single administration. The disadvantage is that the test does not estimate the stability of the score. However, its major problem is the issue of how to split the scale. Whatever method is chosen to split the scale (e.g., odd-even split), the split-halves reliability test considers only one possible split rather than all the possible splits. This problem brings us to the last and final reliability test.

The internal consistency reliability test, unlike the split-halves test, reveals the internal relationship among the items of a questionnaire. Two methods were considered for estimating the internal consistency reliability: the Kuder-Richardson 20 formula (KR20) and the coefficient alpha method. KR20 is designed to estimate the reliability of questionnaires with questions that have two possible answers, such as true-false. The coefficient alpha method is suitable for calculating the reliability of questionnaires with questions that have many possible answers [Cronbach 1951, Ebel 1965, Kaiser and Michael 1975]. In the coefficient alpha method, which was used in this study, the reliability of a questionnaire is calculated by using the correlation between questions that are based on one quality dimension, say availability, and questions that are based on another quality dimension, say timeliness.

4.5.2 Validity

Three methods are relevant for measuring the validity of a questionnaire: criterion validity, construct validity, and content validity. Criterion validity examines a questionnaire for the predictability of the behavior that the questionnaire is testing. In the case of customer satisfaction, this type of validity examines the relationship between quality dimensions and customer behavior. For example, if customers are satisfied with the service provided, what is the chance that they will increase their business with the company?

The test is valid if the correlation between the customer satisfaction test and increased business reaches an acceptable level previously identified by decision-makers [Golden et al. 1984].

Construct validity involves studying variables that should have a strong relationship with the test domain (customer satisfaction) and variables that should have no relationship with the domain. A test is valid if the scale correlates with the variables that it should (convergent validity) and does not correlate with the variables that it should not (discriminate validity) [Campbell and Fiske 1959]. For example, it is expected that customer satisfaction should be related to the timeliness of service. Also, there should be no connection between customer satisfaction and the color of customers' hair. If a slight correlation is calculated between customer satisfaction and service timeliness or a strong correlation between customer satisfaction and the color of their hair, the test is invalid [Hayes 1992].

Content validity, which was used in this study, is the degree to which the items in the test are representative of all possible items that could be included in the customer satisfaction questionnaire. In other words, does the customer satisfaction questionnaire cover all the quality dimensions that it attempts to measure? Content validity is judged by the people who are most familiar with the purpose of the questionnaire comparing the content domain with the test items [Nunnally 1978]. Following this logic, a questionnaire is valid if it is inclusive of all the quality dimensions that the division chief decided to measure. Therefore, to develop a valid questionnaire, decision-makers should be directly involved in creating their respective questionnaires and should approve the questionnaires to assure that all the quality dimensions are included.

In summary, if a test is valid, the observed scale is equal to the true scale or $X = T$. Referring to equation (4-1), this means that the test is also reliable because $R = 0$. But if the measure is reliable ($R = 0$), it is not necessarily valid ($X = S + T$). Therefore, reliability is a necessary but not sufficient condition for validity [Churchill 1979]. The information on reliability and validity was considered in developing the questionnaires for TSD in order to produce valid and reliable data. In the following section the concept of developing the quality score for an organization is applied to TSD for illustration.

4.6 Present Quality of Division BS_i

The quality of output, as described previously, was measured by assessing the customers' general opinions on the quality of the division's output in fiscal year 1992 (BS_i) and was used as a data point to estimate the quality resource use function. This assessment was done through a questionnaire that was uniquely designed for each division. The variable S_i is an indicator of the general opinion of customers about division i for a given year and set of output. The higher the value of S_i, the higher is the quality of output. The lower bound S_{min} and upper bound S_{max} of the quality scale were arbitrarily selected to be 1 and 5, respectively, according to the Likert scale.

By following the procedures presented in Section 4.3, a list of possible quality dimensions was identified through a literature search for the division chiefs' consideration. This list contains 42 quality dimensions with a brief explanation of each dimension (see Appendix A). Some of the dimensions may be repeated and some may not be applicable to a specific division. After eliminating similar dimensions, the division chiefs considered the following 21 items as proper quality dimensions for their divisions: reliability, responsiveness, competence, access, courtesy, communication, credibility, security, understanding, tangibles, performance, features, conformance, durability, aesthetics, convenience, completeness, timeliness, steering, flexibility, and follow-up.

The questions used were developed by reviewing the literature [Nelson 1978, Parasuraman et al. 1985, Amsden 1989, Armistead 1989, Kennedy and Young 1989, Hyde 1992, Hayes 1992] and a questionnaire from Xerox Corporation. Also, the questions were individually tailored to meet the divisions' requirements and the division chiefs' expectations.

A preparatory questionnaire was developed for each division. To ensure validity, every division chief approved the questions and confirmed that the questionnaire contained all the selected quality dimensions. Next, the division chiefs selected a small group of customers that represented a cross-section of all the customers of the division. The preliminary questionnaire was presented to these sample customers for their input. After the responses to the preliminary questionnaire were received, the questionnaire was revised, proceeded through the same approval cycle as the preparatory questionnaire, and was distributed to all the customers.

The only division that did not follow this procedure was FED. This division did not accept the questionnaire that was designed specifically for them and did not send a preliminary questionnaire to a set of sample customers. FED designed its own questionnaire, which was vague and not very useful for this research. After several discussions with the division chief, an agreement was reached to combine both questionnaires into one and use it for all of their customers.

The preliminary and final questionnaires for all the other divisions did not differ a great deal. Appendix E contains the final questionnaires, and in Section 7.8, the results for each division are presented. It is evident that the questionnaire is a diagnostic tool that points out the problems with the quality of the output. It is up to the division chiefs to take appropriate action to eliminate these problems. In the next section, I offer a method to help decision-makers allocate proper resources so as to improve the quality of division outputs.

4.6.1 General Satisfaction Versus Quality Dimensions

To increase the quality level S, decision-makers should strategically allocate scarce resources to reducing or eliminating any quality deficiency or use the resources available more efficiently. The challenge is to determine or estimate where to concentrate the resources so as increase S_i. The relationship between resources and quality (customer satisfaction) can be developed by executing several resource allocation cycles. Each cycle consists of conducting a survey to determine the level of customer satisfaction and then adjusting resources to improve customer satisfaction and recording the effect of the new resource allocation by conducting another survey after six months or a year.

Because this was the first time that the cost of quality was considered by TSD, historical data were not available. Therefore, it will be impossible to predict the effect of various resource allocations on the quality of output from actual data. Developing the relationship between quality and resources by experimentation is virtually impossible because I would have to systematically change the resources that support the quality of outputs, which is customer satisfaction, and register the change in customer satisfaction by administering a new questionnaire. This process is time consuming and bombards the customers with various questionnaires that will have an adverse effect on their cooperation and the quality of data they provide. Therefore, in this model, the cost of quality will be estimated by the experts, the people who are closest to the operations.

It is much easier to determine the cost for improving a specific quality dimension, such as timeliness or availability (defined in Section 4.3), than the cost for improving the general opinion of customers. Thus, to find the relationship between quality dimensions and current general satisfaction and determine the quality dimensions that most influence the general opinion, a multiple regression analysis was performed between general satisfaction, as the dependent variable, and quality dimensions, as the independent variable. In other words, BS_i was determined as a function of quality dimensions. Then, the cost of improving quality dimensions could be estimated by the division chief, and when the cost of improving each quality dimension was known, the overall cost of improving S could be estimated. The task of developing general satisfaction as a function of quality dimensions was accomplished through regression analysis, which is described next.

4.6.2 Regression Analysis

Regression analysis is a technique that models a dependent variable as a function of independent variables. The general form of this model for m observations and h variables is

$$BS_{im} = \beta_{i0} + \beta_{i1}Q_{im1} + \beta_{i2}Q_{im2} + \dots + \beta_{ih}Q_{imh} + \varepsilon_{im} \qquad \forall\ m \qquad (4\text{-}2)$$

where m is the total number of customers that responded to the division i questionnaire; ε_{im} is the deviation of the calculated value from the observed value of the dependent variable; BS_{im} is the score that a customer of division i gave to the general satisfaction questionnaire in a base year, which is considered a dependent variable; and Q_{imh} are scores for h quality dimensions of division i, which are considered independent variables. Quality dimensions, as defined in Section 4.3, are representative of how the quality of a product or service is evaluated. For a service organization, quality dimensions are attributes such as timeliness and communication. The β_{ih} coefficients are estimated by minimizing the sum of squares of deviations from the observed value of BS_{im}.

$$E = \sum_m \varepsilon^2_{im} = \sum_m (BS_{im} - \beta_{i0} - \beta_{i1}Q_{im1} - \beta_{i2}Q_{im2} - \dots - \beta_{ih}Q_{imh})^2 \qquad (4\text{-}3)$$

A set of simultaneous equations resulting from equating the partial derivative of E with respect to each β_{ih} to zero were generated. The h + 1 simultaneous linear equations are most easily solved with a computer program. The STORM software was used to perform a regression analysis for TSD. The regression equations were developed by starting with null regression and performing a stepwise procedure to the end.

The stepwise procedure decides from a large set of independent variables which one of the variables has the most influence on the dependent variable. In this screening procedure, the user first identifies the dependent variable and a number of independent variables. Then, the user performs a null regression in which the procedure creates a model (relation between independent and dependent variable) with no independent variable. In the next step, known as a forward step, the user enters an independent variable into the model if its significance level in an F-test is less than a preestablished value. Then, in a backward step, the user deletes the variables that are already in the model if under a t-test their significance value is greater than a preestablished value. To avoid cycling, STORM will not allow deleting a preestablished value that is less than an entered preestablished value [Hamilton et al. 1992]. Detailed explanations of the stepwise procedure are presented is various statistics books [McClave and Dietrich 1979, Makridakis et al. 1978].

The equation is also validated as follows: part of the data is used to develop the regression equation; the equation can then be used to predict the dependent variable value for the remaining cases; and the accuracy of the prediction is determined.

In this study, 60 percent of the data was used to develop the regression equation for the validation procedure. Also, for the sake of accuracy of the equation, the variables were entered and deleted from the equation to match the adjusted R^2 as close as possible to the validation R^2, where R^2 is the degree of fitness of the equation to the data set. The validation R^2 is the degree of fitness between the regression equation, which was developed with 60 percent of the data, and the remaining 40 percent of the data. An experimental R^2 of 0.6 or higher is acceptable for this type of study. This claim can be proven by using the F-test, which allows testing the significance of the overall regression model. From Makridakis et al. [1978], the F value can be calculated by using

$$F = [R^2/p]/[(1 - R^2)/(N - p - 1)] \qquad (4\text{-}4)$$

where

N Number of observations

p Number of parameters in regression

For illustration purposes, equation (4-4) is applied to the Facilities Planning Office, where $R^2 = 0.53$, $N = 25$, and $p = 2$ (timeliness and responsiveness). Using appropriate tables, the F value based on p and $N - p - 1$ at 95-percent confidence is 8.65. Now, from equation (4-4), $R^2 = 0.44$. Because the FPO's R^2 (0.53) is greater than the computed R^2 (0.44), there is a 95-percent confidence that the linear regression equation for FPO is representative of the data acquired on FPO.

The customers' general satisfaction as a function of other quality dimensions is listed below for each division. The quality dimensions are identified in parentheses next to the question number in the questionnaire:

FPO: [Adjusted $R^2 = 0.53$] General Satisfaction = 1.6 +
0.39(**Timeliness** #10) + 0.24(**Responsiveness** #9)

OEP: [Adjusted $R^2 = 0.39$] General Satisfaction = 1.96 +
0.456(**Convenience** #3) + 0.1(**Convenience** #4)

TID: [Adjusted $R^2 = 0.68$] General Satisfaction = 0.4 +
0.42(**Communication** #5) + 0.26(**Availability** #3) +
0.186(**Responsiveness** #9c) + 0.1 (**Demand** #20d)

FOD: [Adjusted $R^2 = 0.74$] General Satisfaction = 0.07 +
0.56 (**Communication** #7) + 0.43(**Convenience** #3)

FSD: [Adjusted $R^2 = 0.54$] General Satisfaction = 1.12 +
0.41 (**Communication** #2) + 0.34(**Communication** #6)

FED: [Adjusted $R^2 = 0.83$] General Satisfaction = –0.1 +

0.45 (**Responsiveness** #7d) + 0.27(**Communication** #5) +

0.2 (**Responsiveness** #7b)

The quality dimensions identified in this step and the comments that were solicited through questionnaires will give the decision-makers a basis for estimating the cost of maintaining or improving upon the current level of general satisfaction. For example, if the Facilities Operations Division needs to increase the general satisfaction, it has to concentrate its effort mostly in communication and then convenience because these two dimensions are most closely associated with general satisfaction. However, the relationship between quality dimensions and general satisfaction is only half of the story; the cost of improving quality dimensions is also needed. I discuss this in Chapter 6 by making general assumptions to assess the cost of quality.

Chapter 5

Estimation of Output Bounds and Weights

In this chapter, the weight of each output as a part of the objective function, equation (2-9), is conceptually developed by using the analytic hierarchy process (AHP) and is then applied to TSD as an illustration. The W_{ij} represent the decision-makers' opinions on the importance of the outputs X_{ij} to the customers' general satisfaction. In Section 5.1, I describe several methods that I considered in this study and the reasons behind the selection of AHP. In Section 5.2, the AHP method is applied to TSD and weights for each division are calculated. In Section 5.3, the upper and lower levels of outputs are determined.

5.1 Methods of Estimating Weights

The weight for each output is the only means by which decision-makers can directly influence the objective function of the model. It is important to select a correct technique that is easy to implement and understand. There are several ways to develop the weight of each output. The easiest method is to assume equal weights for all outputs. Another method is to allocate 100 points among outputs in proportion to their importance. Unfortunately, direct methods often fail to yield weights that correspond to trade-offs which people are willing to make [Hobbs et al. 1992]. The reason for this may be a vague definition of "importance" [Schoemaker and Waid 1982]. Another group of methods are based on the multiattribute utility theory developed by Keeney and Raiffa [1976].

Utility is defined as assigning numbers that indicate how much something is valued [Berger 1985]. The concept of the multiattribute utility theory is based on constructing a multiattribute utility function, which requires developing a utility function and scaling factors for each attribute. The single-attribute utility function may be produced by using, for instance, a variable probability method [Von Winterfeld and Edwards 1986]. In a variable probability method, the decision-maker is presented with questions involving two options: (1) a gamble that has the probability P of the best possible outcome and the probability 1 − P of the worst outcome and (2) an intermediate outcome that is considered a sure thing.

The decision-maker is asked to specify a probability P such that he or she would be indifferent between the gamble or taking the intermediate outcome. Mathematically, if O^* is the best possible outcome, O_* is the worst possible outcome, and O is an intermediate outcome, the preference order of the outcomes is

$$O^* \succ O \succ O_* \tag{5-1}$$

The probability that O^* occurs is P, and the probability the O_* occurs is 1 − P. The question is at what value of P the decision-maker is indifferent between taking the gamble (O^* and O_*) or taking the sure thing (O). Once P is identified, the utility of the best and worst outcomes is set to 1 and 0, respectively, and the utility of O is calculated by

$$U(O) = PU(O^{*}) + (1 - P)U(O_{*}) \tag{5-1}$$

The weight is constructed by presenting to the decision-maker a gamble with the probability P(i) of winning the outcome with the best values for attributes and the probability 1 – P(i) of receiving the worst values for all attributes. This gamble is compared with a sure thing that has the worst values on all attributes but the i^{th} one, where it has the best outcome. The decision-maker is asked to adjust the probability P(i) until, in his or her opinion, there is no difference between the gamble and the sure thing. Setting the utility of the best and worst outcomes to 1 and 0, respectively, the value of P(i) elicited from the decision-maker represents the weight of the i^{th} attribute in the multiattribute utility function [Keeney and Raiffa 1976].

Another class of methods is based on using ratio questioning for ranking the alternatives. The method requires information on the ratio of importance of two outputs at a time [Hobbs et al. 1992]. The analytic hierarchy process is a version of the ratio questioning method developed by Saaty [1977]. AHP is one of the easier methods to use and understand because it allows decision-makers to visually see the structuring of the decision process.

AHP may be viewed as a procedure for scaling and weighting attributes and blending them by using the additive value function. It allows and provides a measure of consistency. AHP is also considered by some to be a better method for developing a unidimensional value function by calculating the decision-maker's preference on a ratio scale [Kamenetzky 1982]. The mathematical operations (multiplication, addition, etc.) applied to a ratio scale, unlike the interval scale, will produce a meaningful result [Saaty 1990]. Theoretical work on AHP is found in Harker and Vargas [1987], Harker [1987], and Saaty 1980, 1986]. A brief description of the method is offered in Appendix B.

Schoemaker and Waid [1982] conducted an experimental comparison of five approaches for determining the weights of alternatives in a utility model. The experiment was run with 36 Wharton School sophomores taking an introductory decision science course. This group had been asked to evaluate multiple regression, direct trade-offs, and AHP methods in terms of perceived difficulty and trustworthiness. AHP was perceived to be the easiest and most trustworthy method to use. AHP is also very useful in building an analytical decision procedure for traditional capital budgeting. It allows evaluation of multiple decision criteria that can be tangible, intangible, quantitative, or qualitative [Stout et al. 1991].

AHP has been applied in a variety of planning and priority-setting situations (see e.g., Zahedi [1986], Golden et al. [1989], Golden and Wang [1989]), and it is also applicable to group decision-making [DeSanctis and Gallupe 1985, DeSanctis 1987, Turban 1988].

However, AHP is not without problems. Critics of this method claim that, in some situations, the ranking of alternatives determined by AHP may be changed by adding or deleting an alternative [Dyer 1990, Belton and Gear 1983]. This phenomenon, which is known as rank reversal, is the most controversial issue with this method; however, the method is well defended by Saaty and other AHP loyalists [Saaty 1990, Harker and Vargas 1990].

Several explanations and solutions are proposed to eliminate or excuse this phenomenon. It has been claimed that rank reversal is a natural process and should be expected in real-life situations where the criteria are related to the alternatives under consideration [Saaty 1993, 1992, 1987; Harker 1990]. There are also numerous proposed revisions to the method that will eliminate this occurrence [Dyer 1990, Belton 1986, Sadrian and Kocaoglu 1986]. In this thesis, AHP is used to establish the relative weights of different outputs.

5.2 Estimation of Output Weights W_{ij} for TSD

The weight of each output W_{ij} can be developed by using any of the methods mentioned previously. Each method has its own strengths and weaknesses, and each method is supported and criticized by various scientists. But all experts agree that the method should be suitable to decision-makers. This means that the method should be selected for its practical usefulness, ease of understanding and implementing, and validity. An introductory explanation to the decision-makers of the methods under consideration resulted in their selecting AHP for conducting an experiment. This method was selected because it is easy to apply and comprehend. Also, the decision-makers were pleased with AHP's capability of structuring the decision model. AHP has been applied in many governmental and institutional situations. The most successful applications have been in group decision-making where the group structures the problem in a hierarchy framework and pairwise comparisons are elicited from each level of the hierarchy. However, the number of comparisons can become overwhelming. The number of comparisons is $n(n-1)/2$, where n is the number of outputs. There are 58 outputs X_{ij} that must be compared, resulting in over 1600 comparisons.

To reduce the number of comparisons, TSD's objective statement was developed. Then, a set of attributes or criteria that further define the objective of the directorate was generated. Attributes were compared with each other against the directorate objective. Next, divisions were compared on the basis of their contribution to the attributes that constitute the directorate's objective.

AHP was implemented by presenting two attributes at a time to the decision-makers and attempting to reach agreement among them on the ratio of weights between the two attributes. The outcome of this process is a set of weights for each division with respect to the directorate objective (this process is presented graphically later in this chapter). The outputs of each division are ranked by assigning points or by administering an AHP at the division level.

With this multilevel assessment, the weight of an output is acquired by multiplying its conditional weight estimated within its own division by the weight of the division itself. This procedure will reduce the number of comparisons significantly and present a practical task for decision-makers.

A meeting was scheduled with the division chiefs and the director. The purpose of the meeting was to become familiar with AHP by implementing comparison techniques to develop a relative weight for each division. Before the meeting, a set of preliminary criteria was developed and E-mailed to the division chiefs to give some examples of criteria and to stimulate their thoughts for additional discussion.

The first step after presenting the agenda was to offer a brief explanation of the method. The objective of the directorate was decided on, to be the best provider of service to the R&D organizations of the Center. Decision-makers determined that in order to be the best service provider, TSD must be the best in providing hardware (HWD), facilities (FAC), health and a safe environment (H/S/E) at the workplace, and energy (ENERGY). Hardware means tools, equipment and models that R&D needs to run the necessary tests. Facilities are defined as the research rigs, wind tunnels, and office complexes where research is performed. Health and a safe environment for employees is another important ingredient for a successful R&D organization. The last important element is uninterrupted energy sources to run the research.

The problem is demonstrated in AHP format based on Saaty [1982] (see Table 5.1). The main objective occupies the top level, which is called the focus. The intermediate level comprises several elements that can best advance the objective and are compared with one another against the focus. The lowest level of the structure comprises the divisions, which are compared on their contributions to the elements in the intermediate level.

The six divisions were compared with respect to four attributes. To demonstrate the comparison procedure, I will explain the comparison matrix for hardware (HWD). According to Saaty [1982], first we draw a matrix with HWD in the upper left-hand corner. Then, the divisions are listed in the left column and on the top row (Table 5.2). Before questions are asked, the budget of each division should be known by all the decision-makers in order to help them make informed decisions on the comparison matrices.

The 6-by-6 comparison matrix has 36 entries. How much does one division contribute to HWD relative to another division? The diagonal entries are 1.00 because there each division is compared with itself. From the division chiefs' experience and preference, the values of the other 30 entries were provided according to the divisions' contribution to HWD.

In this type of matrix, the elements that appear in the left-hand column are always compared with the elements appearing in the top row. The value is given to the element in the column as it compares with the element in the top row. If the element in the left-hand column is less favorable, the value is a fraction. The reciprocal value is entered in the position where the element in the left-hand column appears in the top row and the element in the top row appears in the left-hand column. For example in Table 5.2, FPO contributes one-ninth of the FSD contribution and one-eighth of TID contribution to HWD. This means that FSD contributes 9 times more than FPO and TID contributes 8 times more that FPO, as recorded in the first row and first column of the matrix.

Next, the matrix is normalized by dividing each entry by the total of its column. Finally, each row is averaged by adding the values in each row of the normalized matrix and dividing by the number of entries in each row. This operation yields the fraction of overall contribution of each division with respect to the HWD, which is called the priority vector (Table 5.3). In the mathematical context the comparison matrix is a single-ranked matrix because every row is a multiplier of the first row.

All entries of this matrix are positive, and the matrix has reciprocity, where an entry c_{ij} is equal to $1/c_{ji}$. According to Saaty [1977], a single-ranked reciprocal matrix with positive entries is consistent if and only if the only eigenvalue of the comparison matrix λ_{max} is equal to n, where n is the number of objects compared. A measure for consistency is established to be

$$CR = (\lambda_{max} - n)/(n - 1) \qquad (5\text{-}2)$$

In order to approximate λ_{max} for an inconsistent matrix, such as a comparison matrix, every column is multiplied by the relative priority of the division from the priority vector. For example, in Table 5.4 the FPO column is multiplied by the FPO element of the priority vector (0.03). Next, each element in the column "ROW TOTAL" is divided by its corresponding element of the priority vector. If the matrix was 100 percent consistent, all the values in the new column (RT/PV) would have been n, which is 6 here. The average value of this new column (RT/PV) is the estimation of λ_{max} [Saaty 1982].

Now that λ_{max} is estimated, the value of CR is known. Saaty and Mariano [1979] found mean inconsistency for samples of 500 random filled matrices of each size from 2-by-2 to 10-by-10 matrices. The numerical judgments were taken, at random, from the scale 1/9, 1/8, 1/7, ..., 1/2, ..., 1, 2, ..., 9. Then by using a reciprocal matrix, the following average consistencies for different-order random matrices were determined:

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	.58	.9	1.12	1.24	1.32	1.41	1.45	1.49

CI is the ratio of CR over the appropriate random consistency and is recommended to be 0.1 or less for a consistent judgment. A decision based on inconsistent judgment will not be accurate and should be avoided.

Following the same procedures, a priority vector for all other elements in the intermediate level (FAC, H/S/E, ENERGY) was developed. Next, a comparison matrix was developed where these elements were compared with each other against the objective of the directorate. The range of each attribute value was recognized by decision-makers as evidenced from the consensus for various scores in the comparison matrix. The final result of the process is presented in the final matrix.

The results of this exercise, which are given in Appendix B, raised some concerns. Decision-makers were troubled with the fact the OEP's weight (0.15) was higher than FOD's weight (0.12); yet most of TSD's resources are appropriated to FOD. They believed that an organization supporting the R&D operation should have higher priority than the environmental program. Further investigation revealed that facilities and operation was not included in the previous attributes. In this context, facilities and operation is the element that captures the efforts of TSD in providing facilities and maintaining central systems, such as a steam plant and a compressed air system, to support R&D activities.

Therefore, another AHP was conducted, like the previous one, with five attributes: hardware (HWD), facilities and operation (FAC/OPER), health and safe environment (H/S/E), energy (ENERGY), and R&D operation (R&D OPER) (See Table 5.1). The R&D operation accounts for TSD's efforts in running the research rigs and R&D testing. The second AHP produced a divisional ranking (Table 5.20) that was reasonable and acceptable to the division chiefs. Tables 5.5 to 5.20 present the results of the final ranking for the divisions.

Table 5.1 Second Hierarchy for TSD Outputs

FOCUS: TSD MISSION			R&D TEST			
ATTRIBUTES:	HWD	FAC/OPER	H/S/E	ENERGY	R&D OPER	
DIVISIONS:	FPO	OEP	TID	FOD	FSD	FED

Table 5.2 Initial Weight Ratio (Column/Row) for Hardware

HWD	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	0.33	0.13	0.33	0.11	0.33
OEP	3.00	1.00	0.20	1.00	0.13	3.00
TID	8.00	5.00	1.00	7.00	0.20	7.00
FOD	3.00	1.00	0.14	1.00	0.11	1.00
FSD	9.00	8.00	5.00	9.00	1.00	9.00
FED	3.00	0.33	0.14	1.00	0.11	1.00
TOTAL	27.00	15.67	6.61	19.33	1.66	21.33

CI = 0.08

Table 5.3 Normalized Matrix With Eigenvector for Hardware

HWD	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR (PV)
FPO	0.04	0.02	0.02	0.02	0.07	0.02	0.03
OEP	0.11	0.06	0.03	0.05	0.08	0.14	0.08
TID	0.30	0.32	0.15	0.36	0.12	0.33	0.26
FOD	0.11	0.06	0.02	0.05	0.07	0.05	0.06
FSD	0.33	0.51	0.76	0.47	0.60	0.42	0.52
FED	0.11	0.02	0.02	0.05	0.07	0.05	0.05
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5.4 Pairwise Comparison Matrix for Hardware

HWD	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.03	0.03	0.03	0.02	0.06	0.02	0.18	6.23
OEP	0.09	0.08	0.05	0.06	0.06	0.16	0.50	6.40
TID	0.24	0.39	0.26	0.42	0.10	0.37	1.79	6.81
FOD	0.09	0.08	0.04	0.06	0.06	0.05	0.38	6.23
FSD	0.27	0.63	1.31	0.54	0.52	0.48	3.75	7.28
FED	0.09	0.03	0.04	0.06	0.06	0.05	0.32	6.07
							AVR.:	6.50

Table 5.5 Initial Weight Ratio (Column/Row) for Facilities and Operations

FAC/OPER	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	7.00	7.00	0.33	9.00	1.00
OEP	0.14	1.00	3.00	0.02	5.00	0.14
TID	0.14	0.33	1.00	0.20	3.00	0.14
FOD	3.00	5.00	5.00	1.00	6.00	1.00
FSD	0.11	0.20	0.33	0.17	1.00	0.14
FED	1.00	7.00	7.00	1.00	7.00	1.00
TOTAL	5.40	20.53	23.33	2.90	31.00	3.43

CI = 0.10

Table 5.6 Normalized Matrix With Eigenvector for Facilities and Operations

FAC/OPER	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR
FPO	0.19	0.34	0.30	0.11	0.29	0.29	0.25
OEP	0.03	0.05	0.13	0.07	0.16	0.04	0.08
TID	0.03	0.02	0.04	0.07	0.10	0.04	0.05
FOD	0.56	0.24	0.21	0.34	0.19	0.29	0.31
FSD	0.02	0.01	0.01	0.06	0.03	0.04	0.03
FED	0.19	0.34	0.30	0.34	0.23	0.29	0.28
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5.7 Pairwise Comparison Matrix for Facilities and Operation

FAC/OPER	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.25	0.55	0.34	0.10	0.26	0.28	1.80	7.08
OEP	0.04	0.08	0.15	0.06	0.15	0.04	0.51	6.44
TID	0.04	0.03	0.05	0.06	0.09	0.04	0.30	6.17
FOD	0.76	0.40	0.24	0.31	0.18	0.28	2.17	7.05
FSD	0.03	0.02	0.02	0.05	0.03	0.04	0.18	6.17
FED	0.25	0.55	0.34	0.31	0.21	0.28	1.94	6.91
							AVR.:	6.64

Table 5.8 Initial Weight Ratio (Column/Row) for Health and Safe Environment

H/S/E	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	0.13	0.14	0.14	0.20	0.14
OEP	8.00	1.00	3.00	3.00	6.00	4.00
TID	7.00	0.33	1.00	1.00	3.00	3.00
FOD	7.00	0.33	1.00	1.00	4.00	2.00
FSD	5.00	0.17	0.33	0.25	1.00	3.00
FED	7.00	0.25	0.33	0.50	0.33	1.00
TOTAL	35.00	2.21	5.81	5.89	14.53	13.14

CI = 0.10

Table 5.9 Normalized Matrix With the Eigenvector for Health and Safe Environment

H/S/E	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR
FPO	0.03	0.06	0.02	0.02	0.01	0.01	0.03
OEP	0.23	0.45	0.52	0.51	0.41	0.30	0.40
TID	0.20	0.15	0.17	0.17	0.21	0.23	0.19
FOD	0.20	0.15	0.17	0.17	0.28	0.15	0.19
FSD	0.14	0.08	0.06	0.04	0.07	0.23	0.10
FED	0.20	0.11	0.06	0.08	0.02	0.08	0.09
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5.10 Pairwise Comparison Matrix for Health and Safe Environment

H/S/E	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.03	0.05	0.03	0.03	0.02	0.01	0.16	6.21
OEP	0.21	0.40	0.56	0.56	0.62	0.37	2.72	6.74
TID	0.19	0.13	0.19	0.19	0.31	0.28	1.28	6.81
FOD	0.19	0.13	0.19	0.19	0.41	0.18	1.29	6.91
FSD	0.13	0.07	0.06	0.05	0.10	0.28	0.69	6.72
FED	0.19	0.10	0.06	0.09	0.03	0.09	0.57	6.15
							AVR.:	6.59

Table 5.11 Initial Weight Ratio (Column/Row) for Energy

ENERGY	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	3.00	4.00	0.17	4.00	1.00
OEP	0.33	1.00	4.00	0.33	4.00	3.00
TID	0.25	0.25	1.00	0.14	3.00	0.33
FOD	6.00	3.00	7.00	1.00	7.00	3.00
FSD	0.25	0.25	0.33	0.14	1.00	0.17
FED	1.00	0.33	3.00	0.33	6.00	1.00
TOTAL	8.83	7.83	19.33	2.12	25.00	8.50

CI = 0.11

Table 5.12 Normalized Matrix With Eigenvector for Energy

ENERGY	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR
FPO	0.11	0.38	0.21	0.08	0.16	0.12	0.18
OEP	0.04	0.13	0.21	0.16	0.16	0.35	0.17
TID	0.03	0.03	0.05	0.07	0.12	0.04	0.06
FOD	0.68	0.38	0.36	0.47	0.28	0.35	0.42
FSD	0.03	0.03	0.02	0.07	0.04	0.02	0.03
FED	0.11	0.04	0.16	0.16	0.24	0.12	0.14
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5.13 Pairwise Comparison Matrix for Energy

ENERGY	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.18	0.52	0.23	0.07	0.14	0.14	1.27	7.18
OEP	0.06	0.17	0.23	0.14	0.14	0.41	1.15	6.61
TID	0.04	0.04	0.06	0.06	0.10	0.05	0.35	6.24
FOD	1.06	0.52	0.40	0.42	0.24	0.41	3.05	7.23
FSD	0.04	0.04	0.02	0.06	0.03	0.02	0.22	6.56
FED	0.18	0.06	0.17	0.14	0.20	0.14	0.89	6.44
							AVR.:	6.71

Table 5.14 Initial Weight Ratio (Column/Row) for R&D Operation

R&D OPER	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	1.00	0.11	0.14	0.33	1.00
OEP	1.00	1.00	0.13	0.14	0.33	0.33
TID	9.00	8.00	1.00	7.00	7.00	9.00
FOD	7.00	7.00	0.14	1.00	1.00	5.00
FSD	3.00	3.00	0.14	1.00	1.00	3.00
FED	1.00	3.00	0.11	0.20	0.33	1.00
TOTAL	22.00	23.00	1.63	9.49	10.00	19.33

CI = 0.08

Table 5.15 Normalized Matrix With Eigenvector for R&D Operation

R&D OPER	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR
FPO	0.05	0.04	0.07	0.02	0.03	0.05	0.04
OEP	0.05	0.04	0.08	0.02	0.03	0.02	0.04
TID	0.41	0.35	0.61	0.74	0.70	0.47	0.55
FOD	0.32	0.30	0.09	0.11	0.10	0.26	0.20
FSD	0.14	0.13	0.09	0.11	0.10	0.16	0.12
FED	0.05	0.13	0.07	0.02	0.03	0.05	0.06
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5.16 Pairwise Comparison Matrix for R&D Operation

R&D OPER	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.04	0.04	0.06	0.03	0.04	0.06	0.27	6.25
OEP	0.04	0.04	0.07	0.03	0.04	0.02	0.24	6.14
TID	0.39	0.31	0.55	1.37	0.83	0.53	3.97	7.27
FOD	0.30	0.27	0.08	0.20	0.12	0.29	1.25	6.41
FSD	0.13	0.12	0.08	0.20	0.12	0.18	0.81	6.81
FED	0.04	0.12	0.06	0.04	0.04	0.06	0.36	6.11
							AVR.:	6.50

Table 5.17 Initial Weight Ratio (Column/Ratio) for R&D Test

R&D TEST	HWO	FAC/OPER	H/S/E	ENERGY	R&D OPER
HWO	1.00	8.00	5.00	7.00	0.50
FAC/OPER	0.13	1.00	1.00	1.00	0.33
H/S/E	0.20	1.00	1.00	4.00	0.14
ENERGY	0.14	1.00	0.25	1.00	1.00
R&D OPER	2.00	3.00	7.00	1.00	1.00
TOTAL	3.47	14.00	14.25	14.00	2.98

CI = 0.08

Table 5.18 Normalized Matrix With Eigenvector for R&D Test

R&D TEST	HWO	FAC/OPER	H/S/E	ENERGY	R&D OPER	PRI VECTOR
HWO	0.29	0.57	0.35	0.50	0.17	0.38
FAC/OPER	0.04	0.07	0.07	0.07	0.11	0.07
H/S/E	0.06	0.07	0.07	0.29	0.05	0.11
ENERGY	0.04	0.07	0.02	0.07	0.34	0.11
R&D OPER	0.58	0.21	0.49	0.07	0.34	0.34
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00

Table 5.19 Pairwise Comparison Matrix for R&D Test

R&D TEST	HWO	FAC/OPER	H/S/E	ENERGY	R&D OPER	ROW TOTAL	RT/PV
HWO	0.38	0.58	0.53	0.75	0.05	2.29	6.10
FAC	0.05	0.07	0.11	0.11	0.04	0.37	5.11
H/S/E	0.08	0.07	0.11	0.43	0.02	0.70	6.56
ENERGY	0.05	0.07	0.03	0.11	0.11	0.37	3.42
R&D OPER	0.75	0.22	0.75	0.11	0.11	1.93	5.71
						AVR.:	5.38

Table 5.20 TSD's Divisions Final Weight

	HWD				FAC/ OPER				H/S/E				ENERGY				R&D OPER				OVERALL PRIORITY
FPO	0.03	×	0.38	+	0.25	×	0.07	+	0.03	×	0.11	+	0.18	×	0.11	+	0.04	×	0.34	=	0.07
OEP	0.08	×	0.38	+	0.08	×	0.07	+	0.40	×	0.11	+	0.17	×	0.11	+	0.04	×	0.34	=	0.11
TID	0.26	×	0.38	+	0.05	×	0.07	+	0.19	×	0.11	+	0.06	×	0.11	+	0.55	×	0.34	=	0.31
FOD	0.06	×	0.38	+	0.31	×	0.07	+	0.19	×	0.11	+	0.42	×	0.11	+	0.20	×	0.34	=	0.18
FSD	0.52	×	0.38	+	0.03	×	0.07	+	0.10	×	0.11	+	0.03	×	0.11	+	0.12	×	0.34	=	0.25
FED	0.05	×	0.38	+	0.28	×	0.07	+	0.09	×	0.11	+	0.14	×	0.11	+	0.06	×	0.34	=	0.08
																					1.00

On a request of OEP's division chief, the same procedure was executed for OEP to develop the rank of outputs. The range of outputs was known before the exercise, and they are defined later in this chapter. AHP was applied at the division level by presenting two attributes at a time to the decision-makers of the division and attempting to reach agreement on the ratio of weights between the two attributes. This approach presented a few problems. The branch chiefs had difficulty deciding on the objective of the division. It was hard to develop consensus on the attributes of the objective, and voting on the outputs and attributes was inconsistent.

The difficulties with the implementation of AHP at this level can be attributed to the limited knowledge of each branch chief of the other branches' activities. Also, branch chiefs are too involved with the activities in their own branches to have an objective opinion on the other branches' importance and worth to the division. The division chief, on the other hand, has a perfect bird's-eye view of the entire division and is apprised of the directorate priority enabling him or her to evaluate the outputs more or less objectively. For these reasons, it was decided to involve only the division chief in ranking the outputs of the divisions.

This was considered a very successful implementation of AHP where decision-makers were very comfortable and enthusiastic with the method. The steps of the technique were easily understood and accepted as a valid procedure for constructing the decision model. However, the validity of the method has been questioned by some of the theorists in the decision analysis field [Dyer 1990, Belton and Gear 1983].

To produce valid weights from this experiment, two measures were taken: (1) the range of each output was displayed while decision-makers were comparing various outputs and (2) the rank of the divisions produced by AHP was examined by using the "swing weighting" method. For properly examining the validity of AHP, it is essential to present the rank of outputs from the swing-weighting method before calculating the final rank from the AHP method and after developing comparison matrices.

In the swing-weighting method, the decision-maker is asked the question, If all divisions were at their worst contribution levels to the TSD objective and it is possible to move only one of the divisions to its best level of contribution, which division would be the most desirable to move to its best level? After elevating the most desirable one to the best possible outcome, the decision-maker is then asked what would be the second most desirable one to move, and so on [Fast and Looper 1988].

This procedure was administered with each division chief individually, and every one of them ranked the divisions in three general groups of high, medium, and low priority levels. The divisions and their weights created by implementing AHP are shown in parentheses here. The high-priority group consists of TID (0.31) and FSD (0.25), the medium-priority group includes FOD (0.18) and OEP (0.11), and the low-priority group includes FED (0.08) and FPO

(0.07). The swing-weighting procedure provided a rank order of the divisions independent from AHP that concurs with the results of AHP.

5.3 Upper and Lower Bounds of Outputs UX_{ij}, LX_{ij}

In this section, the limits of outputs are presented, and the value of outputs for a typical year, which I call the base year, are offered. The base year for TSD is fiscal year 1992. The base year data are required to establish the resources used as a function of the level of output produced.

Let X_{ij} be the amount of output j that is produced by division i using various resources. Let UX_{ij} and LX_{ij} be the maximum and minimum limits of X_{ij}, respectively. A typical minimum level of output is usually set by regulations. For example, reports on energy consumption at Lewis are filed quarterly with NASA Headquarters. Also, a system's requirements may impose a minimum level of an output. For example, repairs on roads, roofs, or steam pipes are dictated by their age and condition and not by a management decision. UX_{ij} is usually set by policies outside the organization's controls, such as restriction on the size of government.

Let BX_{ij} be the amount of output that is produced in a particular year (the base year). These data are required to determine the resource use function of outputs RX_{ij}. The following questions were presented to the appropriate supervisors who oversee the production of the output in TSD divisions:

1. What is the definition of your output?

2. What is the measuring unit of your output?

3. How many units of output were produced in fiscal year 1992 (BX_{ij})?

4. What is the maximum number of units that can be produced (UX_{ij})?

5. What is the minimum number of units that should be produced (LX_{ij})?

The answers to these questions and the weight for each output are presented in Tables 5.21 to 5.27. These weights are division chiefs' judgments on the importance of each output. The weight of each suboutput, such as X22A in Table 5.22, is determined by dividing the output X22 by the number of suboutputs, which is four in this case. The Facilities Operations Division (FOD) outputs are divided into two tables (5.24 and 5.25): institutional support and R&D support.

Table 5.21 Facilities Planning Office Outputs

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
Facilities Planning (X11)	29%	# of projects ($1000K units)	20	16	0
Center-Funded Projects (X12)	24%	# of tasks ($100K units)	40	26	0
Space Management (X13)	18%	ft^2 of space assigned	150,000	69,200	0
Real Property Management (X14)	14%	# of facilities updated	100	10	0
Energy Management (X15)	10%	# of projects ($10K units)	100	10	0
Calspan Contract (X16)	5%	# of work orders	100	43	7

Table 5.22 Office of Environmental Program Outputs

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
Industrial Hygiene (X21)	28%				
(X21A)		# of safety permits	500	277	0
(X21B)		# of reports	60	48	12
(X21C)		# of asbestos samplings	7,000	3,000	0
(X21D)		# of remediations	120	50	8
Environmental Compliance (X22)	39%				
(X22A)		lbs, hazard waste removal	2,000,000	721,000	350,000
(X22B)		# of reports issued	24	12	0
(X22C)		# of water samples	2,000	1,000	1,000
(X22D)		# of drawings reviewed	40	20	0
Hazardous Chemical Handling (X23)	13%				
(X23A)		# of chemical evaluations	10	3	0
(X23B)		# of training programs	20	12	10
(X23C)		# of safety data sheets	1,200	1,000	1,000
Health Physics (X24)	15%				
(X24A)		# of samplings for employees	1,200	596	500
(X24B)		# of reports	20	10	0
(X24C)		# of safety permits (X-Ray)	180	97	0
Chemical Analysis (X25)	5%	# of chemical tests	4,000	2,016	500

Table 5.23 Test Installation Division Outputs

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
Technical Support for Facilities (X31)	5%	# OF HOURS	33K	32K	25K
Technical Support for Laboratories (X32)	25%	# OF HOURS	165K	160K	125K
Hardware Installation (X33)	30%	# OF HOURS	198K	193K	150K
Hardware Maintenance (X34)	25%	# OF HOURS	165K	160K	125K
Operation Services (X35)	15%	# OF HOURS	99K	97K	75K

Table 5.24 Facilities Operations Division Outputs (Institutional)

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
CUSTODIAL SERVICES (X41)		MILLION ft^2 OF BUILDINGS	2.5	2.5	2.5
SOLID WASTE DISPOSAL (X42)		# OF DUMPSTERS	65 Reg & 24 Slab	65 Reg & 24 Slab	65 Reg & 24 Slab
GROUND MAINTENANCE (X43)		ACRE OF GROUND ACRE OF PARKING LOT MILES OF ROADS	86 25 7	86 25 7	86 25 7
ENGINEERING SUPPORT (X44)	5%				
(X44A)		# OF CONFIGURATION CONTROL	15	3	2
(X44B)		# OF RECERTIFICATION SYSTEMS	120	24	12
(X44C)		# OF DRAWINGS UPDATED	40	1	0
(X44D)		# OF PM SYST.	5,000	500	250
CENTER OPERATION ENG (X45)	5%	CONSTRUCTION DOLLARS	1,788k	1,500k	1,250k
PROJECT MANAGEMENT (X46)	14%				
ROAD AND PARKING MAINT (X46A)		yd^2 OF PARKING LOT AND ROADS	240,000	100,000	80,000
INSULATION OF STEAM PIPE (X46B)		ft OF PIPE COVERED	10,000	3,000	0
ENVIRONMENTAL PROJECTS (X46C)		# MAN HOURS	100,000	25,000	0

Table 5.24 Concluded.

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
ROOFING (X46D)		ft^2 OF REPAIR	150,000	68,000	0
MASONRY REPAIR (X46E)		ft^2 OF REPAIR	75,000	4,000	0
CONSTRUCTION SERVICES (X46F)		# OF WORK ORDERS	500	200	0
MILLWRIGHTS SERVICES (X46G)		# MAN HOURS	100,000	36,000	2,080
HIGH VOLTAGE MAINTENANCE (X46H)		# MAN HOURS	50,000	24,960	0
INSTITUTIONAL SUPPORT (X47)	14%	# OF TASKS	10,000	9,500	8,000
FIRE PROTECTION (X48)		NOT IN THE STUDY	N/A	N/A	N/A
SECURITY (X49)		NOT IN THE STUDY	N/A	N/A	N/A

Table 5.25 Facilities Operations Division Outputs (Research and Development)

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
CENTRAL CONTROL OPERATION (X410)	18%	# OF MACHINE HOURS	84,561	21,203	0
RESEARCH SYSTEMS OPERATION (X411)	17%	# OF HOURS OF OPERATION AND MAINTENANCE	106,400	106,400	0
SYSTEM CONTROL ENGINEERING (X412)	9%				
(X412A)		# OF WORK ORDERS	220	134	100
(X412B)		# OF SOFTWARE ACTION	100	33	33
RESEARCH SYSTEMS ENG. (X413)	9%	# OF TROUBLESHOOTING PROJECTS	6 MINOR	6 MINOR	4 MINOR
ELECTRIC POWER SYSTEM (X414)	9%	CONSTRUCTION $	10	1	0

Table 5.26 Fabrication Support Division Outputs

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
FABRICATION PROCUREMENT (X51)	25%	PROCUREMENT DOLLARS	7,166 ($K)	6,286 ($K)	6,286 ($K)
INSPECTION AND MATERIAL PROCESSING (X52)	19%	# OF HOURS	6,496	5,906	5,906
RESEARCH INSTRUMENTATION (X53)	19%	# OF HOURS	44,465	35,859	35,859
MACHINING (X54)	19%	# OF HOURS	622,080	46,080	46,080
MODEL DEVELOPMENT (X55)	12%	# OF HOURS	13,954	10,492	10,492
METAL FABRICATION (X56)	6%	# OF HOURS	34,390	28,421	28,421

Table 5.27 Facilities Engineering Division Outputs

OUTPUT NAME	WEIGHT	MEASURING UNITS	OUTPUT MAX VALUE (UX)	FY-92 BASE YEAR (BX)	OUTPUT MIN VALUE (LX)
MANAGEMENT OPERATION (X61)	25%	# OF TASKS (MKF)	500	430	350
ENVIRONMENTAL SUPPORT (X62)	25%	# OF TASKS	70	30	30
ELECTRICAL, MECHANICAL AND ARCHITECTURAL (X63)	25%	# OF CoF TASKS ($100K Units)	1,500	1,256	1,000
CONSTRUCTION MANAGEMENT (X64)	25%	# OF CONSTRUCTION CONTRACT	52	46	40

Chapter 6

Resource Use Functions

In this chapter, the resource constraint set is formulated by establishing the resource use functions for every output from the base-year data. In Section 6.1, the basis for calculating the resource use functions for output X_{ij} and quality S_i is presented. In Sections 6.2 and 6.3, the methods of estimating the output and quality resource use functions, respectively, are described. In Section 6.4, the mathematical model for TSD in its final form is presented. In Section 6.5, it is proven that the local optimum is the global optimum of the model.

6.1 Introduction

The organization is assumed to have several divisions, and the divisions are considered to be black boxes where internal policies and the intricacy of the mechanisms that drive a division are not examined. Instead, the relationships between the inputs RX and RS and the output quantity X and quality S are defined for the base year. These relationships, which I call resource use functions, should be ideally estimated from empirical data.

This empirical approach searches for historical data from several years and then draws a pattern between resources and production. If historical data on customer satisfaction or outputs are not available (as is true with most government organizations), engineering analysis might be used to estimate resource use functions. In engineering analysis, the analyst follows the production process every step of the way and measures the resources, such as time, money, and people, required to produce various levels and quality of output. This process is repeated several times to validate the resource use function and is obviously time consuming for an organization with numerous products and not practical for this study.

The only viable option was to use expert judgment to determine the parameters. The question presented to the experts was, In your judgment, what resources are used to produce one unit of output in the base year (fiscal year 1992)? Once this question was answered, a data point on the chart of resource use versus production X_{ij} was determined. The second point was assumed to be at zero production and zero cost. Similarly, two points can be identified on the resource-use-versus-quality S_i chart. It is evident that numerous functions can be generated from each chart that include these two points and that different functions might produce substantially different results.

The inputs of the divisions were collected by interviewing the decision-makers or by inspecting the current budget allocation. The resource are listed in Appendix D for the base year. The eight types of resources are all money and people, which are assumed to be not interchangeable. The following are various resources, their types, and their indices:

K = 1 Civil servant (FTE)

K = 2 Support service contractor (SSC)

K = 3 Institutional budget ($ ROS)

K = 4 Program support budget ($ FS9)

K = 5 Co-ops (COP)

K = 6 Training budget ($ TRN)

K = 7 Travel budget ($ TRV)

K = 8 Equipment budget ($ EQP)

To establish the cost of maintaining quality $RS_{ik}(S_i)$, an assumption was made that the resources allocated to manage the directorate are the cost of quality. The remaining resources appropriated to the division were considered to be the cost of producing the divisions output $RX_{ijk}(X_{ij})$. In the following sections, detailed procedures are presented to establish the production and quality resource use functions for TSD.

6.2 TSD Production Resource Use Function $RX_{ijk}(X_{ij})$

In general, three types of production resource use functions can be assumed: concave, convex, and linear (Figure 6.1).

If the function is assumed to be exponential (a special form of convex), it is assumed that after a certain point the production cost increases slightly as production increases dramatically, as is sometimes characteristic of a mass production organization. This assumption will not be valid in an organization such as NASA, where products are one of a kind. The asymptotic (a special form of concave) assumption of the production resource use function is valid only if the organization has reached the point of diminishing returns. This important principle of production theory states that adding labor and variable resources (money and people) to a fixed capital (heavy machinery and facilities) may increase return per unit of input initially when capital is underutilized. But once the fixed capital is used efficiently, additional variable input will decrease the rate of production to a point that adding resources will reduce output [Wachtel 1988]. Therefore, if this condition exists, a maximum limit of production should be imposed for the sake of efficiency.

PRODUCTION vs. RESOURCES
FOR ANNUAL CONSTRUCTION OF FACILITIES BUDGET REQUEST

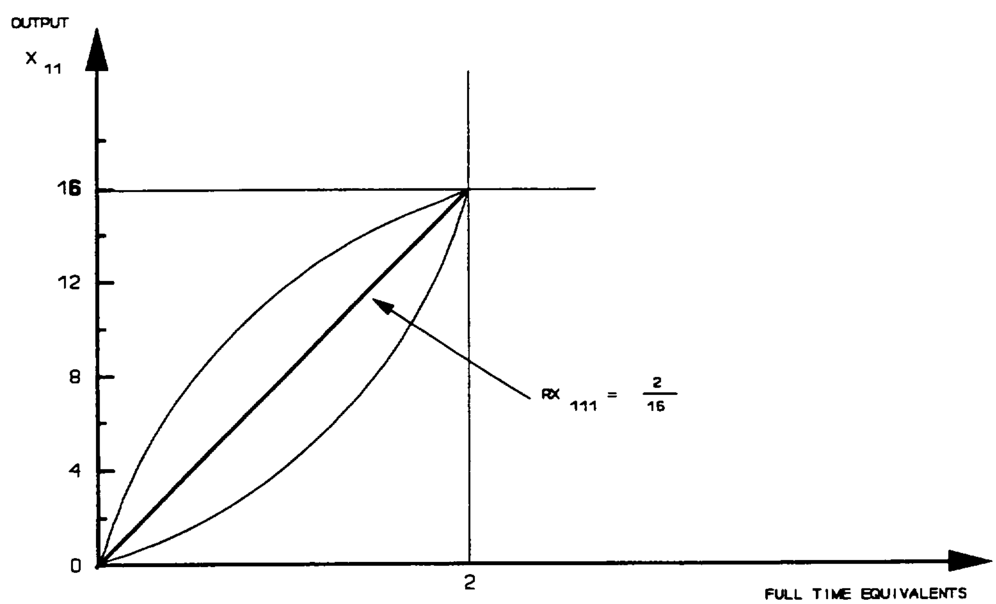

Figure 6.1 Production Resource Use Function.

After interviewing the decision-makers at TSD, it was determined that TSD's production has not reached the point of diminishing returns. Actually, with current fiscal constraints and budget cuts, we can assume that it will be difficult to find any government organization which has reached that point. Therefore, an asymptotic resource use function would not be a good assumption for this problem. A simple and plausible assumption for the production resource use function is that it is linear or proportional. With these assumptions

$$RX_{ij}(X_{ij}) = RX_{ijk}X_{ij} \tag{6-1}$$

where RX_{ijk} is the amount of resource k that is needed to produce X_{ij}. To estimate RX_{ijk}, the amount of resources that are used in the base year BRX_{ijk} is divided by the number of outputs produced BX_{ij} in that year.

$$RX_{ijk} = BRX_{ijk}/BX_{ij} \tag{6-2}$$

For example, as shown in Table 6.1, the output X11 has a base-year value (BX_{111}) of sixteen $1 million dollars in projects that were planned by two FTEs (BRX_{111}) in fiscal year 1992. The RX_{111}, which stands for the resource use function of input type 1 used to produce the output 1 from division 1, can be calculated by using equation (6-2):

$$RX_{111} = 2/16 \text{ (FTE/Million Dollar Projects)}$$

In Tables 6.1 to 6.7, the resources exclusively dedicated to production and the outputs produced from these resources are specified for each division for fiscal year 1992. The Facilities Operations Division (FOD) activities are divided into two tables (6.4 and 6.5): institutional support and R&D support.

Table 6.1 FY92 Resources Allocated to 7010 Facilities Planning Office for Production Only

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP #	K = 6 TRN $K	K = 7 TRV $K	K = 8 EQP $K	OUTPUT MEASUREMENT UNITS (UNITS)	DESCRIPTION
7010	Annual CoF Budget Request (X11)	2								16	# of projects ($1000K units)
7010	Center Funded Projects (X12)	1	0	493	576					26	# of tasks ($100K units)
7010	Space Management (X13)	1	1	1,027						69,200	ft^2 of space assigned
7010	Real Property Management (X14)	1								10	# of facilities updated
7010	Energy Management (X15)	1								10	# of projects ($10K units)
7010	Calspan Contract Management (X16)	1								43	# of work orders executed

Table 6.2 FY92 Resources Allocated to 7020 (Office of Environmental Programs) for Production Only

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP #	K = 6 TRN $K	K = 7 TRV $K	K = 8 EQP $K	OUTPUT MEASUREMENT UNITS (UNITS)	DESCRIPTION
7021	Industrial Hygiene (X21)	2.60	2.00	245.00	135.00	1.00	1.90	2.60	30.00		Total input of the Branch
	(X21A)	0.40	0.50	61.25			0.19	0.26	3.00	277	# of safety permits
	(X21B)	1.00	0.25	61.25			0.19	0.26	3.00	48	# of reports
	(X21C)	0.60	0.63	61.25	67.50	1.00	0.76	1.04	12.00	3,000	# of asbestos sampling
	(X21D)	0.60	0.62	61.25	67.50		0.76	1.04	12.00	50	# of remediations
7022	Environmental Compliance (X22)	7.00	6.00	868.00	86.00		4.50	6.10	10.00		Total input of the Branch
	(X22A)	0.50	3.00	100.00	86.00		2.25	3.05	5.00	721,000	lbs, hazard. waste removed
	(X22B)	3.50	1.50	610.00	0.00		1.13	1.53	2.50	12	# of reports issued
	(X22C)	2.00	1.00	128.00	0.00		1.13	1.53	2.50	1,000	# of water samples
	(X22D)	1.00	0.50	30.00	0.00		0.00	0.00	0.00	20	# of drawings reviewed
7023	Hazardous Chemical Handling (X23)	2.00	3.00	219.00		1.00	1.30	1.80	7.00		Total input of the Branch
	(X23A)	1.00	0.50	36.50			0.65	0.90	1.75	3	# of chemical evaluation
	(X23B)	1.00	0.50	36.50			0.65	0.90	1.75	12	# of training programs
	(X23C)	0.00	2.00	146.00		1.00	0.00	0.00	3.50	1,000	# of safety data sheet
7024	Health Physics (X24)	3.00	1.00	122.00			1.90	2.60	10.00		Total input of the Branch
	(X24A)	1.50	0.00	0.00			0.00	0.00	4.00	596	# of sampling for employees
	(X24B)	0.50	1.00	122.00			0.95	1.30	1.00	10	# of reports
	(X24C)	1.00	0.00	0.00			0.95	1.30	5.00	97	# of safety permits for X-ray and lasers
7025	Chemical Analysis (X25)	5.00	1.00	222.00	182.00	1.00	3.20	4.40	40.00	2,016	# of chemical tests

Table 6.3 FY92 Resources Allocated to 7200 (Test Installations Division) for Production Only

ORG CODE	PRODUCT TITLE	K = 1 FTE	K = 2 SSC	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP	K = 6 TRN $K	K = 7 TRV $K	K = 8 EQP $K	OUTPUT MEASUREMENT UNITS (UNITS)	DESCRIPTION
7200	Facility Tech. Support (X31)	62	6			7			38	32K	# OF HOURS
	Laboratory Tech. Support (X32)	74	16	318		5			43	160K	# OF HOURS
	Hardware Installation (X33)	65	9	319		8			39	193K	# OF HOURS
	Hardware Maintenance (X34)	68	8	191		8			42	160K	# OF HOURS
	Operation Services (X35)	69	7	0		8			44	97K	# OF HOURS

Table 6.4 FY92 Resources Allocated to 7300 (Facilities Operations Division) for Production Only (Institutional)

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 K$	K = 5 COP #	K = 6 TRN $K	K = 7 TRV $K	K = 8 EQP $K	OUTPUT MEASUREMENT UNITS (OUTPUT)	MEASUREMENT
7301	Management Support										
	(X41)	12.00	3.00	243.00						N/A	N/A
	(X42)									N/A	N/A
	(X43)									N/A	N/A
7302	Engineering Support (X44)	5.00	25.50		1,266.00				10.00		Total Input of the Branch
	(X44A)	0.50	2.55		126.60					3	# OF CONFIG CONTROL
	(X44B)	2.50	12.75		633.00					24	# OF RECERTIFICATION
	(X44C)	0.75	3.83		189.90					1	# OF DRAWINGS UPDATED
	(X44D)	1.25	6.38		316.50					500	# OF SYSTEMS IN PM
7320	Center Operation Engineering (X45)	11.00	5.00	239.00	110.00					1,500	CONSTRUCTION DOLLARS
7360	Project Management (X46)	18.00	61.00	1,988.00	2,942.00						Total Input of the Branch
	(X46A)	2.70	9.15	298.20	441.30					100K	yd^2 OF PARKING LOT & ROADS
	(X46B)	0.54	1.83	59.64	88.26					3,000	ft OF PIPE COVERED
	(X46C)	3.42	11.59	377.72	558.98					25K	# OF MAN HOURS
	(X46D)	0.72	2.44	79.52	117.68					68K	ft^2 OF REPAIR
	(X46E)	1.08	3.66	119.28	176.52					4,000	ft^2 OF REPAIR
	(X46F)	3.42	11.59	377.72	558.98					200	# OF WORK ORDERS
	(X46G)	2.70	9.15	298.20	441.30					36K	# OF MAN HOURS
	(X46H)	3.42	11.59	377.72	558.98					25K	# OF MAN HOURS
7370	Institutional Support (X47)	18.00	262.00	666.00	2,196.00					9,500	# OF TASKS
7380	Fire Department (X48)	24.00	1.00	64.00						N/A	N/A
7390	Security (X49)	10.00	64.00	2,600.00						N/A	N/A

Table 6.5 FY92 Resources Allocated to 7300 (Facilities Operations Division) for Production Only (Research and Development)

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP #	K = 6 TRN $K	K = 7 TRV$K	K = 8 EQP $K	OUTPUT MEASUREMENT UNITS (UNITS	DESCRIPTION
7303	Central Control Operation (X410)	23							10	21,203	# of Machine Hours
7304	Research System Operation (X411)	9	61						5	106,400	# of hrs. of Operation & Maintenance
7310	System Control Engineering (X412)	8	2		1,380				41		Total input of the Branch
	(X412A)	4	1		690				20.5	134	# of Work Orders
	(X412B)	4	1		690				20.5	33	# of Software Action
7330	Research System Engineering (X413)	6	3	7,449	3,972				180	6	# of Projects
7340	Electric Power System (X414)	5	2	129	219					1	Construction $

Table 6.6 FY92 Resources Allocated to 7400 (Fabrication Support Division) for Production Only

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP #	K = 6 TRN $K	K = 7 TRV K$	K = 8 EQP K$	OUTPUT MEASUREMENT UNITS (UNITS)	DESCRIPTION
7410	Fabrication Procurement (X51)	12	2								
7420	Metallurgical Support (X52)	9	22		55				255	5,906	# OF HOURS
7430	Research Instrumentation (X53)	28	1		60	3			103	25,859	# OF HOURS
7440	Machining (X54)	36	8		135	2			205	46,080	# OF HOURS
7450	Model Development (X55)	10			30				50	10,492	# OF HOURS
7460	Metal Fabrication (X56)	26	2		20				100	28,421	# OF HOURS

Table 6.7 FY92 Resources Allocated to 7600 (Facilities Engineering Division) for Production Only

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP #	K = 6 TRN $K	K = 7 TRV $K	K = 8 EQP $K	OUTPUT MEASUREMENT UNITS (UNITS)	DESCRIPTION
7601	Management Operations (X61)	6	5	39	79		4.20	8.20	18	430	# of Tasks
	Environmental Support (X62)	5	2							30	# of Tasks
	Mechanical, Electrical, Architectural (X63)	49	15	128	259		25.30	37.30	167	1,256	# of CoF Tasks ($100K units)
7650	Construction Management (X64)	17	4	95	190		8.70	5.50	25	46	# of Construction Contract

6.3 TSD Quality Resource Use Function $RS_{ik}(S_i)$

The same dilemma in developing production resource use functions also exists with the quality resource use function. Only two data points can be identified. As explained before, three types of quality resource use functions can be assumed: concave, convex, and linear. If the quality resource use function is assumed to be exponential (a special form of convex), it is assumed that after a certain point the quality cost remains unchanged as quality increases. This assumption is obviously unreasonable.

If the quality resource use function is assumed to be linear, the cost of increasing present quality per unit of quality is the same whether the present quality is near its lowest or highest value. This assumption is not valid because, intuitively, the marginal cost of increasing quality should be less at the lower end of the quality scale than at the higher end.

Therefore, the quality cost function can be reasonably assumed to be asymptotic (a special form of concave), meaning that the cost of quality increases rapidly as the quality approaches its maximum value (Figure 6.2). The relationship between resources and quality is assumed to be asymptotic with the following form:

$$S_i = S_{max}(1 - m_{ik}^{RS_{ik}(S_i)}) + m_{ik}^{RS_{ik}(S_i)} \tag{6-3}$$

where S_{max} is the maximum score (here, 5) that can be given in a questionnaire. $RS_{ik}(S_i)$ is the amount of resource of type k, which could be money, people, or equipment, that is required to maintain quality at the S_i level. The value of S_i at zero amount of resource is 1.

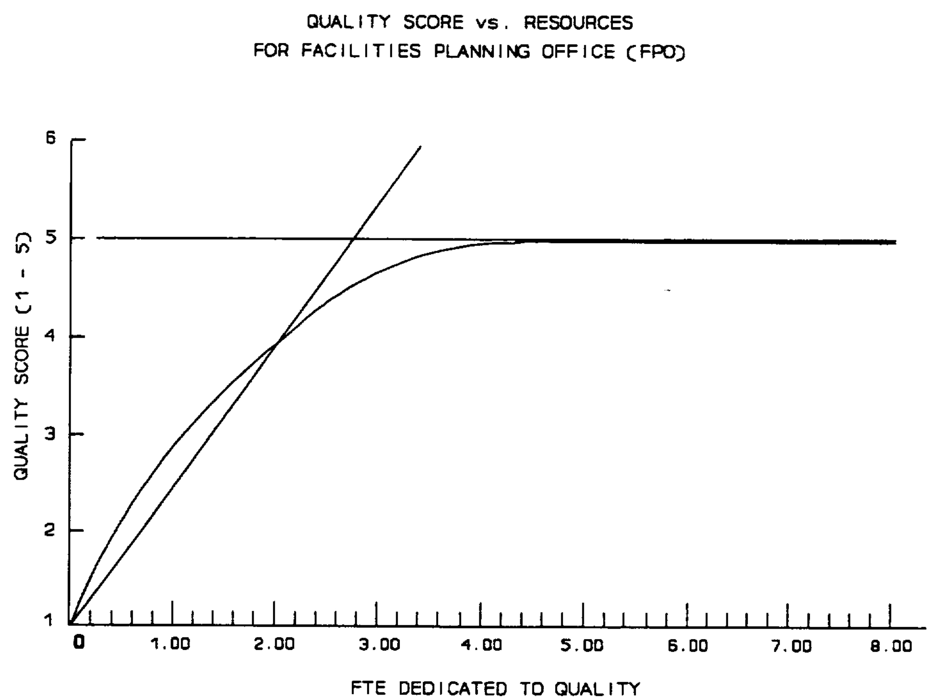

Figure 6.2 Quality Resource Use Function.

Equation (6-3) suggests that the closer the quality to its maximum level, the higher is the cost of maintaining it. Rearranging equation (6-3) gives

$$RS_{ik}(S_i) = \ln[(S_{max} - S_i)/(S_{max} - 1)]/\ln(m_{ik}) \tag{6-4}$$

The parameter m_{ik} (<1) is calculated from quality data for the base year BS_i and the resources devoted to maintaining quality during the base year $BRS_{ik}(BS_i)$. BS_i was estimated by averaging the general satisfaction score that each division received from the customers throughout the questionnaire. This procedure indicates that the opinions of all customers are equally important for TSD.

The value of $BRS_{ik}(BS_i)$ was determined by estimating the amount of resources committed to improving the division's customer satisfaction. For example, it was assumed that division chiefs, secretaries, branch chiefs, and people in any other administrative positions directly affect customer satisfaction by planning, reviewing, and assigning resources to various products of the organization. This assumption is valid because the managers in TSD are mainly responsible for providing the best service possible to the other directorates at the Center.

Another assumption was that funding for training is also dedicated to improving customer satisfaction. This assumption is reasonable because the training budget is mostly associated with administration, as shown in Table 6.8.

The travel budget was also credited to quality improvement because it is closely related to the training budget. Table 6.9 displays some costs of quality for the directorate.

Table 6.8 FY92 Training Instances by Percentage Within TSD

TYPE	FY88	FY89	FY90	FY91	FY92
EXECUTIVE AND MANAGEMENT	0.1	0.4	0.9	0.5	0.4
SUPERVISORY	2.8	2	2.4	2	1.6
LEGAL, MEDICAL, SCIENTIFIC	3.3	3.7	4.2	4.1	3.3
ADMINISTRATION	**44.6**	**39.6**	**42.1**	**60.7**	**70.4**
CLERICAL	0.8	1	0.5	0.6	0.4
TRADE, CRAFT	15.6	18.4	15.1	7.7	6.6
GENERAL	17.8	14.2	13.2	12.8	10.3
COMPUTER HARDWARE AND SOFTWARE	15	20.8	21.4	11.6	6.9

Table 6.9 FY92 Resources Allocated to the Quality of Output in Various Divisions

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP #	K = 6 TRN $K	K = 7 TRV $K	K = 8 EQP $K	QUALITY SCORE
7010	Division Office	2	1				5	4.6	37	3.71
Total	**RS_1**	**2**	**1**				**5**	**4.6**	**37**	
	m_{1k}	0.5679	0.3225				0.7975	0.7819	0.9699	
7020	Division Office	2	4	189			1.3	3.8	6	3.99
7021	Branch Office	1	1				1.9	2.6		
7022	Branch Office	1	1				4.5	6.1		
7023	Branch Office	1	1				1.3	1.8		
7024	Branch Office	1	1				1.9	2.6		
7025	Branch Office	1	1				3.2	4.4		
Total	**RS_2**	**7**	**9**	**189**			**14.1**	**21.3**	**6**	
	m_{2k}	0.8215	0.8582	0.9927			0.9070	0.9374	0.7950	
7200	Division Office	8	20	42			65	50	64	4.21
	Tech Support for Fac	1.65								
	Tech Support for Labs	1.97								
	Hardware Installation	1.73								
	Hardware Maintenance	1.81								
	Operation Services	1.84								
Total	**RS_3**	**17**	**20**	**42**			**65**	**50**	**64**	
	m_{3k}	0.9089	0.922	0.9621			0.9753	0.9681	0.975	
7300	Division Office	8								3.63
7301	Branch Office	9	3							
7302	Branch Office	1	1							
7303	Branch Office	1		113			40	42.8	137	
7304	Branch Office	1	1						30	
7310	Branch Office	1	1						10	
7320	Branch Office	1	1							
7330	Branch Office	1	1							
7340	Branch Office	1	1							
7360	Branch Office	1	1							

Table 6.9 Concluded.

ORG CODE	PRODUCT TITLE	K = 1 FTE #	K = 2 SSC #	K = 3 ROS $K	K = 4 FS9 $K	K = 5 COP #	K = 6 TRN $K	K = 7 TRV $K	K = 8 EQP $K	QUALITY SCORE
7370	Branch Office	1	1							4.28
7380	Branch Office	1	1							
7390	Branch Office	1	1							
Total	**RS_4**	**28**	**13**	**113**			**40**	**42.8**	**177**	
	m_{4k}	0.9596	0.9072	0.9906			0.9736	0.9753	0.9940	
7400	Division Office	1	1	20			30.5	26.5		
7410	Branch Office	1	1							
7420	Branch Office	1	1							
7430	Branch Office	1	1							
7440	Branch Office	1	1		1212					3.27
7450	Branch Office	1								
7460	Branch Office	1	1							
Total	**RS_5**	**7**	**6**	**20**			**30.5**	**26.5**		
	m_{5k}	0.7833	0.7521	0.9181			0.9455	0.9375		
7600	Division Office	2		605	**1212**		38.2	51	60	
	Management Operation	1	1		0.9993					
	Environmental Support									
	Mechanical, Electrical and Architectural	3	3							
	Construction Management	2	1							
Total	**RS_6**	**8**	**5**	**605**			**38.2**	**51**	**60**	
	$m_{6k}2$	0.9077	0.8460	0.9986			0.9783	0.9837	0.9862	

6.4 TSD Quality Resource Use Function Parameter m_{ik}

Now that resources and level of quality had been determined, the parameter m_{ik} could be calculated by using equation (6-4) and the base-year resources used. On the asymptotic curve, equation (6-4), two points were identified. The first point was at quality level 1 and zero cost. The second point was generated by estimating resources and quality for the base year.

For example, consider the division office for FSD (7400). The m_{51} (division 5 and resource 1) can be calculated by inputting the base-year values of the parameters $BRS_{51}(S_5) = 7$, $BS_5 = 4.28$, and $S_{max} = 5$ in equation (6-4), resulting in

$$7 = [\ln(5 - 4.28)/(5 - 1)]/\ln(m_{ik}) \qquad (6\text{-}5)$$

$$m_{51} = e^{[\ln(0.72/4)]/7} = 0.783 \qquad (6\text{-}6)$$

With the calculated value of m_{51}, a general formulation for equation (6-4), the resource use function of FSD is estimated from the quality of the FSD output:

$$RS_{51}(S_5) = [\ln(5 - S_5)/(5 - 1)]/\ln(0.783) \qquad (6\text{-}7)$$

Although these are not nearly enough points to construct a function that one can be fully confident in, it provides the best possible answer at this time. As more data become available, a more accurate resource use function can be estimated. With the above assumptions, a more specific version of the model is presented in the next section.

6.5 TSD Mathematical Model

Based on the assumptions outlined earlier in Chapters 2 and 6, the TSD mathematical model in its final form is

$$\text{Max } Z = \sum_i S_i \sum_j W_{ij} X_{ij}/(UX_{ij}) \tag{6-8}$$

subject to

$$\sum_i \ln[(S_{max} - S_i)/(S_{max} - 1)]/\ln(m_{ik})$$

$$+ \sum_i \sum_j RX_{ijk} X_{ijk} \leq B_k \qquad \forall k \tag{6-9}$$

$$S_{min} \leq S_i \leq S_{max} \qquad \forall i \tag{6-10}$$

$$LX_{ij} \leq X_{ij} \leq UX_{ij} \qquad \forall i,j \tag{6-11}$$

All variables are nonnegative.

The decision variables are

S_i General opinion of customers on the quality of division i outputs on a 1 to 5 scale

X_{ij} Units of output j produced by division i

The parameters are

B_k Total resource of type k available to the organization

LX_{ij} Lower bound of X_{ij}

m_{ik} Quality cost parameter for division i and resource k

RX_{ijk} Units of resource k required to produce one unit of X_{ij}

S_{max} Upper bound of S_i

S_{min} Lower bound of S_i

UX_{ij} Upper bound of X_{ij}

W_{ij} Weight of output j of division i

This problem has a convex feasible region but a nonconcave objective function. These conditions can make the problem nonconcave, where the local optima are not necessarily global optima. A problem is concave if the feasible region is convex and the objective function is strongly quasi-concave [Chankong 1989]. Global optimality can be proven for a two-dimensional version of the TSD problem where only the variables S_1 and X_{11} are considered. However, the general problem, with n variables, does not necessarily produce a global optimum because adding quasi-concave functions will not necessarily result in a quasi-concave function.

The following example is constructed to demonstrate that in the general TSD problem, local optima are not necessarily global optima and therefore the problem is nonconvex.

$$\text{Max } Z = 0.9S_1X_1 + S_2X_2 \tag{6-12}$$

subject to

$$\ln[(S_{max} - S_1)/(S_{max} - 1)]/\ln(m) + X_1 + \ln[(S_{max} - S_2)/(S_{max} - 1)]/\ln(m) + X_2 \le B_1 \tag{6-13}$$

$$S_{min} \le S_1,\ S_2 \le S_{max} \tag{6-14}$$

$$0 \le X_1,\ X_2 \tag{6-15}$$

where

$$S_{min} = 1$$

$$S_{max} = 5$$

$$B_1 = 30$$

$$m = 0.5679$$

Two feasible solutions to this model are examined where one has a better value of the objective than the other. Then, the feasible point with the lower value of the objective is proven to be a local optimum, proving that the problem is nonconvex.

The first solution is provided by fixing X_2 and S_2 values at zero and calculating the optimum value of S_1 and X_1 by using equations (6-12) through (6-15). The problem becomes

$$\text{Max } Z = 0.9S_1X_1 \tag{6-16}$$

subject to

$$\ln[(5 - S_1)/(5 - 1)]/\ln(0.5679) + X_1 + \ln[(5)/(5 - 1)]/\ln(0.5679) \leq 30 \tag{6-17}$$

$$1 \leq S_1 \leq 5 \tag{6-18}$$

$$X_1 \geq 0 \tag{6-19}$$

The first solution resulted in $S_1 = 4.68091$, $X_1 = 25.92543$, $S_2 = 0$, $X_2 = 0$, and $Z = 109.215$. The second solution is determined by setting S_1 and X_1 equal to zero and solving equations (6-12) through (6-15). The second solution is $S_1 = 0$, $X_1 = 0$, $S_2 = 4.68091$, $X_2 = 25.92543$, and $Z = 121.35$. These solutions are both feasible, but the second solution is clearly better because of its higher objective function value (121.35 versus 109.215). If it can be shown that the first solution (Z = 109.215) is a local optimum, the problem has a local optimum that is not globally optimal, and hence the problem is nonconvex.

From the first solution, which is a feasible point, a search for a feasible direction to improve the objective function value is conducted. By following the method of Zoutendijk [1960] (page 418 of Bazaraa et al. [1993]) for nonlinear inequality constraint problems, the feasible direction is determined for a general problem: Minimize f(x) subject to $g_i(x) \leq 0$ for i = 1,...,m. Let x be a feasible solution to the general problem, and let $I = \{i{:}g_i(x) = 0\}$, where I is the index of binding constraints. The following direction-finding problem is defined:

$$\text{Minimize } p \tag{6-20}$$

subject to

$$\nabla f(x)^t d - p \leq 0 \tag{6-21}$$

$$\nabla g_i(x)^t d - p \leq 0 \qquad \text{for } i \in I \tag{6-22}$$

$$-1 \leq d_j \leq 1 \qquad \text{for } j = 1,\ldots,n \tag{6-23}$$

where $\{d_1, d_2, d_3, d_4\}$ are decision variables.

Applying this method to equations (6-12) through (6-15) for solution 1 results in

$$\underset{\{d_1,\, d_2,\, d_3,\, d_4\}}{\text{Minimize}}\ p \tag{6-24}$$

subject to

$$-0.9S_1d_1 - 0.9X_1d_2 - S_2d_3 - X_2d_4 - p \le 0 \tag{6-25}$$

$$d_1 - d_2/[\ln(0.5679)(5 - S_1)] + d_3 - d_4/[\ln(0.5679) \times (5 - S_2)] - p \le 0 \tag{6-26}$$

$$-d_3 - p \le 0 \tag{6-27}$$

$$-d_4 - p \le 0 \tag{6-28}$$

$$-1 \le d_j \le 1 \qquad \text{for } j = 1,\ldots,4$$

Equations (6-18) and (6-19) are not binding for S_1 and X_1, respectively, and only binding for S_2 and X_2, resulting only in equations (6-27) and (6-28). Solving this problem for solution 1 ($S_1 = 4.68091$, $X_1 = 25.92543$, $S_2 = 0$, $X_2 = 0$) resulted in no feasible direction for improving the objective function value, so that the feasible point is locally optimum. On the other hand, it is clear that this local optimum is not globally optimal because feasible solution 2 has an objective value of 121.35 ($S_1 = 0$, $X_1 = 0$, $S_2 = 4.68091$, $X_2 = 25.92543$, $Z = 121.35$). Therefore, solution 1, the local optimum, is not a global optimum and our problem, equations (6-8) through (6-12), is nonconvex. We can thus conclude that the solution found by GAMS is not necessarily a global optimum, since GAMS uses local gradient information to search for the optimal solution.

Determining the global optimum for a nonconvex problem is a classical problem that is well researched. The methods that have been developed can be divided into two categories: deterministic methods and stochastic methods

[Dixon and Szego 1978]. Deterministic methods, which include trajectory methods [Brian 1972], the deflection method [Goldstein and Price 1971], and interval arithmetic methods [Hansen 1980], do not have any random or stochastic features. Stochastic methods, generally, sample the objective function at randomly selected points in the feasible region. These methods normally combine the random sampling with a phase where local minimization algorithms are performed from some of the sample points. Stochastic methods provide an attractive choice from the theoretical and computational points of view. A paper by Byrd et al. [1990] suggests that stochastic methods can be used to solve the global optimization problem while exploiting parallel algorithms. In particular, the problem can be decomposed into several independent problems and solved concurrently.

In the first step of the Byrd et al. [1990] method, the feasible region R is divided into p equal-size subregions. The second step consists of a three-phase iteration. In the first phase of each iteration, the sampling phase, each processor generates 1/p of the sample points (where p is the number of processors) and evaluates the objective function at each point. The starting points, in the second phase, are selected by each processor from its own subsample space. In the third phase, local minimization is performed from all starting points. Each starting point is assigned to a processor, which performs a minimization from that point. Another starting point is assigned to the processor as soon as it terminates its current minimization. This procedure continues until local searches from all starting points are completed. Then, in the third and final step, if the stopping rule is satisfied, the lowest local minimum is regarded as the global minimum. If the stopping rule is not satisfied, return to the first step.

PART THREE

RESULTS AND CONCLUSIONS

Chapter 7

Results

In this chapter, the outcome of the model and several sensitivity analyses are presented. In Section 7.1, the solution procedure is outlined, and the methods and software used to solve this model are presented. In Section 7.2, the optimum and present resource allocations are presented in graphical form for each resource category (Figures 7.1 to 7.8) and are compared in Section 7.3. In Section 7.4, the impact of equal-versus-assigned weights on the results is examined, and in Section 7.5, the effect of budget size on the outcome is analyzed. In Section 7.6, the effect of two different quality resource use functions on the results is presented. In Section 7.7, the relative values of the various resources are presented. In Section 7.8, the results of the questionnaire are presented and the level of customer satisfaction is described.

7.1 Solution Procedure

The problem presented in Chapter 6, equations (6-8) to (6-11), is nonlinear with inequality constraints. The objective function is quadratic. The constraint set is also nonlinear because of the quality resource use function. As demonstrated in Section 6.5 the problem is convex, so any local optimum is also a global optimum. Such problems can often be solved by using software such as GINO or GAMS. GAMS was used to solve the TSD model.

GAMS is a compiler that can create large-scale optimization models. Nonlinear models are solved by employing a Fortran-based system called GAMS/MINOS. GAMS/MINOS uses a projected Lagrangian algorithm to solve these kinds of problems. A sequence of linearly constrained subproblems must be created and solved with the aim of converting the nonlinear constraints to linear ones. After defining a linearly constrained problem, GAMS/MINOS employs the reduced-gradient algorithm to minimize the objective function and find the local optimum.

Nonsmooth and discontinuous functions should be avoided for this nonlinear solver. Also, integer restrictions cannot be imposed directly. GAMS/MINOS is designed to find local optima. The functions must be smooth (first derivatives exist and are continuous), but they need not be separable. See Murtagh and Saunders [1982] for additional information. The TSD model meets the above conditions and the model is optimized by using GAMS software.

In implementing the TSD model, some of the outputs, such as garbage removal, security, and fire protection services, that did not have any range (i.e., LX = UX) were not considered, and their associated budget was removed from the model.

7.2 Optimum Resource Allocation Results

The optimum resource allocation is presented in the form of several graphs. There is a chart for each type of resource (FTE, SSC, etc.) that presents the fiscal year 1992 level of resource committed to each division as well as the optimum level. These charts are presented in Figures 7.1 to 7.8, and are discussed below.

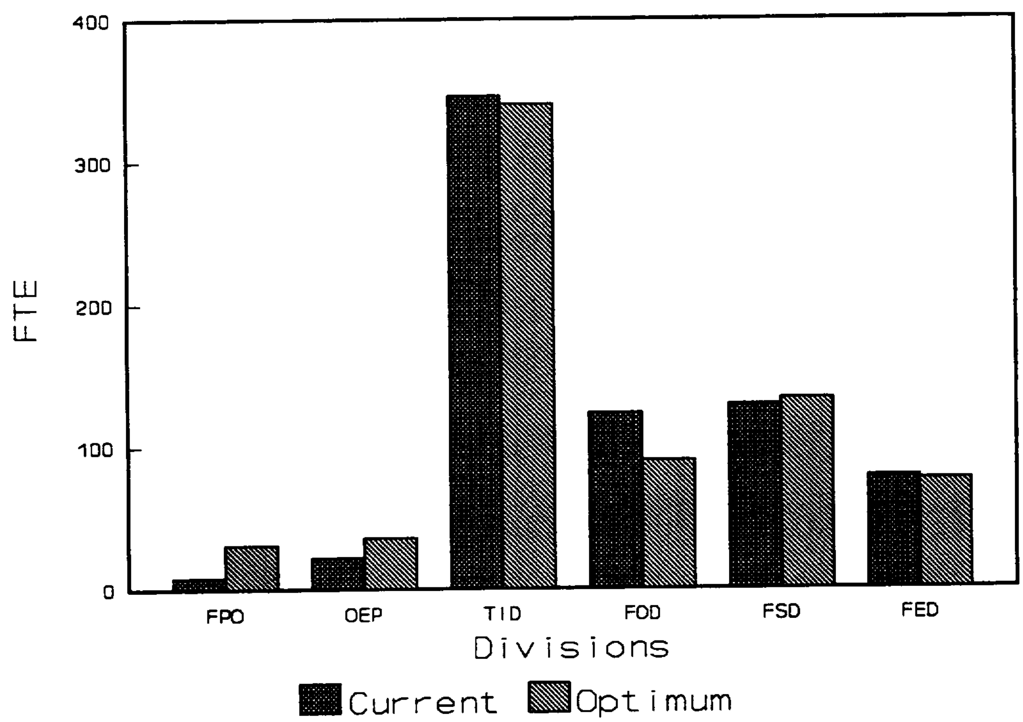

Figure 7.1 Full-Time Equivalents Required for Each Division.

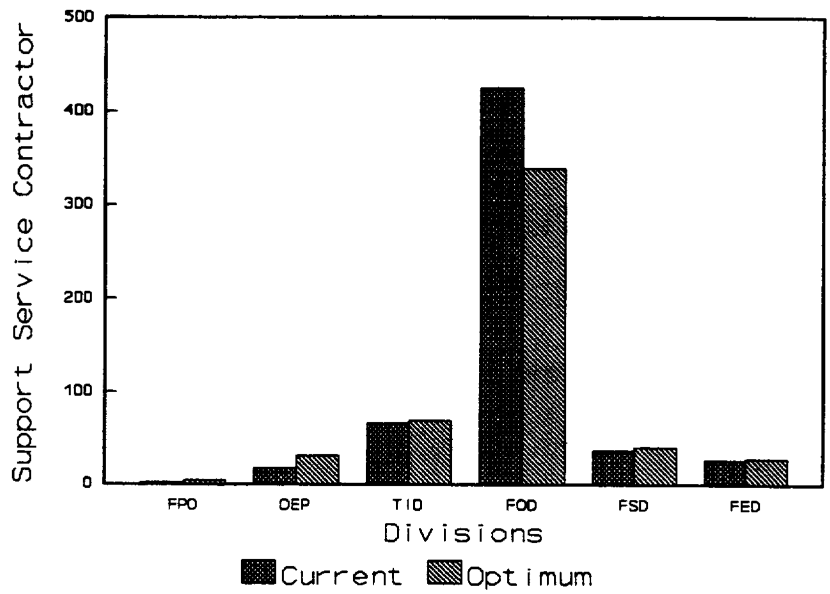

Figure 7.2 Support Service Contractors Required for Each Division.

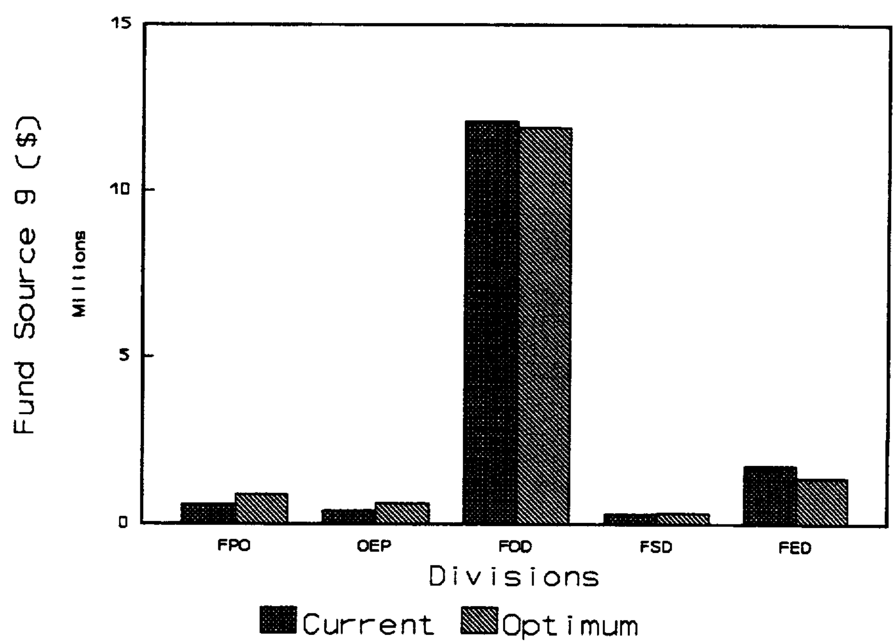

Figure 7.3 Fund Source 9 Money Required for Each Division.

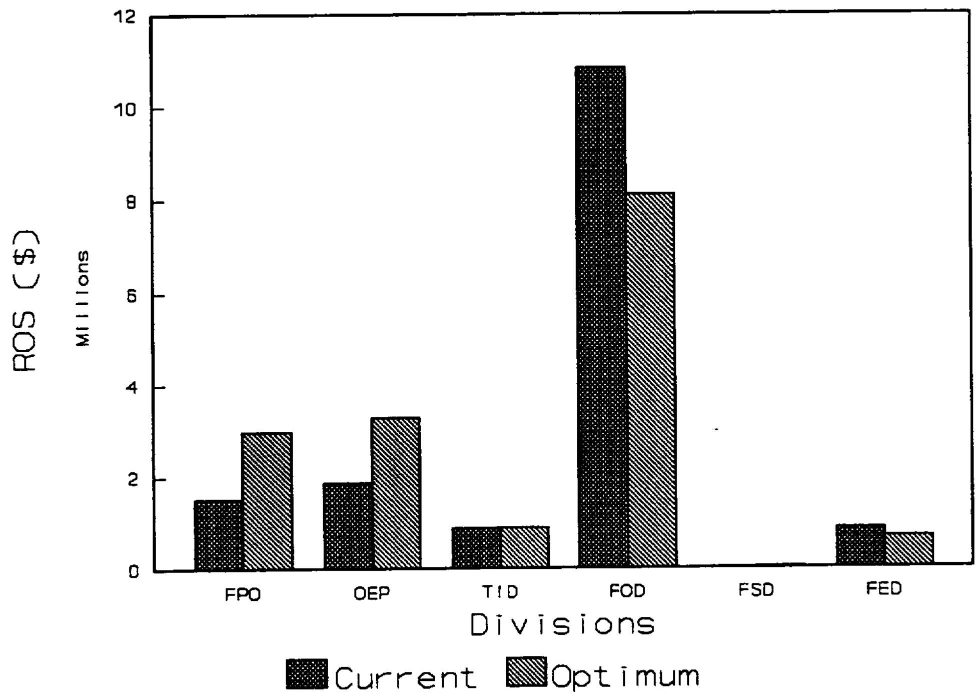

Figure 7.4 Research Operation Support Required for Each Division.

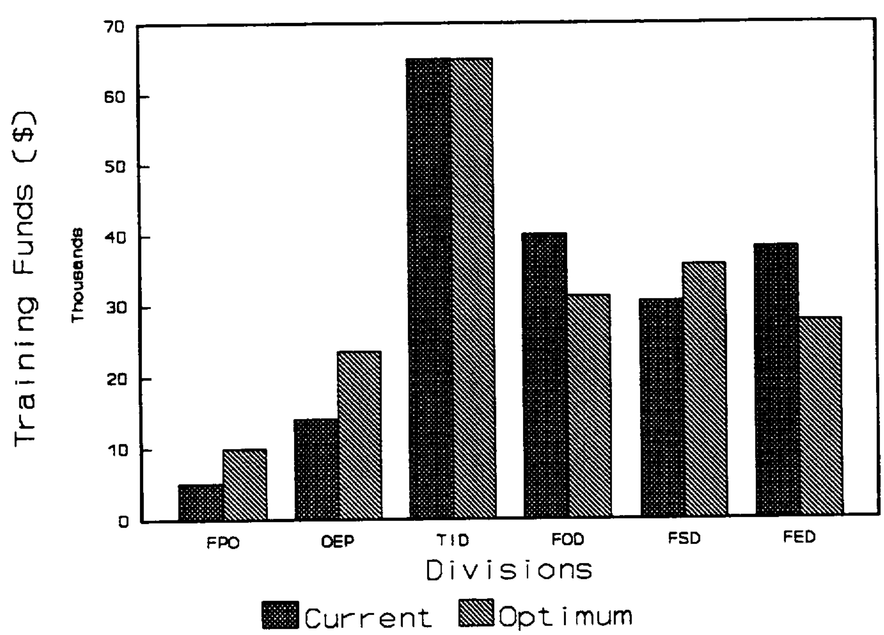

Figure 7.5 Training Funds Required for Each Division.

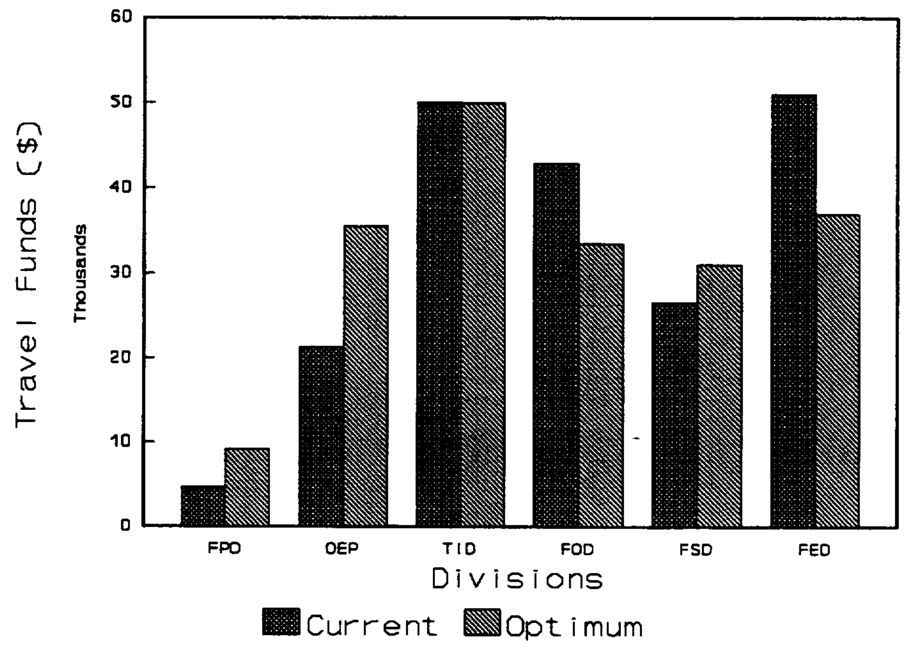

Figure 7.6 Travel Funds Required for Each Division.

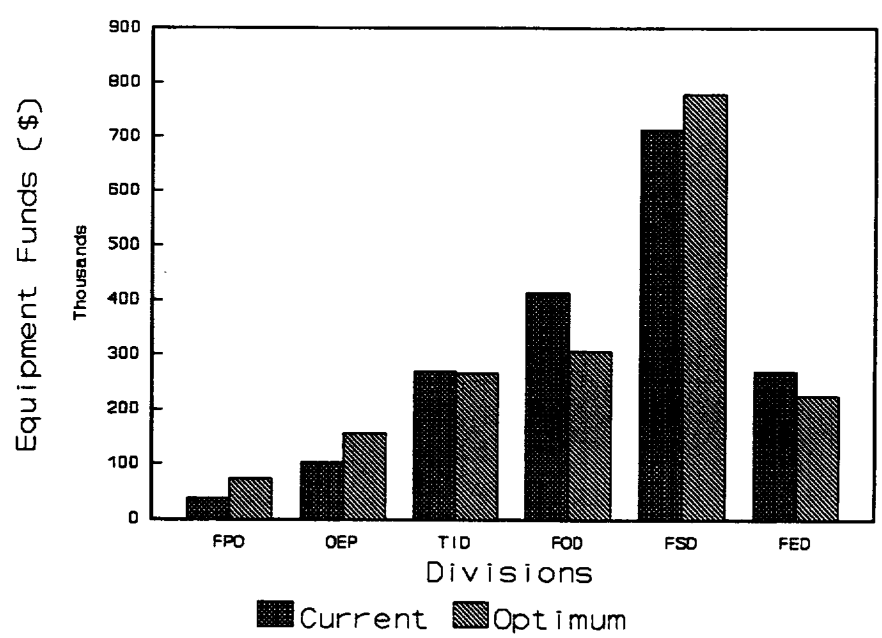

Figure 7.7 Equipment Funds Required for Each Division.

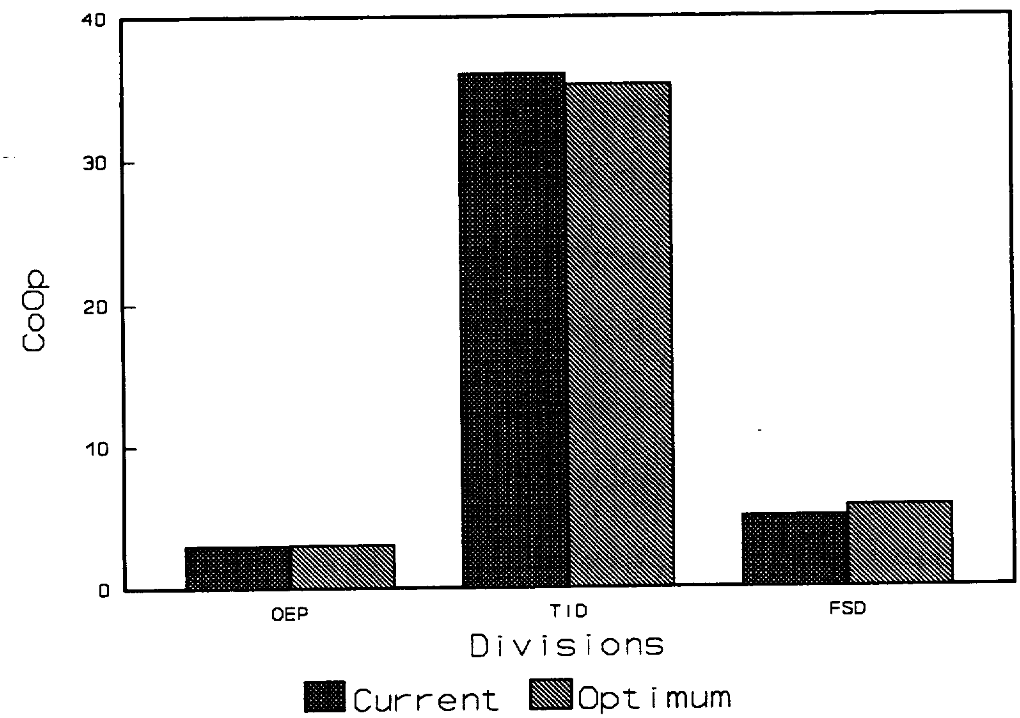

Figure 7.8 Co-Ops Required for Each Division.

7.3 Optimum Versus Present Resource Allocation

In this section, the optimum and present resource allocations are compared in each resource category. These comparisons are important because they provide insight into the shifts of resources among divisions. In Sections 7.3.1 through 7.3.6, explanations are offered for the change in resources, the value of objective functions, and the quality and quantity of the outputs of various divisions. The results of the model directly depend on the inputs of the model: resource use functions, weight of outputs, definition of outputs, and methods of measuring outputs. The accuracy of the outcome is directly correlated with the accuracy of the inputs of the model. The purpose of subsequent sections is merely to explain the results in order to illustrate the capability of the model.

7.3.1 Analysis of FTE Allocation

As illustrated in Figure 7.1, the FPO and OEP divisions received more FTEs in the optimization; these FTE levels can be credited to the low cost of operation in these two divisions. Also, their customer satisfaction scores are relatively high, supporting the results of the model, which allocated more resources to these divisions in order to increase the number of satisfied customers. This result is demonstrated later in this section by an analysis of the constraint set and objective function coefficients of the model.

Other divisions' FTE levels, with the exception of FOD, did not differ significantly. The decrease in FOD's FTE allocation can be attributed to this division's having the most resources in TSD and not scoring very high in customer satisfaction. This decrease was to be expected, given that the model reduced the resources of FOD to compensate for the increase in other divisions. The same conclusion can be drawn for the SSC, ROS, CoOp, and EQP categories of resources. Only three divisions (OEP, TID, and FSD) needed CoOp resources. The above conclusions can be justified as follows.

Mathematically, a partial derivative value of the objective function with respect to resources use of an output $\partial Z/\partial RX_{ijk}(X_{ij})$ is an indication of the resource cost of improving the objective. For instance, if this value is small for

X_{ij} and resource k relative to $X_{i'j'}$ for the same resource, more units of resource k will likely give more "bang for the buck" if devoted to $X_{i'j'}$. This partial derivative can be calculated as

$$\partial Z/\partial RX_{ij}(X_{ij}) = (\partial Z/\partial X_{ij})[\partial X_{ij}/\partial RX_{ij}(X_{ij})] \tag{7-1}$$

Now, from equations (6-1) and (2-9),

$$RX_{ij}(X_{ij}) = RX_{ijk}X_{ij} \tag{7-2}$$

$$Z = \sum_i S_i \sum_j W_{ij}[X_{ij}/(UX_{ij})] \tag{7-3}$$

Then, calculating the appropriate partial derivatives from equations (7-2) and (7-3) and substituting in equation (7-1) yield

$$\partial Z/\partial RX_{ij}(X_{ij}) = (S_i W_{ij}/UX_{ij})(1/RX_{ij}) \tag{7-4}$$

For illustration purposes, consider the FTE (k = 1) allocation for an output from FPO, say X12, and another output from FOD, say X411 (Table 7.1).

Table 7.1 Partial Derivative of Objective Function Value With Respect to Production Cost

OUTPUT	S_i	W_{ij}/UX_{ij}	RX_{ijk}	$\partial Z/\partial RX_{ijk}(X_{ij})$
X12	3.71	0.001015	0.0192	0.196
X411	3.63	0.000000288	0.00007519	0.01388

The $\partial Z/\partial RX_{ij}(X_{ij})$ value in Table 7.1 indicates that if one additional FTE is allocated to X12, the objective function value will increase by 0.196, which is 14 times more than the increase in the objective function value (0.01388) if the same FTE is allocated to the output X411. Therefore, it is reasonable to expect that X12 will receive more FTEs than X411. This conclusion is shown in Figure 7.1, where FTE is reduced in FOD (X411) while increased in FPO (X12).

7.3.2 Analysis of FS9, TRN, and TRV Allocations

The optimum distribution of fund source 9 (FS9), $k = 4$, did not change from the current distribution, meaning that TSD presently uses FS9 in the best way according to the assumptions of the model. This conclusion was unexpected, but it may be attributed to the fact that TID, the division with the highest weight, does not require FS9 funding. The FS9 is provided by taxing the customers, who are the R&D directorates in the Center. This fund, in some cases, is monitored by customers, who give additional scrutiny in disbursing this resource. This result is interesting because if we believe that FS9 has an optimum allocation because customers have more control of this resource, we are supporting the market economy at Lewis. By "market economy," we mean that all the directorates are charged for the services that they receive from other directorates and there are no centralized budgets that fund special categories of services. An example of market economy is that every directorate at Lewis pays its own electric bill instead of TSD paying the entire electric bill for the Center.

The remaining resource categories, training (TRN) and travel (TRV), were increased for divisions with a high customer satisfaction score and decreased for the divisions with a low customer satisfaction score as shown in Tables 7.2 and 7.3. This result was expected because the TRN and TRV budgets contribute only to maintaining customer satisfaction (see Tables 6.10 and 6.11).

Table 7.2 Training Budget Versus Customer Satisfaction Score

	FPO	OEP	TID	FOD	FSD	FED
PERCENT INCREASE	127.5	49	17.1	−30.7	26.6	−58.5
QUALITY SCORE FROM SOLUTION	4.696	4.487	4.405	3.096	4.596	2.177

Table 7.3 Travel Budget Versus Customer Satisfaction Score

	FPO	OEP	TID	FOD	FSD	FED
PERCENT INCREASE	127.4	49	17.5	−30.7	33.9	−58.5
QUALITY SCORE FROM SOLUTION	4.969	4.487	4.405	3.096	4.596	2.177

7.3.3 Overall Customer Satisfaction

Overall customer satisfaction Z, equation (2-9), is presented in Table 7.4 for the entire directorate and its constituent divisions for the current and optimal resource allocations. This table represents the increase or decrease of objective function value for the directorate and divisions as a result of optimum resource allocation.

Table 7.4 Objective Function Value for Directorate and Divisions

Objective Function Value	Z_{Direct}	Z_{FPO}	Z_{OEP}	Z_{TID}	Z_{FOD}	Z_{FSD}	Z_{FED}
Present	2.94	0.134	0.206	1.269	0.382	0.748	0.196
Optimum	3.53	0.326	0.451	1.294	0.332	0.889	0.197

The optimum resource allocation increased the directorate overall customer satisfaction by 20.1 percent (from 2.9 to 3.5). The overall customer satisfaction increased in all the divisions, except FOD, which shows a slight decrease. A shift in overall objective value function is due to a shift in quality and quantity of the division outputs. The next two sections explain the shift in quality and quantity of output in various divisions.

7.3.4 Shift in Output Level by Division

The shift in output level can be attributed to the resource use function RX_{ijk} and the weight of outputs W_{ij} in FOD. For more specifics, refer to Appendix C, where the result of a run is presented in four columns. Each decision variable is assigned four values, lower (lower bound of variable), level (the optimum value), upper (upper bound of variable), and marginal.

The values in the marginal column are the amount of change in the objective function value, which we try to maximize, for one unit increase of variable. In other words, the marginal value of a variable is the partial derivative of the objective with respect to the variable. For instance, the marginal value for the variable X11 (range 16 to 20) is 0.005, meaning that if the variable X11 could increase by one unit, the objective function value (customer satisfaction) will increase by 0.005, or 0.11 percent (0.005/3.53).

The marginal values of the variables in FOD (X44A to X414) are mostly negative (because they are at their lower bounds) or very small positive numbers "EPS" (because they are between bounds). Therefore, increasing these variables (level of output) will not increase the objective function value (customer satisfaction) significantly and, in some instances, will decrease the objective function value.

The question that one can ask is, How is it possible that increasing production can reduce customer satisfaction? The answer is that increasing production will result in increasing the resources to that output, which are calculated by the resource use function RX_{ijk}. Because the resources of the directorate B_k are limited, an increase of resource to an output with less contribution to the objective function value will reduce the resources to available outputs with a higher contribution. The outcome is an overall reduction in the objective function value. Therefore, the resource allocation is directly related to the marginal value of variables, and marginal values are determined from the cost of operation RX_{ijk} and the weight of the output W_{ij} as illustrated in Table 7.1.

7.3.5 Shift in Quality of Output by Division

This shift is due to the cost of customer satisfaction RS_{ik} and the weight of output $\bar{W}_{ij}$. As mentioned earlier (Section 6.3), the cost of maintaining the quality of a division is simplistically assumed to be the cost of managing the division. All else being equal, the model increases the division quality that has the lowest cost margin of quality improvement to gain the best results for resources used.

As illustrated in Tables 6.9 and 6.10, FOD and FED had a relatively high cost of maintaining quality and a low quality score in the base year. For these reasons, the model allocated less resources to FOD and FED.

I analyzed this last point mathematically as follows: a partial derivative value of the objective function with respect to resources use of an output $\partial Z/\partial RS_{ik}(S_i)$ has a positive correlation with the amount of resources allocated to the outputs:

$$\partial Z/\partial RS_{ik}(S_i) = (\partial Z/\partial S_i)[\partial S_i/\partial RS_{ik}(S_i)] \tag{7-4}$$

If equations (6-3), (6-4), and (2-9) are rewritten,

$$S_i = S_{max}\,(1 - m_{ik}^{RS_{ik}(S_i)}) + m_{ik}^{RS_{ik}(S_i)} \tag{7-5}$$

$$RS_{ik}(S_i) = \ln[(S_{max} - S_i)/(S_{max} - 1)]/\ln(m_{ik}) \tag{7-6}$$

$$Z = \textstyle\sum_i S_i \sum_j W_{ij}[X_{ij}/(UX_{ij})] \tag{7-7}$$

Then, from equation (7-5),

$$\partial S_i/\partial RS_{ik}(S_i) = -4\ln(m_{ik})e^{\ln(m_{ik})RS_{ik}(S_i)} \tag{7-8}$$

Then, substituting $RS_{ik}(S_i)$ from equation (7-6) gives

$$\partial S_i/\partial RS_{ik}(S_i) = -4\ln(m_{ik})[(S_{max} - S_i)/(S_{max} - 1)] \tag{7-9}$$

and from equation (7-7)

$$\partial Z/\partial S_i = W_{ij}[X_{ij}/(UX_{ij})] \tag{7-10}$$

Therefore, equation (7-4) becomes

$$\partial Z/\partial RS_{ik}(S_i) = \{-4\ln(m_{ik})[(S_{max} - S_i)/(S_{max} - 1)]\}\{W_{ij}[X_{ij}/(UX_{ij})]\} \tag{7-11}$$

In equation (7-11), the parameters S_i and X_{ij} are the only variables, and all other parameters have a constant value. For illustration purposes, consider the FTE (k = 1) allocation for an output from FPO, say X12, and another output from FOD, say X411 (Table 7.5)

Table 7.5 Partial Derivative of Objective Function Value With Respect to Quality Cost

OUTPUT	S_i	$W_{ij}X_{ij}/UX_{ij}$	m_{ik}	$\partial Z/\partial RS_{ik}(S_i)$
X12	3.71	0.0162	0.5679	0.012
X411	3.63	0.0306	0.9596	0.002

The $\partial Z/\partial RS_{ik}(S_i)$ value in Table 7.5 indicates that if one additional FTE is allocated to X12 for improving the quality, the objective function value will increase by 0.012, which is six times more than the increase in the objective function value (0.002) if the same FTE is allocated to the output X411. Therefore, it is reasonable to expect that X12 will receive more FTEs than

X411. This conclusion is exhibited in Figure 7.1, where FTE is reduced in FOD while increased in FPO.

7.3.6 Shift in Resource Allocation

The shifts in production levels and quality as explained previously require shifts in resource allocation among divisions. As explained in Section 7.3.2, the effect of each variable on the objective function value is the marginal value of the variable. Because the model is designed to maximize the objective function value, it is reasonable that variables with high positive marginal values will rise further to increase the objective function value.

Because there is a direct relation between resources and the value of variables (linear for X_{ij} and asymptotic for S_i), an increase in the value of a variable is directly correlated with an increase in the allocated resources to the variable. This is the reason behind shifting resources from a variable with a lower marginal value to one with a higher marginal value.

For example, consider the shift in the number of FTEs between FPO and FOD. Referring to Appendix C, the marginal values of the FPO outputs (X11 to X16) are large positive numbers, whereas the marginal values of the FOD outputs are mostly negative or small positive numbers. Therefore, the model will be inclined to allocate enough resources for FPO to produce the maximum number of outputs in order to increase the objective function value. On the other hand, the resources to the FOD output, with the negative marginal value, will be minimized in order to prevent the decline of objective function value. Indeed, this is so; FPO's outputs are at their upper bounds and FOD's are often at their lower bound. Hence, there will be fewer FTEs for FOD and more for FPO.

7.4 Impact of Equal Versus Assigned Weights

To examine the sensitivity of the results to the weights W_{ij}, I executed the model with equal importance on divisions to examine the impact of the weights on the resource allocation. The weight of each division $\sum_j W_{ij}$ was assumed to be 1/6, or 16.7 percent. Then, this weight was distributed among the outputs of the division consistent with the internal priority of the division, which was decided by the division chief. The FTE allocation of this run is compared with the run for the nonequal-weight case in Figure 7.9.

As demonstrated in Figure 7.9, the resource allocation model is sensitive to the weights of the divisions. I expected that outputs would increase as the weights of outputs increased and decrease as the weights of outputs decreased. The outputs of divisions changed as I expected, with the exception of FPO. The outputs of FPO are at their maximum levels with the assigned weight (0.07); and although the weight of the division increased to 0.167, the outputs remained constant because they were already at their upper bounds. These results point out the need for weights to be chosen with care.

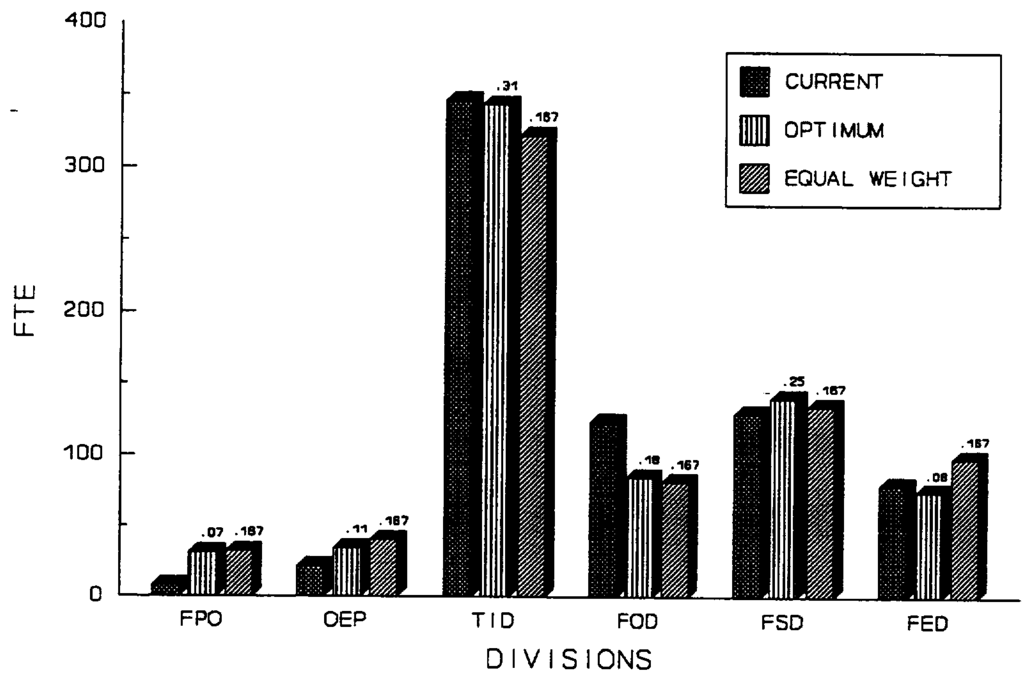

Figure 7.9 Full-Time Equivalents Required With Assigned Versus Equal Weights for Each Division. (Note: Numbers above bars are division weights.)

7.5 Impact of Budget Size on Results

The budget B_k was reduced by 10, 20, and 30 percent across all the resources k to observe the impact of budget reduction on the resource allocation. Also, the model was executed with a 10-percent budget increase. The result of this sensitivity analysis is presented in Figure 7.10. The figure does not include the 30-percent budget cut because the problem then becomes infeasible. Therefore, with the current structure of the organization and present constraints, the resource allocation cannot be optimized when the budget is cut by 30 percent.

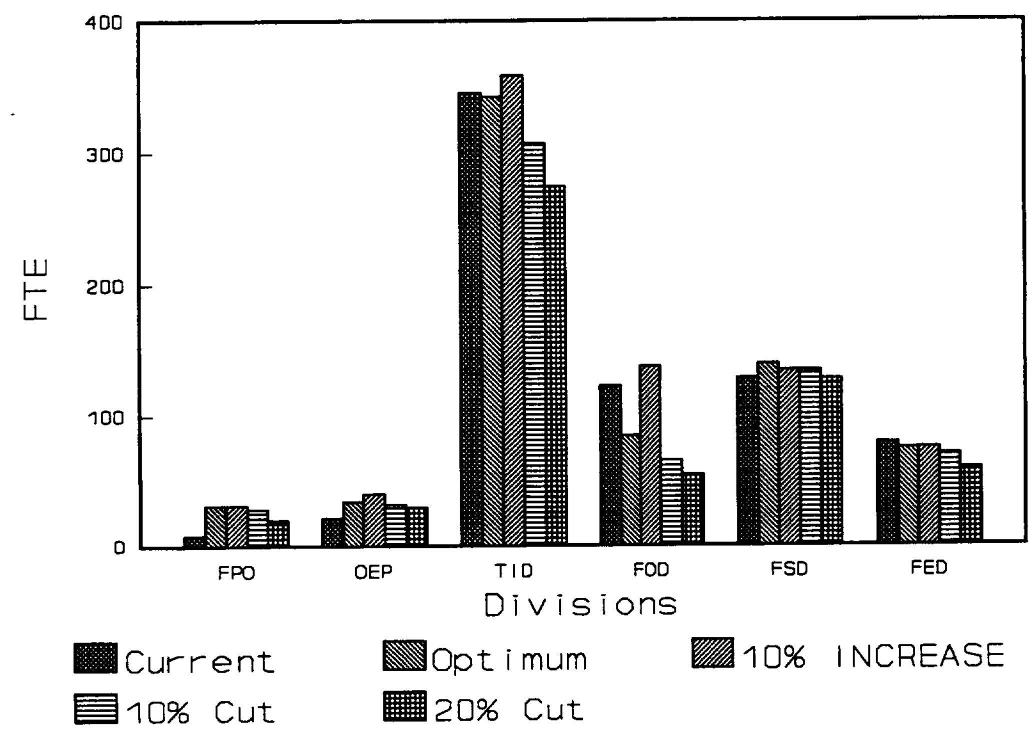

Figure 7.10 Full-Time Equivalents Required With Various Budget Levels.

If the budget is cut by 10 percent, the FOD allocation will be cut the most because that division has the most resources in the directorate and not very high customer satisfaction rank among all other divisions. The objective value function decreases by 10 percent from the optimum value at the present budget level. Again, this determination strictly depends on the metrics that were developed for quantity and quality of outputs and the values assigned to them.

If the budget is cut by 20 percent, the resource allocation follows the same pattern as the 10-percent cut but with more reduction. The optimum overall customer satisfaction will drop to Z = 2.8 from Z = 3.5, which is the optimum overall customer satisfaction with the current budget level. Also, the overall customer satisfaction with a 20-percent cut will be 5 percent below the present level of customer satisfaction without optimization (Z = 2.93, Table 7.4).

On the other hand, if the current budget is increased by 10 percent across the resources, all divisions receive near or above their current levels of resources, with the exception of FSD. The FTE allocation to FSD decreases in this scheme. Examining the output levels for each product of FSD revealed that the X56 output level is reduced from its upper bound to its lower bound. This change impacts the number of FTEs required for the output and reduces it to a level that supports the new level of X56, which is 26 percent above the current nonoptimum value and 6 percent above the current optimum value. Thus, the point of diminishing return has been reached because the objective function's optimum value rose only 6 percent with a 10-percent increase in resources. This behavior was expected for the model because since there is a maximum limit for customer satisfaction regardless of the amount of input to the process owing to upper bounds on X_{ij} and S_i.

7.6 Impact of Quality Resource Use Function Formulation

As an example of a sensitivity analysis with respect to the constraint set, two quality resource use functions RS were developed. One function was created with the assumption that with zero resources the quality score will be zero. The other was created with the assumption that with zero resources the quality score will instead be 1. The two resource use functions are similar especially for $S_i > 3.5$, which is where most divisions are. Figure 7.11 illustrates two typical functions for FTE allocation to OEP.

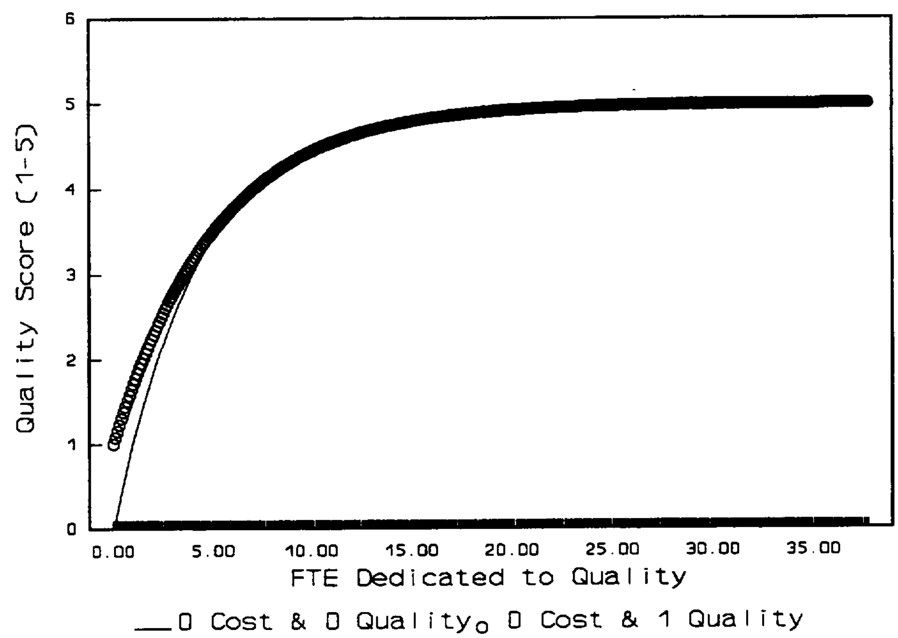

Figure 7.11 Quality Resource Use Function for OEP.

The objective function value for the formulation with the alternative function (zero resource implies a quality score of 1) equaled 3.529, about 0.5 percent higher than the one with zero resource that implies zero quality score (3.5075). Also, the resource allocation for each output changed less than 1 percent between the two runs. Therefore, the quality resource use function does not significantly affect the solution, at least within the range tested here.

7.7 Where Would New Resources Be Most Valuable?

The resources in different categories, as explained earlier, are not interchangeable at present and do not have the same units (dollars and people). But, if the opportunity arose to reallocate an additional dollar or an additional person in any categories with similar units, where would it be the most valuable? For instance, would \$1 investment in resource category X result in a greater increase in the objective function value than \$1 investment in category Y?

To answer this question, refer again to Appendix C, where the results of the model are presented. Two types of resources can be considered: those that have units of people and those that have units of dollars. I will consider each in turn. From the input of the model, the results indicate that in the people group the Co-Op category is the most valuable one, followed by FTE. This ranking was determined through the marginal values of FTE and Co-Op (see Section 7.3). However, after adding one person to the Co-Op category budget, the Co-Op category becomes as valuable as the FTE category. The second person added to the Co-Op category budget drops its marginal value to zero, meaning that additional Co-Op personnel will not increase the value of the objective function. At the same time, the value of FTE (marginal value) remains constant at 0.002 per FTE, which indicates that the objective function value will increase 0.002 for each additional FTE. This conclusion is the result of three separate runs with the above data.

In the group with dollar units, training is the most valuable resource, meaning that an additional dollar in the training funds will cause the most increase in the objective function value according to the marginal value of the resource. The marginal value of the training fund is 0.004 per dollar, which is double the marginal value of FTE. This result indicates that if FTE can be measured in dollar units like training, it would be much more beneficial to invest additional dollars in training than in FTE.

7.8 Results of Survey on TSD's Customer Satisfaction

I now turn from a discussion of the model results to a review of the outcome of the customer satisfaction survey. This survey played a significant role in determining the quality of output and consequently in resources allocated (see Section 6.4). It is also appropriate to present these data here in order to give a comprehensive account of all the results of this study.

Figure 7.12 represents the percentage of the respondents that gave various scores (1 to 5) for general satisfaction with each of the TSD divisions. Clearly, with the exception of FED, 50 to 60 percent of the informants gave 4 out of a possible 5 to each division indicating they were "satisfied" with the service received. Figure 7.13 compares the customers' general satisfaction score with respect to other quality dimensions, showing that TSD needs to improve

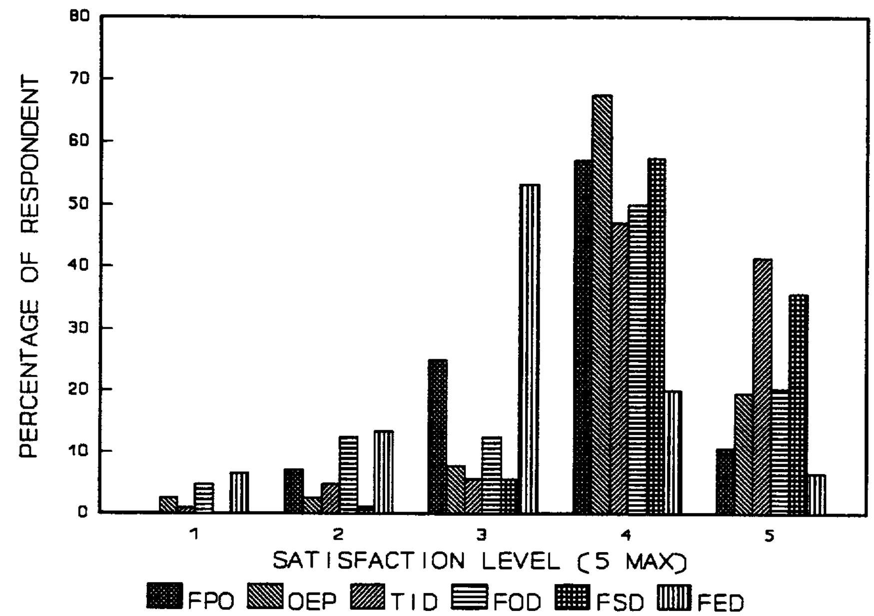

Figure 7.12 General Satisfaction Score for Each Division.

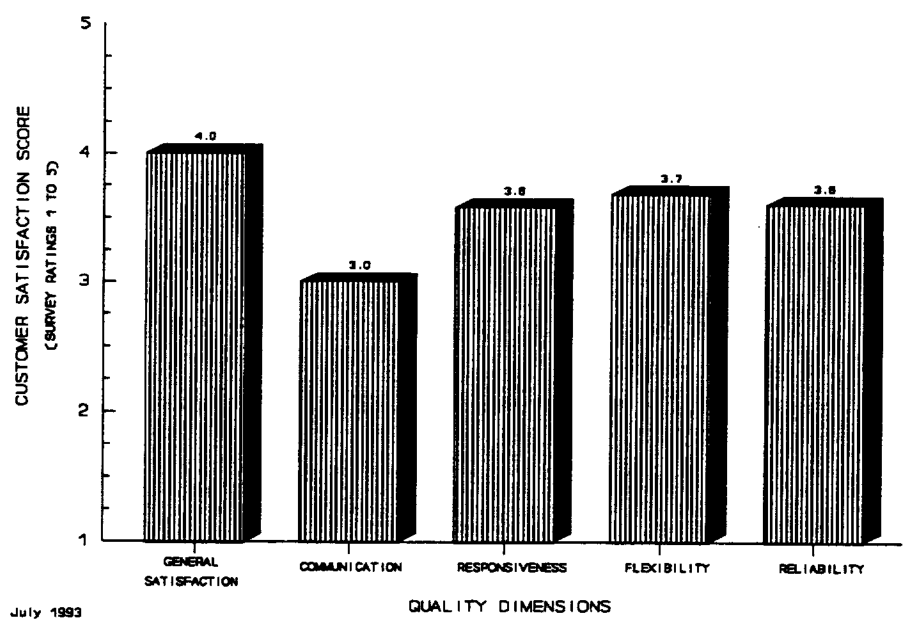

Figure 7.13 Technical Services Directorate Customer Satisfaction.

communication with their customers. Also, the general satisfaction score is very much dependent on the communication score. This is evident from the regression analysis performed in Chapter 4. Three of the six divisions, TID, FOD, and FSD, have communication as the major quality dimension in determining general satisfaction. These three divisions serve most of the TSD customers, another reason why communication is a significant element of general satisfaction.

Figure 7.14 represent the levels of customer general satisfaction with TSD, showing that 52 percent of the customers are satisfied with TSD services and 30 percent are strongly satisfied.

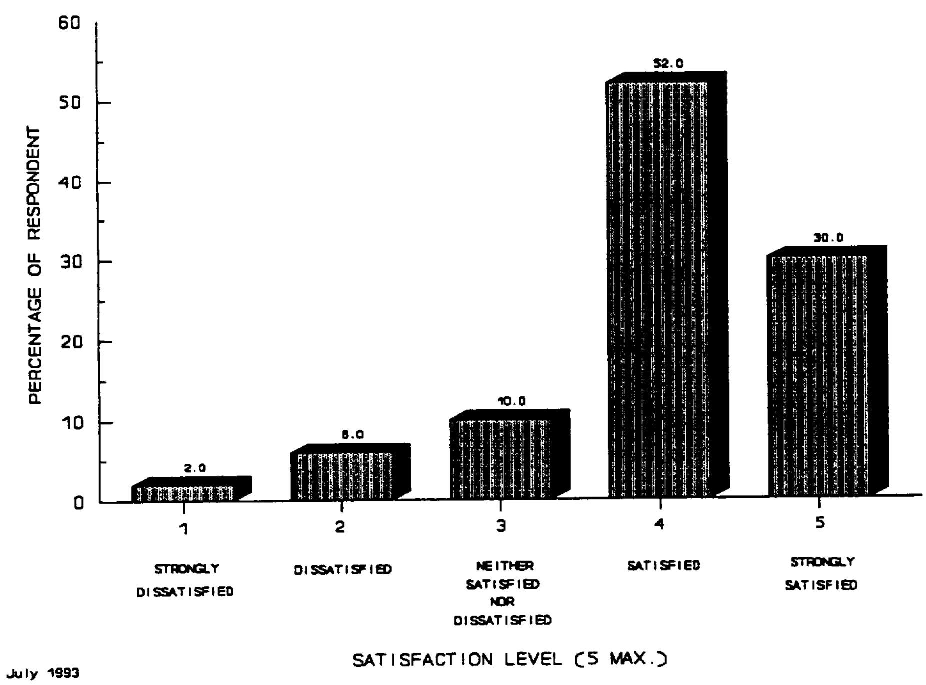

Figure 7.14 General Satisfaction Score for TSD.

Chapter 8

Conclusions

The need for this study is evident considering the $3.8 billion daily cost of operating the Federal Government [Department of Commerce, 1992] and its impact on the national debt. The constraints on the Federal budget, especially on the nonentitlement programs such as NASA, demand superior and less costly operations. We have to operate smartly and efficiently to meet our objectives with fewer resources. Every tool available must be used to help us accomplish our mission. This thesis focuses on creating a tool that optimizes resource allocation according to the quantity and quality of the outputs of the organization. The quality definition is based on the total quality management (TQM) philosophy.

This tool is a mathematical model of the organization that is designed to capture the organization's objectives, the decision-makers' views, and the customers' opinions on the outputs of the organization. Using nonlinear optimization software, the model answers the question, What is the best method, within the government regulations, of disbursing the limited resources to have the most satisfied customers?

This study identified the input (resources) to the organization, developed metrics to measure the output of the organization, considered the customers' opinions on the output, and packaged all the information into one nonlinear programming model. Then, the model adjusted the resources assigned to each output systematically to find the combination of resources with the highest customer satisfaction.

The solution is global optimum and unique, but it depends on the assumptions. The model can be a good and capable tool with which the decision-makers can examine all the scenarios before making any decision. But, like any other model, the accuracy of its output is directly related to the accuracy of the input. As TQM matures in government, more factual data will be available and the model will give more reliable information. The main contributions of this thesis are (1) developing metrics for the organization's output, (2) estimating the impact of resource reallocation in real time, (3) providing a structured system for tracking and evaluating improvement in the organization, and (4) bringing customers' issues and demands to the forefront.

The challenge with implementing the model was in defining the outputs of the Technical Services Directorate (TSD) and the metrics to measure them. This difficulty can be attributed to the nature of NASA, where most of the products are one of a kind, and that this was the first attempt to quantify the outputs of TSD.

The weights that were assigned to each output made a significant impact on the results of the model. Section 7.4 illustrates the results of equal weights versus assigned weights. The outputs and consequently the resources associated with the outputs increased and decreased with the weight of the output. If the output was already at its upper bound even at a lower weight, the change in weight did not affect the output level. An example for this case is the FTE allocation for FPO, which is demonstrated in Figure 7.9.

The resource use functions and the base year's quality and quantity of outputs also played a significant role in the result of the model. To increase the quality and quantity levels S and X, decision-makers should strategically allocate scarce resources and use them more efficiently. In other words, decision-makers should do more with less to reduce RS and RX coefficients.

The influence of budget size was tested by increasing the budget by 10 percent and decreasing it by 10, 20, and 30 percent. The model became infeasible with a 30-percent budget cut and gave divisions near or above their current level of resources with a 10-percent increase in the budget.

Given the limitations and assumptions of the model, the most obvious way to increase the quality of output in TSD is to improve communication with the customers. Communication received a low score from the customers, and it is one of the quality dimensions that has a significant impact on the overall general satisfaction with the divisions. Among resources, training (TRN) has the most "bang for the buck," followed by the number of FTEs. This means that, if permissible, an additional dollar should be invested in training rather than in an FTE.

TSD will certainly benefit from involving the customers in every aspect of its operation and aligning the organization to the customers' specific programs.

This additional scrutiny from the customers will adjust resource allocation to produce more satisfied customers, as demonstrated in allocation of the fund source 9 (FS9) resource.

The mathematical model is designed to elevate the quality and quantity of all the directorate outputs. Therefore, it is possible that additional resources will be continuously allocated to the outputs that already have a high S value. The directorate budget is finite; hence, the additional funding that is appropriated to the product with a high S value reduces the funding to the product with a low S value. This part of the model does not allow the products with lower S values to receive additional funding to increase their customer satisfaction scores. Therefore, to give these products a chance, a policy might be suggested to improve less successful products, such as one-time capital investment.

The model may be improved in the future by adding multiyear optimization for a period of 5 to 10 years, requiring additional information and strict policies on maintaining budgetary data. Also, future research to consider the relationship among various divisions' inputs and outputs may be appropriate.

Appendix A

Quality Dimensions

Parasuraman et al. [1985] have developed 10 service quality dimensions:

(1) Reliability.—The firm performs the service right the first time and honors its promises, such as accurate billing and correct recordkeeping.

(2) Responsiveness.—Employees are willing or ready to provide timely service.

(3) Competence.—Employees have the required skills and knowledge to perform the service.

(4) Access.—Access by telephone is easy, the waiting time to receive service is reasonable, and location and operating hours are convenient.

(5) Courtesy.—Contact personnel are polite, respectful, considerate, and friendly.

(6) Communication.—Customers are kept informed in language they can understand and are listened to.

(7) Credibility.—Employees are trustworthy, believable, and honest and have the customers' best interests at heart.

(8) Security.—Customers are free from danger, risk, or doubt, and their confidentiality and privacy are respected.

(9) Understanding.—The service provider makes the effort to understand the customers' needs and requirements.

(10) Tangibles.—Physical facilities, appearance of personnel, tools, or equipment used, and physical representation of service are satisfactory.

Kennedy and Young [1989] developed six quality dimensions for service-oriented organizations.

(1) Availability—the degree to which the customer can contact the service provider.

(2) Responsiveness—the degree to which the service provider reacts to customers' needs and requirements.

(3) Convenience—the degree of ease with which the customers can interact with the service provider, which includes the facility location, office hours, meeting facilities, and effective communications skills.

(4) Timeliness—the degree to which the total job is accomplished within the customer's stated timeframe.

(5) Completeness—the degree to which the total job is finished, including implementation, documentation, and follow-up.

(6) Pleasantness—the degree to which the provider uses professional behavior and manner while working with the customer.

Garvin [1988] concluded that service quality has eight dimensions:

(1) Performance—the primary operating characteristics of a product or the speed or the absence of waiting time in the service area.

(2) Features—secondary characteristics that supplement the product's or service's basic function.

(3) Reliability—the probability of a product's malfunctioning within a specific time or consistency of service.

(4) Conformance—the degree to which a product's or service's characteristics meet preestablished standards.

(5) Durability—the amount of use one gets from a product before it breaks down and must be replaced.

(6) Serviceability—the speed, courtesy, competence, and ease of repair.

(7) Aesthetics—the way that a product looks, feels, and sounds and the general appearance of the output and operating environment.

(8) Perceived quality—the product's or service's image and reputation, which are the perception of quality rather than the reality.

Armistead [1989] claimed customer service is based on six dimensions:

(1) Flexibility—coping with mistakes, either your own or those of customers, customizing the service, and introducing new services.

(2) Absence of fault—correctness of information or advice, correctness of the specification, the physical items of the service package, and control procedures to measure and monitor the physical aspects of the service package.

(3) A framework of time—the availability of the service, the responsiveness of the service organization, and the waiting or queuing time for the service.

(4) Style—the attitudes of service personnel, the accessibility of the entire organization to the customers, the ambiance of the service, and the perceived value of the service.

(5) Steering—the clarity of the service in terms of where to go, what to do, who to see, and the sense that the customer is important and in control.

(6) Safety—the customers feeling at ease with their position in the service organization. The factors are honesty, security, trust, and confidentiality.

Nelson [1990] established five quality dimensions in the health care industry that could be useful in this research because of its service orientation nature:

(1) Access—appointment waiting time, telephone access, physical location, and operating hours.

(2) Technical management—qualifications of staff, quality mechanism, and technical skills.

(3) Interpersonal management—the way complaints or suggestions are handled, the amount of time spent with the client, and the courtesy of employees.

(4) Continuity of care—consistent attention to customers and the customer knowing who should address his or her specific problem.

(5) General satisfaction—the general perspective the customer has in dealing with this organization.

Hyde [1992] explained seven quality dimensions for TQM in the public sector:

(1) Reaction time—responsiveness to problems or emergencies.

(2) Timeliness—commitment to scheduled compliance.

(3) Commitment to budget and cost control.

(4) Defect rate—the rate of error or compliance.

(5) Professionalism—the work attitude and commitment to quality.

(6) Service attitude—identifying with the customers' needs.

(7) Follow-up—responding to the customers' complaints and rectifying the service provider's mistakes.

Appendix B

Analytic Hierarchy Process

In AHP, the problem is decomposed into its elements and organized in a multilevel structure where the main objective occupies the top level, which is called the focus. Each intermediate level is made of several elements, called criteria, that are compared with one another against an element at the next higher level. The lowest level of the structure comprises alternatives that are under consideration [Saaty 1982].

With this structure in mind, the principle of discrimination and comparative judgments is utilized to establish priorities among the criteria and alternatives. The method of applying this principle is the pairwise comparisons process. The best way to explain that is to demonstrate the process for a typical hierarchical structure shown in Table B.1.

Table B.1. Typical Hierarchical Structure

Level 1: Focus			A		
Level 2: Criteria		B1	B2	B3	
Level 3: Criteria	C1	C2	C3	C4	C5
Level 4: Alternatives		D1	D2	D3	

The process begins from the lowest level of the AHP structure, which is level 4, the alternatives. Every element of this level is compared with the rest of the elements of the same level against all the elements from the next higher level. In other words, the elements on any level (except the lowest level) become categories of comparison for the elements on the next lower level [Saaty 1982, Saaty and Kearn 1985].

Analytically, the comparison is performed in a matrix form. The matrix is constructed from the ratios of the relative importance of the elements of each level with respect to a criterion provided by the elements in the next higher level. The relative importance of an element is expressed by a numerical value from 1 through 9. The scale of nine units is based purely on experience, and it is proven to be adequate to portray the discrimination among the elements [Saaty 1982].

As an example, consider the typical hierarchical structure presented in Table B.1. The comparison matrix for the fourth level is formed from the ratios of the impact of each element (D1, D2, D3) to an element at the third level (C1 to C5). Because there are five elements in the third level, there will be five comparison matrices for the fourth level [Saaty and Kearn 1985].

The relative importance of an element is designated by the decision-maker and reflects his or her judgments and personal views on the subject element. The key function of the hierarchical modeling is to translate human values into a mathematical format where it can be studied and optimized by applying all the mathematical tools and capabilities.

The last step of AHP is to solve the pairwise matrices and pull all the judgments together into a single number that demonstrates the priority of each element with respect to the others. To illustrate this process, consider the example in Table B.1. The comparative matrix for the lowest level of the model comprises the criteria from the third level listed in the upper left-hand corner. The alternatives, D1 to D3, are listed in the top row and the left-hand column. Table B.2 demonstrates a typical three-element comparative matrix [Saaty 1982].

Table B.2. Comparative Matrix

C1	D1	D2	D3
D1	I	1/m	1/n
D2	m	1	1/p
D3	n	p	1

The diagonal entries are always 1 because an element is compared with itself. An entry such as m is the ratio of the relative importance of D2 over D1 with respect to C1. For example, if C1 is "comfort" and D2 is a type of car, say Lexus, and D1 is another type, say Yugo, then D2 is m times more comfortable than D1. This is the reason that the entries across the diagonal are reciprocals as indicated.

Once the matrix is filled, in order to synthesize the judgments, the matrix is normalized by dividing each entry by the total value of its column. In this step, entry 1 will be transformed to 1/(1 + m + n). The rows of the normalized matrix will be averaged to produce the overall ranking of the elements. This process will continue until the overall importance of every element of the hierarchical model is developed [Saaty 1982].

In the mathematical context, the comparison matrix, which is referred to as C hereafter, is a single-rank matrix because every row is a multiplier of the first row.

$$C = \begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_n \\ \hline C_1 & w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ C_2 & w_2/w_1 & w_2/w_2 & & w_2/w_n \\ \vdots & \vdots & \vdots & & \vdots \\ C_n & w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{array}$$

All entries of this matrix are positive and the matrix has the reciprocal property where an entry c_{ij} is equal to $1/c_{ji}$. It is interesting to note that if C is multiplied by the vector $w = (w_1, \ldots, w_n)$, the resulting vector is nw.

$$Cw = nw \tag{B-1}$$

From the above equation, $(C - In)w = 0$ is ascertained, where w is the only unknown. The nonzero value for w is possible only if $C - In = 0$, meaning that n is the eigenvalue of C. Because the rank of C is 1, there is only one eigenvalue that is nonzero and equal to n. This eigenvalue is called λ_{max}. The priority vector is any column of the matrix C with a different constant multiplier. It is desired to normalize the solution so that its components sum to unity. The normalized vector w creates a unique solution no matter which column is used. The final priority vector that is developed through the above procedure is actually this normalized solution.

According to Saaty [1977], a reciprocal matrix with positive entries is consistent if and only if $\lambda_{max} = n$, where n is the number of objects that are compared. A measure for consistency is established to be CR = $(\lambda_{max} - n)/(n - 1)$. Equation (B-1) can be rewritten as

$$Cw = \lambda_{max} w \tag{B-2}$$

and λ_{max} is approximated by using equation (B-2), the normalized vector w, and the matrix C.

Now that λ_{max} is computed, the value of CR is known. Saaty and Mariano [1979] found mean inconsistency for samples of 500 random filled matrices of each size from 2-by-2 to 10-by-10 matrices. The numerical judgments were taken at random from the scale 1/9, 1/8, 1/7, ..., 1/2, ..., 1, 2, ..., 9. Then, using a reciprocal matrix would give the following average consistencies for different-order random matrices:

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	.58	.9	1.12	1.24	1.32	1.41	1.45	1.49

A value of 10 percent or less for the ratio of CR over the appropriate random consistency is recommended for a consistent judgment.

Tables B.3 to B.19 represent the first AHP that was conducted with the decision-makers.

Table B.3 First Hierarchy for TSD Outputs

FOCUS: TSD MISSION R&D TEST

ATTRIBUTES: HWD FAC H/S/E ENERGY

DIVISIONS: FPO OEP TID FOD FSD FED

Table B.4 Initial Weight Ratio (Column/Row) for Hardware

HWD	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	0.33	0.14	0.33	0.11	0.33
OEP	3.00	1.00	0.20	1.00	0.13	3.00
TID	7.00	5.00	1.00	7.00	0.20	7.00
FOD	3.00	1.00	0.14	1.00	0.11	1.00
FSD	9.00	8.00	5.00	9.00	1.00	9.00
FED	3.00	0.33	0.14	1.00	0.11	1.00
TOTAL	26.00	15.67	6.63	19.33	1.66	21.33

CI = 0.08

Table B.5 Normalized Matrix With Eigenvector for Hardware

HWD	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR (PV)
FPO	0.04	0.02	0.02	0.02	0.07	0.02	0.03
OEP	0.12	0.06	0.03	0.05	0.08	0.14	0.08
TID	0.27	0.32	0.15	0.36	0.12	0.33	0.26
FOD	0.12	0.06	0.02	0.05	0.07	0.05	0.06
FSD	0.35	0.51	0.75	0.47	0.60	0.42	0.52
FED	0.12	0.02	0.02	0.05	0.07	0.05	0.05
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table B.6 Pairwise Comparison Matrix for Hardware

HWD	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.03	0.03	0.04	0.02	0.06	0.02	0.19	6.27
OEP	0.09	0.08	0.05	0.06	0.06	0.16	0.51	6.41
TID	0.21	0.40	0.26	0.43	0.10	0.38	1.78	6.87
FOD	0.09	0.08	0.04	0.06	0.06	0.05	0.38	6.21
FSD	0.27	0.64	1.29	0.55	0.52	0.49	3.75	7.26
FED	0.09	0.03	0.04	0.06	0.06	0.05	0.33	6.05

AVR. : 6.51

Table B.7 Initial Weight Ratio (Column/Row) for Facilities

FAC	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	7.00	8.00	3.00	9.00	1.00
OEP	0.14	1.00	3.00	0.20	5.00	0.14
TID	0.13	0.33	1.00	0.20	3.00	0.14
FOD	0.33	5.00	5.00	1.00	3.00	1.00
FSD	0.11	0.20	0.33	0.33	1.00	0.14
FED	1.00	7.00	7.00	1.00	7.00	1.00
TOTAL	2.71	20.53	24.33	5.73	28.00	3.43

CI = 0.10

Table B.8 Normalized Matrix With Eigenvector for Facilities

FAC	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR
FPO	0.37	0.34	0.33	0.52	0.32	0.29	0.36
OEP	0.05	0.05	0.12	0.03	0.18	0.04	0.08
TID	0.05	0.02	0.04	0.03	0.11	0.04	0.19
FOD	0.12	0.24	0.21	0.17	0.11	0.29	0.19
FSD	0.04	0.01	0.01	0.06	0.04	0.04	0.03
FED	0.37	0.34	0.29	0.17	0.25	0.29	0.29
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table B.9 Pairwise Comparison Matrix for Facilities

FAC	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.36	0.56	0.38	0.57	0.30	0.29	2.46	6.80
OEP	0.05	0.08	0.14	0.04	0.17	0.04	0.52	6.51
TID	0.05	0.03	0.05	0.04	0.10	0.04	0.30	6.24
FOD	0.12	0.40	0.24	0.19	0.10	0.29	1.34	7.00
FSD	0.04	0.02	0.02	0.06	0.03	0.04	0.21	6.30
FED	0.36	0.56	0.33	0.19	0.23	0.29	1.97	6.89
							AVR.:	6.62

Table B.10 Initial Weight Ratio (Column/Row) for Health and Safe Environment

H/S/E	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	0.13	0.14	0.14	0.20	0.14
OEP	8.00	1.00	4.00	4.00	6.00	4.00
TID	7.00	0.25	1.00	1.00	3.00	3.00
FOD	7.00	0.25	1.00	1.00	4.00	2.00
FSD	5.00	0.17	0.33	0.25	1.00	3.00
FED	7.00	0.25	0.33	0.50	0.33	1.00
TOTAL	35.00	2.04	6.81	6.89	14.53	13.14

CI = 0.11

Table B.11 Normalized Matrix With Eigenvector for Health and Safe Environment

H/S/E	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR
FPO	0.03	0.06	0.02	0.02	0.01	0.01	0.03
OEP	0.23	0.49	0.59	0.58	0.41	0.30	0.43
TID	0.20	0.12	0.15	0.15	0.21	0.23	0.17
FOD	0.20	0.12	0.15	0.15	0.28	0.15	0.17
FSD	0.14	0.08	0.05	0.04	0.07	0.23	0.10
FED	0.20	0.12	0.05	0.07	0.02	0.08	0.09
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table B.12 Pairwise Comparison Matrix for Health and Safe Environment

H/S/E	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.03	0.05	0.02	0.02	0.02	0.01	0.16	6.27
OEP	0.21	0.43	0.70	0.69	0.61	0.36	3.00	6.93
TID	0.18	0.11	0.17	0.17	0.30	0.27	1.21	6.94
FOD	0.18	0.11	0.17	0.17	0.40	0.18	1.22	7.05
FSD	0.13	0.07	0.06	0.04	0.10	0.27	0.68	6.69
FED	0.18	0.11	0.06	0.09	0.03	0.09	0.56	6.19
							AVR.:	6.68

Table B.13 Initial Weight Ratio (Column/Row) for Energy

ENERGY	FPO	OEP	TID	FOD	FSD	FED
FPO	1.00	3.00	4.00	0.17	4.00	1.00
OEP	0.33	1.00	4.00	0.33	4.00	3.00
TID	0.25	0.25	1.00	0.14	3.00	0.33
FOD	6.00	3.00	7.00	1.00	7.00	3.00
FSD	0.25	0.25	0.33	0.14	1.00	0.17
FED	1.00	0.33	3.00	0.33	6.00	1.00
TOTAL	8.83	7.83	19.33	2.12	25.00	8.50

CI = 0.11

Table B.14 Normalized Matrix With Eigenvector

ENERGY	FPO	OEP	TID	FOD	FSD	FED	PRI VECTOR
FPO	0.11	0.38	0.21	0.08	0.16	0.12	0.18
OEP	0.04	0.13	0.21	0.16	0.16	0.35	0.17
TID	0.03	0.03	0.05	0.07	0.12	0.04	0.06
FOD	0.68	0.38	0.36	0.47	0.28	0.35	0.42
FSD	0.03	0.03	0.02	0.07	0.04	0.02	0.03
FED	0.11	0.04	0.16	0.16	0.24	0.12	0.14
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table B.15 Pairwise Comparison Matrix for Energy

ENERGY	FPO*PV	OEP*PV	TID*PV	FOD*PV	FSD*PV	FED*PV	ROW TOTAL	RT/PV
FPO	0.18	0.52	0.23	0.07	0.14	0.14	1.27	7.18
OEP	0.06	0.17	0.23	0.14	0.14	0.41	1.15	6.61
TID	0.04	0.04	0.06	0.06	0.10	0.05	0.35	6.24
FOD	1.06	0.52	0.40	0.42	0.24	0.41	3.05	7.23
FSD	0.04	0.04	0.02	0.06	0.03	0.02	0.22	6.56
FED	0.18	0.06	0.17	0.14	0.20	0.14	0.89	6.44
							AVR.:	6.71

Table B.16 Initial Weight Ratio (Column/Row) for R&D Test

R&D TEST	HWD	FAC	H/S/E/	ENERGY
HWD	1.00	8.00	5.00	7.00
FAC	0.13	1.00	1.00	1.00
H/S/E/	0.20	1.00	1.00	4.00
ENERGY	0.14	1.00	0.25	1.00
TOTAL	1.47	11.00	7.25	13.00

CI = 0.08

Table B.17 Normalized Matrix With Eigenvector for R&D Test

R&D TEST	HWD	FAC	H/S/E/	ENERGY	PRI VECTOR
HWD	0.68	0.73	0.69	0.54	0.66
FAC	0.09	0.09	0.14	0.08	0.10
H/S/E/	0.14	0.09	0.14	0.31	0.17
ENERGY	0.10	0.09	0.03	0.08	0.07
TOTAL	1.00	1.00	1.00	1.00	1.00

Table B.18 Pairwise Comparison Matrix for R&D Test

R&D TEST	HWD* PV	PAC* PV	H/S/E/*PV	ENERGY* PV	ROW TOTAL	RT/PV
HWD	0.66	0.78	0.84	0.52	2.81	4.26
FAC	0.08	0.10	0.17	0.07	0.42	4.33
H/S/E/	0.13	0.10	0.17	0.30	0.70	4.15
ENERGY	0.09	0.10	0.04	0.07	0.31	4.12
					AVR.:	4.21

Table B.19 TSD's Divisions Weights After First AHP

	HWD				FAC				H/S/E/				ENERGY				OVERALL PRIORITY
FPO	0.03	x	0.66	+	0.36	x	0.10	+	0.03	x	0.17	+	0.18	x	0.07	=	0.07
OEP	0.08	x	0.66	+	0.08	x	0.10	+	0.43	x	0.17	+	0.17	x	0.07	=	0.15
TID	0.26	x	0.66	+	0.05	x	0.10	+	0.17	x	0.17	+	0.06	x	0.07	=	0.21
FOD	0.06	x	0.66	+	0.19	x	0.10	+	0.17	x	0.17	+	0.42	x	0.07	=	0.12
FSD	0.52	x	0.66	+	0.03	x	0.10	+	0.10	x	0.17	+	0.03	x	0.07	=	0.36
FED	0.05	x	0.66	+	0.29	x	0.10	+	0.09	x	0.17	+	0.14	x	0.07	=	0.09
																	1.00

Appendix C

Results of Model Execution

APPENDIX C : RESULTS OF THE MODEL EXECUTION

```
G E N E R A L   A L G E B R A I C   M O D E L I N G   S Y S T E M
MODEL STATISTICS    SOLVE ALLTSD USING NLP FROM LINE 773

MODEL STATISTICS

BLOCKS OF EQUATIONS     53      SINGLE EQUATIONS      53
BLOCKS OF VARIABLES    107      SINGLE VARIABLES     107
NON ZERO ELEMENTS      391      NON LINEAR N-Z        97
DERIVATIVE POOL         65      CONSTANT POOL         88
CODE LENGTH           1149

GENERATION TIME       =         0.374 MINUTES

EXECUTION TIME        =         0.492 MINUTES
```

```
G E N E R A L   A L G E B R A I C   M O D E L I N G   S Y S T E M
SOLUTION REPORT     SOLVE ALLTSD USING NLP FROM LINE 773


               S O L V E     S U M M A R Y

     MODEL   ALLTSD                OBJECTIVE  Z
     TYPE    NLP                   DIRECTION  MAXIMIZE
     SOLVER  MINOS5                FROM LINE  773

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE               3.5288

 RESOURCE USAGE, LIMIT          16.087      1000.000
 ITERATION COUNT, LIMIT        567          1000
 EVALUATION ERRORS               0             0

     M I N O S    5.2    (Mar 1988)
     = = = = =

     B. A. Murtagh, University of New South Wales
       and
     P. E. Gill,  W. Murray,  M. A. Saunders and M. H. Wright
     Systems Optimization Laboratory, Stanford University.

         ==============================
         M I N O S    5.2    (Mar 1988)
         ==============================

 OPTIONS file
 ------------
      BEGIN GAMS/MINOS OPTIONS

              MAJOR ITERATIONS LIMIT         50.0
              MINOR ITERATIONS LIMIT         200

      END GAMS/MINOS OPTIONS

 WORK SPACE NEEDED (ESTIMATE)  --     7503 WORDS.
 WORK SPACE AVAILABLE          --     8100 WORDS.

 EXIT -- OPTIMAL SOLUTION FOUND
 MAJOR ITNS, LIMIT               10      50
 FUNOBJ, FUNCON CALLS          1349    1349
 SUPERBASICS                      6
 INTERPRETER USAGE             5.62
 NORM RG / NORM PI        4.186E-07
```

G E N E R A L   A L G E B R A I C   M O D E L I N G   S Y S T E M
SOLUTION REPORT   SOLVE ALLTSD USING NLP FROM LINE 773

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU FTEFPO	.	.	.	-0.002
---- EQU FTEOEP	.	.	.	-0.002
---- EQU FTETID	.	.	.	-0.002
---- EQU FTEFOD	.	.	.	-0.002
---- EQU FTEFSD	.	.	.	-0.002
---- EQU FTEFED	.	.	.	-0.002
---- EQU SSCFPO	.	.	.	EPS
---- EQU SSCOEP	.	.	.	EPS
---- EQU SSCTID	.	.	.	EPS
---- EQU SSCFOD	.	.	.	EPS
---- EQU SSCFSD	.	.	.	EPS
---- EQU SSCFED	.	.	.	EPS
---- EQU ROSFPO	.	.	.	-5.427E-6
---- EQU ROSOEP	.	.	.	-5.427E-6
---- EQU ROSTID	.	.	.	-5.427E-6
---- EQU ROSFOD	.	.	.	-5.427E-6
---- EQU ROSFSD	.	.	.	-5.427E-6
---- EQU ROSFED	.	.	.	-5.427E-6
---- EQU FS9FPO	.	.	.	EPS
---- EQU FS9OEP	.	.	.	EPS
---- EQU FS9FOD	.	.	.	EPS
---- EQU FS9FSD	.	.	.	EPS
---- EQU FS9FED	.	.	.	EPS
---- EQU COPOEP	.	.	.	-0.003
---- EQU COPTID	.	.	.	-0.003
---- EQU COPFSD	.	.	.	-0.003
---- EQU TRNFPO	.	.	.	-0.004
---- EQU TRNOEP	.	.	.	-0.004
---- EQU TRNTID	.	.	.	-0.004
---- EQU TRNFOD	.	.	.	-0.004
---- EQU TRNFSD	.	.	.	-0.004
---- EQU TRNFED	.	.	.	-0.004
---- EQU TRVFPO	.	.	.	EPS
---- EQU TRVOEP	.	.	.	EPS
---- EQU TRVTID	.	.	.	EPS
---- EQU TRVFOD	.	.	.	EPS
---- EQU TRVFSD	.	.	.	EPS
---- EQU TRVFED	.	.	.	EPS
---- EQU EQPFPO	.	.	.	EPS
---- EQU EQPOEP	.	.	.	EPS
---- EQU EQPTID	.	.	.	EPS
---- EQU EQPFOD	.	.	.	EPS
---- EQU EQPFSD	.	.	.	EPS
---- EQU EQPFED	.	.	.	EPS

```
---- EQU FTECON          -INF    707.000    707.000      0.002
---- EQU SSCCON          -INF    555.733    574.000        EPS
---- EQU ROSCON          -INF  15969.000  15969.000  5.4272E-6
---- EQU FS9CON          -INF  14050.149  15104.000        EPS
---- EQU COPCON          -INF     44.000     44.000      0.003
---- EQU TRNCON          -INF    193.000    193.000      0.004
---- EQU TRVCON          -INF    187.280    196.000        EPS
---- EQU EQPCON          -INF   1742.894   1806.000        EPS
---- EQU OBJECT            .          .          .       1.000
```

G E N E R A L   A L G E B R A I C   M O D E L I N G   S Y S T E M
SOLUTION REPORT   SOLVE ALLTSD USING NLP FROM LINE 773

```
FTEFPO
FTEOEP
FTETID
FTEFOD
FTEFSD
FTEFED
SSCFPO
SSCOEP
SSCTID
SSCFOD
SSCFSD
SSCFED
ROSFPO
ROSOEP
ROSTID
ROSFOD
ROSFSD
ROSFED
FS9FPO
FS9OEP
FS9FOD
FS9FSD
FS9FED
COPOEP
COPTID
COPFSD
TRNFPO
TRNOEP
TRNTID
TRNFOD
TRNFSD
TRNFED
TRVFPO
TRVOEP
TRVTID
TRVFOD
TRVFSD
TRVFED
EQPFPO
EQPOEP
EQPTID
EQPFOD
EQPFSD
EQPFED
FTECON       FTE CONSTRAINT
SSCCON       SSC CONSTRAINT
ROSCON       ROS CONSTRAINT
```

FS9CON	FS9 CONSTRAINT
COPCON	CO-OP CONSTRAINT
TRNCON	TRAINING COSTRAINT
TRVCON	TRAVEL CONSTRAINT
EQPCON	EQUIPMENT CONSTRAINT
OBJECT	OBJECTIVE VALUE

G E N E R A L   A L G E B R A I C   M O D E L I N G   S Y S T E M
SOLUTION REPORT   SOLVE ALLTSD USING NLP FROM LINE 773

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR S1	1.000	4.696	5.000	.
---- VAR S2	1.000	4.487	5.000	.
---- VAR S3	1.000	4.405	5.000	.
---- VAR S4	1.000	3.096	5.000	.
---- VAR S5	1.000	4.596	5.000	.
---- VAR S6	1.000	2.177	5.000	.
---- VAR X11	.	20.000	20.000	0.005
---- VAR X12	.	40.000	40.000	0.002
---- VAR X13	.	1.5000E+5	1.5000E+5	EPS
---- VAR X14	.	100.000	100.000	2.6467E-4
---- VAR X15	.	100.000	100.000	1.3318E-4
---- VAR X16	7.000	100.000	100.000	1.1889E-4
---- VAR X21A	.	500.000	500.000	6.6142E-5
---- VAR X21B	12.000	60.000	60.000	5.4371E-4
---- VAR X21C	.	7000.000	7000.000	3.4467E-6
---- VAR X21D	8.000	120.000	120.000	2.6683E-4
---- VAR X22A	3.5000E+5	7.5520E+5	2.0000E+6	EPS
---- VAR X22B	.	24.000	24.000	0.001
---- VAR X22C	1000.000	2000.000	2000.000	2.0026E-5
---- VAR X22D	.	40.000	40.000	0.001
---- VAR X23A	.	10.000	10.000	0.001
---- VAR X23B	10.000	20.000	20.000	7.0303E-4
---- VAR X23C	1000.000	1200.000	1200.000	1.2558E-5
---- VAR X24A	500.000	1200.000	1200.000	2.4018E-5
---- VAR X24B	.	20.000	20.000	0.002
---- VAR X24C	.	180.000	180.000	1.6848E-4
---- VAR X25	500.000	1410.147	4000.000	.
---- VAR X31	25000.000	25000.000	33000.000	-2.365E-6
---- VAR X32	1.2500E+5	1.6500E+5	1.6500E+5	1.0713E-6
---- VAR X33	1.5000E+5	1.9800E+5	1.9800E+5	1.2776E-6
---- VAR X34	1.2500E+5	1.6500E+5	1.6500E+5	1.0830E-6
---- VAR X35	75000.000	99000.000	99000.000	EPS
---- VAR X44A	2.000	15.000	15.000	2.0452E-4
---- VAR X44B	12.000	12.000	120.000	-1.044E-4
---- VAR X44C	.	.	40.000	-9.955E-4
---- VAR X44D	250.000	250.000	5000.000	-2.506E-6
---- VAR X45	1.2500E+6	1.5896E+6	1.7880E+6	EPS
---- VAR X46A	80000.000	80000.000	2.4000E+5	EPS
---- VAR X46B	.	10000.000	10000.000	EPS
---- VAR X46C	.	.	1.0000E+5	EPS
---- VAR X46D	.	1.5000E+5	1.5000E+5	EPS
---- VAR X46E	.	.	75000.000	EPS
---- VAR X46F	.	.	500.000	-2.227E-5
---- VAR X46G	2080.000	2080.000	1.0000E+5	EPS

----	VAR X46H	.	.	50000.000	EPS
----	VAR X47	8000.000	10000.000	10000.000	3.9372E-6
----	VAR X410	.	.	84651.000	EPS
----	VAR X411	.	1.0640E+5	1.0640E+5	EPS
----	VAR X412A	100.000	220.000	220.000	6.2978E-5
----	VAR X412B	33.000	100.000	100.000	4.3615E-5
----	VAR X413	4.000	5.425	6.000	.
----	VAR X414	.	.	10.000	-0.004
----	VAR X51	6.2850E+6	6.2850E+6	7.1660E+6	EPS

G E N E R A L   A L G E B R A I C   M O D E L I N G   S Y S T E M
SOLUTION REPORT   SOLVE ALLTSD USING NLP FROM LINE 773

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR X52	5906.000	6469.000	6469.000	3.1099E-5
---- VAR X53	35859.000	44465.000	44465.000	3.1518E-6
---- VAR X54	46080.000	46080.000	6.2208E+5	-1.283E-6
---- VAR X55	10492.000	13954.000	13954.000	8.2037E-6
---- VAR X56	28421.000	34390.000	34390.000	EPS
---- VAR X61	350.000	500.000	500.000	6.3847E-5
---- VAR X62	30.000	70.000	70.000	2.9608E-4
---- VAR X63	1000.000	1000.000	1500.000	-4.314E-5
---- VAR X64	40.000	52.000	52.000	1.8845E-4
---- VAR FTE1	-INF	31.227	+INF	.
---- VAR FTE2	-INF	34.223	+INF	.
---- VAR FTE3	-INF	343.074	+INF	.
---- VAR FTE4	-INF	84.246	+INF	.
---- VAR FTE5	-INF	139.840	+INF	.
---- VAR FTE6	-INF	74.390	+INF	.
---- VAR SSC1	-INF	4.285	+INF	.
---- VAR SSC2	-INF	26.399	+INF	.
---- VAR SSC3	-INF	69.260	+INF	.
---- VAR SSC4	-INF	391.193	+INF	.
---- VAR SSC5	-INF	40.251	+INF	.
---- VAR SSC6	-INF	24.345	+INF	.
---- VAR ROS1	-INF	2984.618	+INF	.
---- VAR ROS2	-INF	3154.934	+INF	.
---- VAR ROS3	-INF	901.449	+INF	.
---- VAR ROS4	-INF	8398.092	+INF	.
---- VAR ROS5	-INF	26.803	+INF	.
---- VAR ROS6	-INF	503.104	+INF	.
---- VAR FS91	-INF	886.154	+INF	.
---- VAR FS92	-INF	536.884	+INF	.
---- VAR FS94	-INF	11283.436	+INF	.
---- VAR FS95	-INF	333.742	+INF	.
---- VAR FS96	-INF	1009.933	+INF	.
---- VAR COP2	-INF	3.033	+INF	.
---- VAR COP3	-INF	35.247	+INF	.
---- VAR COP5	-INF	5.720	+INF	.
---- VAR TRN1	-INF	11.374	+INF	.
---- VAR TRN2	-INF	21.029	+INF	.
---- VAR TRN3	-INF	76.128	+INF	.
---- VAR TRN4	-INF	27.734	+INF	.
---- VAR TRN5	-INF	40.868	+INF	.
---- VAR TRN6	-INF	15.866	+INF	.
---- VAR TRV1	-INF	10.461	+INF	.
---- VAR TRV2	-INF	31.754	+INF	.
---- VAR TRV3	-INF	58.729	+INF	.

----	VAR TRV4	-INF	29.669	+INF	.
----	VAR TRV5	-INF	35.488	+INF	.
----	VAR TRV6	-INF	21.180	+INF	.
----	VAR EQP1	-INF	84.213	+INF	.
----	VAR EQP2	-INF	150.411	+INF	.
----	VAR EQP3	-INF	277.464	+INF	.
----	VAR EQP4	-INF	224.076	+INF	.
----	VAR EQP5	-INF	799.528	+INF	.
----	VAR EQP6	-INF	207.201	+INF	.

```
G E N E R A L   A L G E B R A I C   M O D E L I N G   S Y S T E M
SOLUTION REPORT     SOLVE ALLTSD USING NLP FROM LINE 773


                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR Z             -INF      3.529     +INF        .


**** REPORT SUMMARY :          0     NONOPT
                               0 INFEASIBLE
                               0  UNBOUNDED
                               0     ERRORS


**** FILE SUMMARY

INPUT    A:\CTSD-ML.GMS
OUTPUT   A:\CTSD-ML.LST

EXECUTION TIME       =        0.166 MINUTES
```

Appendix D

TSD Functions and Resources

7010
FACILITIES PLANNING OFFICE

FUNCTIONS	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
• Administrative	2	1	0	5	5	37		
• Facilities planning	2½	¼	0				493	576
• Facilities utilization	1½	¾	0				1,027	
• Energy management	1	0	0					
• Calspan contract management	1	0	0					
TOTAL	**8**	**2**	**0**	**$5K**	**$5K**	**$37K**	**$1,520K**	**$576K**

7010

FACILITIES PLANNING OFFICE

FUNCTIONS

- Facilities Planning
  - o Strategic and master planning
    - Coordinate Centerwide master facilities planning and strategic planning activities
    - Provide focal point for communicating plan details and requirements
    - Develop and maintain Center master facilities plan
  - o CoF planning and advocacy
    - Coordinate Centerwide facilities planning
    - Develop advocacy for CoF projects
    - Provide focal point for communicating facility needs to Headquarters
    - Provide staff support to the Center's Facility Review Board
    - Develop and maintain Center strategic and master facilities plans
  - o Center-funded (non-CoF) planning
    - Provide strategic planning for R&D and institutional facilities
    - Collect and categorize Center-funded facility projects
    - Act as an agent to R&D customers
    - Implement the planned projects throughout the implementing divisions
    - Provide engineering oversight in the design and construction phase of the projects

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	2½	¼	0				$493K	$576K

7010
FACILITIES PLANNING OFFICE

FUNCTIONS

- Facilities utilization

  - o Space management
    - Optimize space allocation, location, and layout planning
    - Forecast Center office space requirements
    - Coordinate onsite and technical space allocation
    - Manage offsite leasing activities
    - Provide management of parking space

  - o Real property
    - Maintain facility utilization data base
    - Maintain facilities capital cost and replacement value records

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	1½	¾	0				$1,027K	

7010

FACILITIES PLANNING OFFICE

FUNCTIONS

- Energy management
  - Coordinate Centerwide energy reduction activities
  - Provide focal point for communicating energy needs to Headquarters
  - Develop and implement energy conservation activities to meet goals set by executive orders and public laws
  - Perform energy survey and identify and request funds for implementing energy conservation measures
  - Survey facilities for dual fuel capability
  - Establish and implement certification procedures for the new facilities' energy performance standards
  - Provide recommendations to the Center Director on energy conservation matters
  - Implement an outreach program including ride-sharing and awareness programs
  - Prepare and submit the following reports:

    a. Overall Energy Plan for FY92 to FY 2000

    b. Annual Energy Plan and Report, specific energy conservation actions

    c. Quarterly Energy Consumption forms

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	1	0	0					

C-3

7010
FACILITIES PLANNING OFFICE

FUNCTIONS

- Calspan contract management
    - Monitor contractor work performance, job quality, and payment
    - Assure operational safety, high morale, and furtherance of equal opportunity goals among contractor employees
    - Gather and compile data from technical representatives and users as input for award fee determination
    - Counsel new and existing users on contract procedures, policy, and standards

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	1	0	0					

7020

OFFICE OF ENVIRONMENTAL PROGRAMS

FUNCTIONS	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
• 7020/Office of Environmental Programs	2	4	0	1.3	1.8	6	189.1	
• 7021/Industrial Hygiene Office	2.6	2	1	1.9	2.6	30	245.1	135
• 7022/Environmental Compliance Office	7	6	0	4.5	6.1	10	867.4	86
• 7023/Hazardous Chemicals Office	2	3	1	1.3	1.8	7	219.2	
• 7024/Health Physics Office	3	1	0	1.9	2.6	10	122.1	
• 7025/Chemical Sampling and Analysis Office	5	1	1	3.2	4.4	40	222.1	182
TOTAL	**21.6**	**17**	**3**	**$14.1K**	**$19.3K**	**$103K**	**$1,865K**	**$403K**

7020
OFFICE OF ENVIRONMENTAL PROGRAMS

FUNCTIONS

- Management of the OEP branch-level offices
- Clerical support for all OEP offices
- Management of support service contractors

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	2	4	0	$1.8K	$1.8K	$6K	$189.1K	

7021

INDUSTRIAL HYGIENE OFFICE

FUNCTIONS

- Review safety permits for health impact
- Survey areas for fumes, dust, noise, and odors and recommend control measures as needed
- Oversee asbestos cleanups and fund proactive asbestos abatements
- Survey fume hoods for ventilation standard compliance
- Review contractor health and safety plans and monitor contractor operations for compliance with Lewis standards

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	2.6	2	1	$1.9K	$2.6K	$30K	$245.1K	$135K

7022
ENVIRONMENTAL COMPLIANCE OFFICE

FUNCTIONS

- Coordinate, arrange, and fund management and disposal of hazardous waste and waste oil generated throughout the Center
- Monitor underground storage tanks
- Provide environmental engineering support for air, water, and waste management issues
- Assist in securing environmental permits for operations
- Coordinate environmental impact/assessment preparations
- Provide sampling and data management for environmental issues

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	7	6	0	$4.5K	$6.1K	$10K	$867.4K	$86K

7023
HAZARDOUS CHEMICALS OFFICE

FUNCTIONS

- Ensure Center compliance with the OSHA Hazard Communication and Laboratory Standards
- Arrange and/or provide training on OSHA standards
- Coordinate MSDS provisions for all buildings
- Coordinate proper labeling for all containers
- Prepare community right-to-know reports
- Coordinate CFC phaseout plans for the Center

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	2	3	1	$1.3K	$1.8K	$7K	$219.2K	

7024
HEALTH PHYSICS OFFICE

FUNCTIONS

- Ensure Center compliance with regulations for the Nuclear Regulatory Commission
- Act as Radiation Safety Officer for Lewis and Plum Brook
- Provide consultation regarding use of ionizing and non-ionizing radiation sources
- Review all safety permits involving the use of lasers

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	3	1	0	$1.9K	$2.6K	$10K	$122.1K	

7025
CHEMICAL SAMPLING AND ANALYSIS OFFICE

FUNCTIONS

- Provide analytical chemistry support for environmental programs and research
- Conduct research on environmental questions

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	5	1	1	$3.2K	$4.4K	$40K	$222.1K	$182K

7200
TEST INSTALLATIONS DIVISION

FUNCTIONS	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
• 7200/Test Installations Division Office	8	20	0	65	50	64	42	455
• 7202/Research Buildup Support Team	8	2	0			4.8		
• 7205/Aircraft Maintenance Branch	8	9	0				828	
• 7210/Altitude, Icing and Engine Components Branch	41	1	5			26.8		
• 7230/Engine Research Branch	58	7	15			42.9		
• 7240/Wind Tunnel Branch	43	4	5			25.8		
• 7250/Energy and Spacecraft Branch	38	1	5			24.1		
• 7260/Communications and Electronics Branch	50	6	1			27.9		
• 7280/Materials Development Branch	45	13	3			27.4		
• 7290/Materials and Engine Components Branch	47	3	2			26.3		
TOTAL	**346**	**66**	**36**	**$65K**	**$50K**	**$270K**	**$870K**	**$455K**

7200
TEST INSTALLATIONS DIVISION OFFICE

FUNCTIONS

- Provide clerical support and budget, personnel, resource tracking and reporting
- All branches provide mechanical, electrical, electronic, and laboratory technical support for all Lewis research activities
- All branches install, operate, maintain, modify, and repair test models, rigs, facilities, and laboratories
- All branches provide the hands-on expertise necessary to transform the engineers' concepts into working research rigs or systems

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	8	20	0	$65K	$50K	$64K	$42K	$455K

7202
RESEARCH BUILDUP SUPPORT TEAM

FUNCTIONS

- Install research rig piping, tubing, and control systems
- Modify and repair existing research rig service systems

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	8	2	0			$4.8K		

7205
AIRCRAFT MAINTENANCE BRANCH

FUNCTIONS

- Provide mechanical and electronic support for research aircraft
- Provide crew support for mission management aircraft
- Manage maintenance control for mission management aircraft

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	8	9	0				$828K	

7210
ALTITUDE, ICING AND ENGINE COMPONENTS BRANCH

FUNCTIONS

- Provide mechanical, electrical, electronic, laboratory, and operational support at the laboratories and facilities listed:
  - PSL, BLDG. 125
  - IRT, BLDG. 11
  - ECRL, BLDG. 102

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	**41**	**1**	**5**			**$26.8K**		

7230
ENGINE RESEARCH BRANCH

FUNCTIONS

- Provide mechanical, electrical, electronic, laboratory, and operational support at the laboratories and facilities listed:

  - INW, BLDG. 37
  - W-WING, BLDG. 23
  - CE-WING, BLDG. 5
  - SE-WING, BLDG. 5
  - SW-WING, BLDG. 5

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	58	7	15			$42.9K		

7240
WIND TUNNEL BRANCH

FUNCTIONS

- Provide mechanical, electrical, electronic, laboratory, and operational support at the laboratories and facilities listed:

  - 8 X 6, BLDG. 55
  - 9 X 15, BLDG. 55
  - 10 X 10, BLDG. 85
  - PLF/NATR, BLDG. 91 (DOME)

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	43	4	5			$25.8K		

7250
ENERGY AND SPACECRAFT BRANCH

FUNCTIONS

- Provide mechanical, electrical, electronic, laboratory, and operational support at the laboratories and facilities listed:
  - EPL, BLDG. 301
  - ECL, BLDG. 302
  - SPRL, BLDG. 309
  - PSF, BLDG. 333
  - EPRG, BLDG. 16

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	38	1	5			$24.1K		

7260
COMMUNICATIONS AND ELECTRONICS BRANCH

FUNCTIONS

- Provide mechanical, electrical, electronic, laboratory, and operational support at the laboratories and facilities listed:

  - IRL, BLDG. 77
  - SVER, BLDG. SVER
  - SDL, BLDG. 56
  - DROP T, BLDG. 45
  - ZERO G, BLDG. 110

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	50	6	1			$27.9K		

7280
MATERIALS DEVELOPMENT BRANCH

FUNCTIONS

- Provide mechanical, electrical, electronic, laboratory, and operational support at the laboratories and facilities listed:

  - M & S, BLDG. 49
  - MPL, BLDG. 105
  - MRL, BLDG. 34
  - SPL, BLDG. 24
  - BML, BLDG. 106
  - HTCL, BLDG. 51

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	45	13	3			$27.4K		

7290

MATERIALS AND ENGINE COMPONENTS BRANCH

FUNCTIONS

- Provide mechanical, electrical, electronic, laboratory, and operational support at the laboratories and facilities listed:

  - RETF, BLDG. 202
  - CCL, BLDG. 203
  - ROC LAB, BLDG. 35
  - ATF, BLDG. 7
  - COMMUNICATIONS, BLDG. 54 & 56

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	47	3	2			$26.3K		

7300

FACILITIES OPERATIONS DIVISION

FUNCTIONS	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
• 7300/Facilities Operations Division Office	8	0	0			137	113	
• 7301/Management and Project Support Office	12	3	0			30	243	
• 7302/Engineering Support Office	5	25.5	0			10		1,266
• 7303/Central Control Oper. Office	23	0	0			10		
• 7304/Research Sys. Oper. Office	9	61	0			5		
• 7310/System Controls Eng. Branch	8	2	0			41		1,380
• 7320/Center Operations Eng. Branch	11	5	0				239	110
• 7330/Research Sys. Eng. Branch	6	3	0				7,449	3,972
• 7340/Electrical Power Sys. Branch	5	2	0			180	129	219
• 7350/Mechanical Support Branch	8	41	0				457	2,996

7300
FACILITIES OPERATIONS DIVISION
Concluded.

FUNCTIONS	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
• 7360/Project Management Branch	15	60	0				1,988	2,142
• 7370/Institutional Support Branch	13	222	0				209	
• 7380/Plant Services & Fire Protection Branch	24	1	0				64	
• 7390/Security Branch	10	64	0				2,600	
TOTAL	**157**	**489.5**	**0**			**$413K**	**$13,491K**	**$11,866K**

7300

FACILITIES OPERATIONS DIVISION OFFICE

FUNCTIONS

- Provide technical and engineering support for the operation, modification, maintenance, installation, and repair of research support facilities, institutional facilities, and systems throughout the Center in the following ways:
    - Schedule and operate the exhausters and compressors of the central process air system and the high-voltage electrical distribution network
    - Manage the contracts that supply skilled tradespeople who operate and maintain the research installation, the research support services, and major equipment and systems, and maintain and repair the utilities systems, buildings, roads, and grounds
    - Manage the Center's buildings and grounds maintenance and the related budgets
    - Manage the Lewis recertification and system configuration control programs
    - Provide emergency response to fire, medical, or other emergency situations
    - Administer a comprehensive and integrated security program that protects the Center's assets and resources

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	8	0	0			$137K	$113K	

7301
MANAGEMENT AND PROJECT SUPPORT OFFICE

FUNCTIONS

- Provide coordination and scheduling for research and maintenance projects
- Manage work control and preventive maintenance programs for Facilities Operations Division

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	12	3	0			$30K	$243K	

7302
ENGINEERING SUPPORT OFFICE

FUNCTIONS

- Provide engineering support for research support systems and CADAM support for the Technical Services Directorate
- Manage the configuration control and the recertification programs for the Center

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	5	25.5	0			$10K		$1,266K

7303
CENTRAL CONTROLS OPERATIONS OFFICE

FUNCTIONS

- Control purchasing, scheduling, equipment operations, valve routing, and distribution of process air services, electrical power, and other utilities to facilities throughout the Center

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	23	0	0			$10K		

7304

RESEARCH SYSTEMS OPERATIONS OFFICE

FUNCTIONS

- Manage the contract for operation and maintenance of the drive systems and air dryers in the 8X6 and 10X10 SWT; the variable frequency power system; the refrigeration plant for the IRT; the combustion air and exhaust systems in the ERB and CAEB; and the cooling tower systems for Cooling Towers 1 through 6

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	9	61	0			$5K		

7310
SYSTEM CONTROLS ENGINEERING BRANCH

FUNCTIONS

- Provide the engineering, centralized operations, maintenance, and management for Lewis' large, complex centralized research support system controls

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	8	2	0			$41K		$1,380K

7320
CENTRAL OPERATIONS ENGINEERING BRANCH

FUNCTIONS

- Provide engineering support for operation, maintenance, and modification of institutional systems including sewer, domestic water, industrial waste, chilled water, gas, steam, cryogenics, low-voltage electrical, HVAC, and other minor systems at Lewis

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	11	5	0				$239K	$110K

7330
RESEARCH SYSTEMS ENGINEERING BRANCH

FUNCTIONS

- Provide the management, engineering, operations, and maintenance for the Center's large, complex centralized research support systems

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	6	3	0				$7,449K	$3,972K

7340
ELECTRICAL POWER SYSTEMS BRANCH

FUNCTIONS

- Manage system engineering, operation, and maintenance of the high-voltage electrical power systems at the Center

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	5	2	0			$180K	$129K	$219K

7350

MECHANICAL SUPPORT BRANCH

FUNCTIONS

- Manage the contract for repair and maintenance of the program and facility support equipment and the transfer of liquid hydrogen
- Manage the contract for rigging and cranes and millwright and pipefitter services to the Center

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	8	41	0				$457K	$2,996K

7360
PROJECT MANAGEMENT BRANCH

FUNCTIONS

- Develop plans and programs for repair and maintenance of buildings and roads
- Manage the contract for maintenance, repair, rehab, installation, and alteration of buildings, experimental facilities, and roads

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	15	60	0				$1,988K	$2,142K

7370
INSTITUTIONAL SUPPORT BRANCH

FUNCTIONS

- Operate, maintain, and modify institutional equipment and systems
- Provide the Center with electrical maintenance, protective systems, communication, and audio/visual services; roads and grounds maintenance; and general carpentry services
- Manage the Center's solid waste disposal contract

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	13	222	0				$209K	

7380

PLANT SERVICES AND FIRE PROTECTION BRANCH

FUNCTIONS

- Manage and direct the plant protection program
- Provide emergency medical and fire services
- Conduct contractor-site safety inspections; EPA waste oil/solvent site inspections; building fire inspections; confined space, welding, and cutting checks; and fire prevention inspections

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	24	1	0				$64K	

7390
SECURITY BRANCH

FUNCTIONS

- Administer a comprehensive and integrated security program consisting of computer, personnel, information, physical, and special projects security for the protection of information, personnel, property, and technology for theft, malicious damage, unauthorized disclosure, loss, criminal acts, espionage, and sabotage, in compliance with applicable laws, regulations, and executive orders

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	10	64	0				$2,600K	

7400
FABRICATION SUPPORT DIVISION

FUNCTIONS	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
• 7400/Fabrication Support Division Office	8	1	0	30.5	26.5		20	
• 7410/Fabrication Procurement Branch	12	2	0					6,285
• 7420/Inspection and Material Processing Branch	9	22	0			255		55
• 7430/Research Instrumen. Branch	28	1	3			103		60
• 7440/Machining Branch	36	8	2			205		135
• 7450/Model Develop. Branch	10	0	0			50		30
• 7460/Metal Fabrica. Branch	26	2	0			100		20
TOTAL	**129**	**36**	**5**	**$30.5K**	**$26.5K**	**$713K**	**$20K**	**$6,585K**

7400

FABRICATION SUPPORT DIVISION OFFICE

FUNCTIONS

- Provide information and hardware required by engineering
- Evaluate, develop, and apply advanced technologies in metallurgy
- Provide support and control the application of equipment and technologies required for fabrication
- Provide metallurgical consultation and material selection services to engineering

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	8	1	0	$30.5K	$26.5K		$20K	

7410
FABRICATION PROCUREMENT BRANCH

FUNCTIONS

- Supervise procurements for the division and requestors Centerwide
- Furnish estimate of cost and manufacturing hours
- Consult with and advise engineers on existing fabrication methods
- Develop technical specifications and prepare solicitation for competition
- Monitor and oversee contracts or task orders after award for conformance to technical and contractual requirements

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	12	2	0					$6,285K

7420
INSPECTION AND MATERIAL PROCESSING BRANCH

FUNCTIONS

- Perform detailed inspection of research hardware fabricated both in-house and on contract
- Provide three-dimensional contour measurements and high-precision concentricity
- Perform both computer-assisted and mechanical inspection of research hardware
- Provide 100% inspection, serialization, and certification of all parts
- Perform nondestructive testing, such as x-ray, ultrasonic, magnetic particle, and liquid penetrant inspection
- Ensure that all inspection equipment is calibrated and traceable to the National Institute of Standards and Technology
- Calibrate Center shops precision tools
- Manage two satellite shops, one dedicated to manufacturing, the other for short run machining

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	9	22	0			$255K		$55K

7430
RESEARCH INSTRUMENTATION BRANCH

FUNCTIONS

- Fabricate, install, and service data collection and control instrumentation on experimental rigs and apparatus in research areas
- Develop new application methods or procedures to fabricate and install state-of-the-art temperature and pressure sensors
- Consult with, and make recommendations with respect to materials selection and fabrication of instrumentation to, engineering and research personnel

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	28	1	3			$103K		$60K

7440
MACHINING BRANCH

FUNCTIONS

- Machine and assemble prototype equipment and hardware
- Provide conventional and advanced machining services
- Provide state-of-the-art capability in machining, welding, and balancing technologies
- Provide consultation services to requestors regarding material, machining, and fabrication

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	36	8	2			$205K		$135K

7450
MODEL DEVELOPMENT BRANCH

FUNCTIONS

- Develop and fabricate research hardware
- Repair and provide maintenance of wood blades for Icing Research Tunnel
- Manufacture models and hardware without the use of blueprints
- Advise engineering staff on materials and fabrication procedures

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	10	0	0			$50K		$30K

7460
METAL FABRICATION BRANCH

FUNCTIONS

- Perform sheetmetal and structural fabrication work
- Work with all conventional metals and high-temperature alloys
- Develop methods and perform welding to join metal pieces together
- Perform hydrostatic pressure and helium gas vacuum leak checking on completed research parts
- Perform bench inspection on all aircraft hardware
- Manufacture parts without the use of blueprints through an interface and link with CADAM
- Consult with and advise engineering staff on fabrication techniques and materials

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-4
TOTAL	26	2	0			$100K		$20K

7600
FACILITIES ENGINEERING DIVISION

FUNCTIONS	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
• 7600/Facilities Engineering Div. Office	2	0	0			60	605	1,212
• 7601/Management Operations Office	7	5	0	4.2	8.2	18	39	79
• 7610/Mechanical Engineering Branch	18	3	0	5.8	14.5	18	14	29
• 7620/Electrical Engineering Branch	19	5	0	10.9	9.7	59	21	43
• 7630/Architectural-Structural Engineering Branch	16	9	0	8.6	13.1	90	93	187
• 7650/Construction Management Branch	17	4	0	8.7	5.5	25	95	190
TOTAL	**79**	**26**	**0**	**$38.2K**	**$51K**	**$270K**	**$867K**	**$1,740K**

7600
FACILITIES ENGINEERING DIVISION OFFICE

FUNCTIONS

- Administration

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	2	0	0			$60K	$605K	$1,740K

7601
MANAGEMENT OPERATIONS OFFICE

FUNCTIONS

- CoF
- Environmental
- FED administrative support
- Engineering and construction services

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	7	5	0	$4.2K	$8.2K	$18K	$39K	$79K

7610
MECHANICAL ENGINEERING BRANCH

FUNCTIONS

- CoF

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	18	3	0	$5.8K	$14.5K	$18K	$14K	$29K

7620
ELECTRICAL ENGINEERING BRANCH

FUNCTIONS

- CoF
- Lewis safety organizations

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	19	5	0	$10.9K	$9.7K	$59K	$21K	$43K

7630
ARCHITECTURAL-STRUCTURAL ENGINEERING BRANCH

FUNCTIONS

- Administrative
- Architectural/interior design—CoF
- Architectural/interior design—non-CoF
- Civil/structural—CoF
- Civil/structural—non-CoF
- Environmental—CoF
- Environmental—non-CoF

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	16	9	0	$8.6K	$13.1K	$90K	$93K	$187K

7650

CONSTRUCTION MANAGEMENT BRANCH

FUNCTIONS

- Engineering
- Inspection
- Contract administration
- Management/supervision

	FTE	SSC	CO-OP	TRAIN	TRAVEL	EQPMNT	FS-3	FS-9
TOTAL	17	4	0	$8.7K	$5.5K	$25K	$95K	$190K

Appendix E

Questionnaires

Dear Customer:

You have been identified as one of the Facilities Planning Office (FPO) customers. Your candid and honest opinion is needed to improve and maintain the quality of our services. Please take a moment and complete the enclosed survey and return it to me by Friday. April 23, 1993 at Mail Stop 501-8. If you wish to remain anonymous, please remove this sheet and mail the remainder. If you have any questions please call me at 3-6753.

Thank You,

James Afarin

CUSTOMER OPINION SURVEY

Thank you for participating in this survey. To better serve you, we would like to know your opinion of the quality of service provided by the Facilities Planning Office (FPO). FPO is charged with facilities planning and utilization, energy management and contract management. The products and services of FPO are: Annual Construction of Facilities (CoF) budget, center funded projects implementation, space management, real property management, energy management and support service contract management. There are no right or wrong answers; however, your honest opinions are very important. If you wish to make additional comments, please use the space provided at the end of the survey. Please evaluate these statements using the following scale:

1- I Strongly Disagree with this statement (SD).

2- I Disagree with this statement (D).

3- I Neither agree nor disagree with this statement (N).

4- I Agree with this statement (A).

5- I Strongly Agree with this statement (SA).

FPO QUESTIONNAIRE

	SD	D	N	A	SA
General Satisfaction					
1. I am generally satisfied with the service I receive from FPO.	1	2	3	4	5
Convenience					
2. FPO personnel are easily accessible at appropriate time to satisfy my requirements.	1	2	3	4	5
3. I know the right person in FPO that I should contact for my problem.	1	2	3	4	5
Communication					
4. FPO keeps me informed on the status of my project	1	2	3	4	5
5. I receive clear and accurate explanation on the procedures and limitations of the FPO services.	1	2	3	4	5
6. I am satisfied with the professionalism of contact personnel at FPO.	1	2	3	4	5
7. I believe that FPO personnel understand my specific needs.	1	2	3	4	5
8. I believe that FPO personnel have my best interest in heart.	1	2	3	4	5
Responsiveness					
9. FPO responds to my complaints and rectifies my problems.	1	2	3	4	5
10. I am satisfied with the time that is required to return my phone call.	1	2	3	4	5
11. I am satisfied with the time that is required to respond to my inquiries in:					
a. CoF budget process	1	2	3	4	5
b. Center funded projects implementation	1	2	3	4	5
c. Space management	1	2	3	4	5
d. Calspan contract management	1	2	3	4	5
e. Real property management	1	2	3	4	5
f. Energy management	1	2	3	4	5

Flexibility

12. I am satisfied with the ability of FPO to cope with mistakes and unforeseen problems. 1 2 3 4 5

13. I am satisfied with the management of FPO in assigning the right person for the job. 1 2 3 4 5

Reliability

14. FPO performs the service right the first time. 1 2 3 4 5

15. FPO performs its services at the time it promises to do so. 1 2 3 4 5

Demand

16. FPO should increase its support in the following areas:

    a. CoF budget process 1 2 3 4 5

    b. Center funded projects implementation 1 2 3 4 5

    c. Space management 1 2 3 4 5

    d. Calspan contract management 1 2 3 4 5

    e. Real property management 1 2 3 4 5

    f. Energy management 1 2 3 4 5

17. What specific thing can FPO do to increase your satisfaction with this organization?

18. What aspect of service from FPO is not covered in this questionnaire?

Additional Comments:

Dear Customer:

You have been identified as one of the Office of Environmental Programs (OEP) customers. Your candid and honest opinion is needed to improve and maintain the quality of our services. Please take a moment and complete the enclosed survey and return it to me by Friday, April 16, 1993 at Mail Stop 501-8. If you wish to remain anonymous, please remove this sheet and mail the remainder. If you have any questions please call me at 3-6753.

Thank You,

James Afarin

CUSTOMER OPINION SURVEY

Thank you for participating in this survey. To better serve you, we would like to know your opinion of the quality of service provided by the Office of Environmental Programs (OEP). OEP serves as a consultant to the staff in environmental compliance. The products and services of OEP include: Industrial hygiene, environmental compliance, hazardous chemicals handling, health physics and chemical sampling and analysis. There are no right or wrong answers; however, your honest opinions are very important. If you wish to make additional comments, please use the space provided at the end of the survey. Please evaluate these statements using the following scale:

1- I Strongly Disagree with this statement (SD).

2- I Disagree with this statement (D).

3- I Neither agree nor disagree with this statement (N).

4- I Agree with this statement (A).

5- I Strongly Agree with this statement (SA).

Please identify the branch that you deal with the most. If you deal with more than one branch, please assign a percentage of interaction to each branch.

Org. Code	Branch Name	Branch Chief
7021	Industrial Hygiene Office	Blotzer
7022	Environmental Compliance Office	Watson
7023	Hazardous Chemicals Office	Dominguez
7024	Health Physics Office	Smith
7025	Chemical Sampling and Analysis Office	Street

OEP QUESTIONNAIRE

1. During the last six months, I received services from OEP ________ times.

	SD	D	N	A	SA
General Satisfaction					
2. I am generally satisfied with the service I receive from OEP.	1	2	3	4	5
Convenience					
3. OEP personnel are easily accessible at appropriate times to satisfy my requirements.	1	2	3	4	5
4. I know the right person in OEP that I should contact for my problem.	1	2	3	4	5
Communication					
5. OEP keeps me informed on the status of my project.	1	2	3	4	5
6. I receive clear and accurate explanation on the procedures and limitations of the OEP services.	1	2	3	4	5
7. I am satisfied with the professionalism of contact personnel at OEP.	1	2	3	4	5
8. I believe that OEP personnel understand my specific needs.	1	2	3	4	5
9. I believe that OEP personnel have my best interest in heart.	1	2	3	4	5
Responsiveness					
10. OEP responds to my complaints and rectifies my problems.	1	2	3	4	5
11. I am satisfied with the time that is required to return my phone call.	1	2	3	4	5
12. I am satisfied with the time that is required to respond to my inquiries in:					
a. Industrial hygiene	1	2	3	4	5
b. Environmental compliance	1	2	3	4	5
c. Hazardous chemicals	1	2	3	4	5
d. Health physics	1	2	3	4	5
e. Chemical sampling and analysis	1	2	3	4	5

Flexibility

13. I am satisfied with the ability of OEP to cope with mistakes and unforeseen problems.	1 2 3 4 5
14. I am satisfied with the management of OEP in assigning the right person for the job.	1 2 3 4 5

Reliability

15. OEP performs the service right the first time.	1 2 3 4 5
16. OEP performs its services at the time it promises to do so.	1 2 3 4 5
17. OEP should increase its support in the following areas:	
a. Industrial hygiene	1 2 3 4 5
b. Environmental compliance	1 2 3 4 5
c. Hazardous chemicals	1 2 3 4 5
d. Health physics	1 2 3 4 5
e. Chemical sampling and analysis	1 2 3 4 5

18. What specific thing can OEP do to increase your satisfaction with this organization?

19. What aspect of service from OEP is not covered in this questionnaire?

Additional Comments:

Dear Customer:

You have been identified as one of the Test Installations Division (TID) customers. Your candid and honest opinion is needed to improve and maintain the quality of our services. Please take a moment and complete the enclosed survey and return it to me by Friday, April 9, 1993 at Mail Stop 501-8. If you wish to remain anonymous, please remove this sheet and mail the remainder. If you have any questions please call me at 3-6753.

Thank You,

James Afarin

CUSTOMER OPINION SURVEY

Thank you for participating in this survey. To better serve you, we would like to know your opinion of the quality of service provided by the Test Installations Division (TID). TID provides mechanical, electrical, electronic and laboratory technical support for all the Center's research activities. The products and services of this division are: Installation of research rigs and supporting systems, modifying and repairing existing research rigs, providing aircraft maintenance and laboratory support. There are no right or wrong answers; however, your honest opinions are very important. If you wish to make additional comments, please use the space provided at the end of the survey. Please evaluate these statements using the following scale:

1- I Strongly Disagree with this statement (SD).

2- I Disagree with this statement (D).

3- I Neither agree nor disagree with this statement (N).

4- I Agree with this statement (A).

5- I Strongly Agree with this statement (SA).

Please identify the branch that you deal with the most. If you deal with more than one branch, please assign a percentage of interaction to each branch.

Org. Code	Branch Name	Branch Chief	Managers
7205	Aircraft Maintenance Branch	Edward N. Hejnal	Reitenbach
7210	Altitude, Icing & Engine Components Branch	Dalgleish	Emerson; Shivak
7230	Engine Research Branch	Albergottie	Lapka; Dorony; Pamer; Cerino
7240	Wind Tunnels Branch	Houghtlen	Gary Wolf; Giomini
7250	Energy & Spacecraft Branch	Cery	Naglowsky; White
7260	Communications & Electronics Branch	Reddish	Kostyack; Travis; Etzler; Antczak
7280	Materials Development Branch	Shepherd	Kelbach; Gross; Schneider
7290	Materials & Engine Components Branch	Petraus	Geil; Aron; Al Wolfe

TID QUESTIONNAIRE

1. During the last six months, I received services from TID _________ times.

	SD	D	N	A	SA
General Satisfaction					
2. I am generally satisfied with the service I receive from TID.	1	2	3	4	5
Availability					
3. TID personnel are available at appropriate times to satisfy my requirements.	1	2	3	4	5
4. TID has adequate tools and equipment to provide the services that I need.	1	2	3	4	5
Communication					
5. I am satisfied with the professionalism of contact personnel in TID.	1	2	3	4	5
6. I am satisfied with the clear communication line to the management of TID.	1	2	3	4	5
7. TID keeps me informed on the status of my project.	1	2	3	4	5
8. I receive clear explanation on the procedures and limitations of the TID services.	1	2	3	4	5
Responsiveness					
9. I am satisfied with the time that is required to:					
a. Return my phone call.	1	2	3	4	5
b. Receive technical support from TID in laboratories.	1	2	3	4	5
c. Receive technical support from TID in facilities.	1	2	3	4	5
d. Receive hardware installation services from TID.	1	2	3	4	5
e. Receive hardware maintenance services from TID.	1	2	3	4	5
f. Receive operation services from TID.	1	2	3	4	5

10. It is easy to obtain:

a. Technical support from TID in facilities. 1 2 3 4 5

b. Technical support from TID in laboratories. 1 2 3 4 5

c. Hardware installation services from TID. 1 2 3 4 5

d. Hardware maintenance services from TID. 1 2 3 4 5

e. Operation services from TID. 1 2 3 4 5

Reliability

11. TID performs its services at the time it promises to do so. 1 2 3 4 5

12. TID performs the service correctly the first time. 1 2 3 4 5

13. TID makes products that meet the pre-established design characteristics. 1 2 3 4 5

14. TID makes products that meet the pre-established operating characteristics. 1 2 3 4 5

Flexibility

15. I am satisfied with the management of TID in assigning the right person for the job. 1 2 3 4 5

16. I can contact the right person in TID for my problem. 1 2 3 4 5

17. I am satisfied with the ability of TID to cope with mistakes and unforeseen problems. 1 2 3 4 5

18. I am satisfied with TID's efforts in customizing services for my specific needs. 1 2 3 4 5

Competence

19. I am satisfied with the technical proficiency of the TID personnel in providing:

a. Technical support from TID in facilities. 1 2 3 4 5

b. Technical support from TID in laboratories. 1 2 3 4 5

c. Hardware installation services from TID. 1 2 3 4 5

d. Hardware maintenance services from TID. 1 2 3 4 5

e. Operation services from TID. 1 2 3 4 5

Demand

20. TID should increase its support in the following areas:

a. Technical support from TID in facilities.	1 2 3 4 5
b. Technical support from TID in laboratories.	1 2 3 4 5
c. Hardware installation services from TID.	1 2 3 4 5
d. Hardware maintenance services from TID.	1 2 3 4 5
e. Operation services from TID.	1 2 3 4 5

21. What specific thing can TID do to increase your satisfaction with this organization?

22. What aspect of service from TID is not covered in this questionnaire?

Additional Comments:

Dear Customer:

You have been identified as one of the Facilities Operation Division (FOD) customers. Your candid and honest opinion is needed to improve and maintain the quality of our services. Please take a moment and complete the enclosed survey and return it to me by Friday, April 23, 1993 at Mail Stop 501-8. If you wish to remain anonymous, please remove this sheet and mail the remainder. If you have any questions please call me at 3-6753.

Thank You,

James Afarin

CUSTOMER OPINION SURVEY

Thank you for participating in this survey. To better serve you, we would like to know your opinion of the quality of service provided by the Facilities Operation Division (FOD). FOD provides technical and engineering support for the operating, modification, maintenance, installation and repair of research support facilities, institutional facilities and various systems. The products and services of FOD are: Engineering support, research support, facilities maintenance, ground maintenance, custodial services, trash removal, security and fire protection. There are no right or wrong answers; however, your honest opinions are very important. If you wish to make additional comments, please use the space provided at the end of the survey. Please evaluate these statements using the following scale:

1- I Strongly Disagree with this statement (SD).
2- I Disagree with this statement (D).
3- I Neither agree nor disagree with this statement (N).
4- I Agree with this statement (A).
5- I Strongly Agree with this statement (SA).

Please identify the branch that you deal with the most. If you deal with more than one branch, please assign a percentage of interaction to each branch.

Org. Code	Branch Name	Branch Chief
7301	Management & Project Support Office	Thomas
7302	Engineering Support Office	Mainthia
7303	Central Control Operations Office	Wroblewski
7304	Research Systems Operations Office	Norton
7310	System Controls Engineering Branch	Webb, Jr.
7320	Center Operations Engineering Branch	Vega
7330	Research Systems Engineering Branch	Horansky
7340	Electrical Power Systems Branch	Torri
7360	Project Management Branch	Craddock
7370	Institutional Support Branch	Jones
7380	Lewis Fire Department	Allen, Jr.
7390	Security Branch	Mohr

FOD QUESTIONNAIRE

1. During the last six months, I received services from FOD _________ times.

	SD	D	N	A	SA
General Satisfaction					
2. I am generally satisfied with the service I receive from FOD.	1	2	3	4	5
Convenience					
3. FOD personnel are easily accessible at appropriate time to satisfy my requirements.	1	2	3	4	5
4. I know the right person in FOD that I should contact for my problem.	1	2	3	4	5
Communication					
5. FOD keeps me informed on the status of my project.	1	2	3	4	5
6. I receive clear and accurate explanation on the procedures and limitations of the FOD services.	1	2	3	4	5
7. I am satisfied with the professionalism of contact personnel at FOD.	1	2	3	4	5
8. I believe that FOD personnel understand my specific needs.	1	2	3	4	5
9. I believe that FOD personnel have my best interest in heart.	1	2	3	4	5
Responsiveness					
10. FOD responds to my complains and rectifies my problems.	1	2	3	4	5
11. I am satisfied with the time that is required to return my phone call.	1	2	3	4	5
12. I am satisfied with the response time in the following area:					
a. Management & Project Support	1	2	3	4	5
b. Engineering Support	1	2	3	4	5
c. Central Control Operation	1	2	3	4	5
d. Research Systems Operations	1	2	3	4	5
e. System Controls Engineering	1	2	3	4	5
f. Center Operations Engineering	1	2	3	4	5
g. Research Systems Engineering	1	2	3	4	5

h. Electrical Power Systems	1 2 3 4 5
i. Project Management	1 2 3 4 5
j. Institutional Support	1 2 3 4 5
k. Fire Department	1 2 3 4 5
l. Security	1 2 3 4 5

Flexibility

13. I am satisfied with the ability of FOD to cope with mistakes and unforeseen problems.	1 2 3 4 5
14. I am satisfied with the management of FOD in assigning the right person for the job.	1 2 3 4 5

Reliability

15. FOD performs the service right the first time.	1 2 3 4 5
16. FOD performs its services at the time it promises to do so.	1 2 3 4 5

Demand

17. FOD should increase its support in the following areas:

a. Management & Project Support	1 2 3 4 5
b. Engineering Support	1 2 3 4 5
c. Central Control Operation	1 2 3 4 5
d. Research Systems Operations	1 2 3 4 5
e. System Controls Engineering	1 2 3 4 5
f. Center Operations Engineering	1 2 3 4 5
g. Research Systems Engineering	1 2 3 4 5
h. Electrical Power Systems	1 2 3 4 5
i. Project Management	1 2 3 4 5
j. Institutional Support	1 2 3 4 5
k. Fire Department	1 2 3 4 5
l. Security	1 2 3 4 5

18. What specific thing can FOD do to increase your satisfaction with this organization?

19. What aspect of service from FOD is not covered in this questionnaire?

Additional Comments:

Dear Customer:

You have been identified as one of the Fabrication Support Division (FSD) customers. Your candid and honest opinion is needed to improve and maintain the quality of our services. Please take a moment and complete the enclosed survey and return it to me by Friday, April 9, 1993 at Mail Stop 501-8. If you wish to remain anonymous, please remove this sheet and mail the remainder. If you have any questions please call me at 3-6753.

Thank You,

James Afarin

CUSTOMER OPINION SURVEY

Thank you for participating in this survey. To better serve you, we would like to know your opinion of the quality of service provided by the Fabrication Support Division (FSD). FSD is charged with instrumentation and fabrication of research hardware. This division satisfies the needs of experimental research by utilizing both an in-house workforce and outside contractual efforts. The products and services of this division are: Hardware fabrication and consultation service. There are no right or wrong answers; however, your honest opinions are very important. If you wish to make additional comments, please use the space provided at the end of the survey. Please evaluate these statements using the following scale:

1- I Strongly Disagree with this statement (SD).

2- I Disagree with this statement (D).

3- I Neither agree nor disagree with this statement (N).

4- I Agree with this statement (A).

5- I Strongly Agree with this statement (SA).

Please identify the branch that you deal with the most. If you deal with more than one branch, please assign a percentage of interaction to each branch.

Org Code	Branch Name	Branch Chief
7410	Fabrication Procurement Branch	William M. Pollman
7420	Inspection and Material Processing	August R. Scarpelli
7430	Research Instrumentation	Frank V. Slam
7440	Machining	Gerald L. Matusik
7450	Model Development	Peter J. Murray
7460	Metal Fabrication	Gerald A. Marquis

FSD QUESTIONNAIRE

1. During the last six months, I received services from FSD _________ times.

	SD	D	N	A	SA
General Satisfaction					
2. I am generally satisfied with the service I receive from FSD.	1	2	3	4	5
Communication					
3. I am satisfied with the professionalism of contact personnel in FSD.	1	2	3	4	5
4. I am satisfied with the clear communication line to the management of FSD.	1	2	3	4	5
5. FSD keeps me informed on the status of my project	1	2	3	4	5
6. I receive clear and accurate explanations of the terms and limitations of FSD services.	1	2	3	4	5
Responsiveness					
7. I am satisfied with the time that is required to receive:					
a. Inspection and Material Processing	1	2	3	4	5
b. Fabrication Procurement	1	2	3	4	5
c. Research Instrumentation	1	2	3	4	5
d. Machining	1	2	3	4	5
e. Model Development	1	2	3	4	5
f. Metal Fabrication	1	2	3	4	5
8. I can obtain services easily in:					
a. Inspection and Material Processing	1	2	3	4	5
b. Fabrication Procurement	1	2	3	4	5
c. Research Instrumentation	1	2	3	4	5
d. Machining	1	2	3	4	5
e. Model Development	1	2	3	4	5
f. Metal Fabrication	1	2	3	4	5

Reliability

9. FSD performs its services at the time it promises to do so.	1 2 3 4 5
10. FSD performs the service correctly the first time.	1 2 3 4 5
11. FSD makes products that meet the pre-established design characteristics.	1 2 3 4 5
12. FSD makes products that meet the pre-established operating characteristics.	1 2 3 4 5
13. FSD fabricated products are durable.	1 2 3 4 5
14. FSD procured products are durable.	1 2 3 4 5

Perceived Quality

15. The quality of FSD fabricated products meets my expectations.	1 2 3 4 5
16. The quality of FSD procured products meets my expectations.	1 2 3 4 5

Flexibility

17. I can contact the right person for my problem easily.	1 2 3 4 5
18. I am satisfied with the management of FSD in assigning the right person for the job.	1 2 3 4 5

Demand

19. FSD should increase its support in the following areas:

a. Inspection and Material Processing	1 2 3 4 5
b. Fabrication Procurement	1 2 3 4 5
c. Research Instrumentation	1 2 3 4 5
d. Machining	1 2 3 4 5
e. Model Development	1 2 3 4 5
f. Metal Fabrication	1 2 3 4 5

20. What specific thing can FSD do to increase your satisfaction with this organization?

21. What aspect of service from FSD is not covered in this questionnaire?

Additional Comments:

Customer:

You have been identified as one of the Facilities Engineering Division (FED) customers. Your candid and honest opinion is needed to improve and maintain the quality of our services. Please take a moment and complete the enclosed survey and return it to me by Friday, April 9, 1993 at Mail Stop 501-8. If you wish to remain anonymous, please remove this sheet and mail the remainder. If you have any questions please call me at 3-6753.

Thank You,

James Afarin

CUSTOMER OPINION SURVEY

Thank you for participating in this survey. To better serve you, we would like to know your opinion of the quality of service provided by the Facility Engineering Division (FED). FED is charged with the designing and managing the construction of the research and institutional facilities and process systems. The products and services of FED are: Facilities design contract management, environmental program management, mechanical engineering design services, electrical engineering design services, architectural and structural design services, and construction management. There are no right or wrong answers; however, your honest opinions are very important. If you wish to make additional comments, please use the space provided at the end of the survey. Please evaluate these statements using the following scale:

1- I Strongly Disagree with this statement (SD).

2- I Disagree with this statement (D).

3- I Neither agree nor disagree with this statement (N).

4- I Agree with this statement (A).

5- I Strongly Agree with this statement (SA).

Please identify the branch that you deal with the most. If you deal with more than one branch, please assign a percentage of interaction to each branch.

Org Code	Branch Name	Branch Chief
7601	Management Operations Office	Seaver
7610	Mechanical Engineering Branch	Guthrie
7620	Electrical Engineering Branch	Schoeffler
7630	Architectural-Structure Engineering Branch	Larson
7650	Construction Management Branch	Boitel, Jr.

FED QUESTIONNAIRE

1. During the last six months, I received services from FED ________ times.

	SD	D	N	A	SA
General Satisfaction					
2. I am generally satisfied with the service I receive from FED.	1	2	3	4	5
Convenience					
3. FED personnel are easily accessible at appropriate time to satisfy my requirements.	1	2	3	4	5
4. I know the right person in FED that I should contact for my problem.	1	2	3	4	5
Communication					
5. FED keeps me informed on the status of my project	1	2	3	4	5
6. I receive clear and accurate explanation on the procedures and limitations of the FED services.	1	2	3	4	5
7. I am satisfied with the consideration, respect and courtesy of contact personnel at FED.	1	2	3	4	5
8. I believe that FED personnel understand my specific needs.	1	2	3	4	5
9. I believe that FED personnel have my best interest in heart.	1	2	3	4	5
Responsiveness					
10. FED responds to my complains and rectifies my problems.	1	2	3	4	5
11. I am satisfied with the time that is required to return my phone call.	1	2	3	4	5
12. I am satisfied with the time that is required to respond to my inquiries in:					
a. Facilities design contract management	1	2	3	4	5
b. Environmental program management	1	2	3	4	5
c. Mechanical engineering design services	1	2	3	4	5
d. Electrical engineering design services	1	2	3	4	5
f. Architectural and structural design services	1	2	3	4	5
g. Construction management	1	2	3	4	5

Flexibility

13. I am satisfied with the ability of FED to cope with mistakes and unforeseen problems. 1 2 3 4 5

14. I am satisfied with the management of FED in assigning the right person for the job. 1 2 3 4 5

Reliability

15. FED performs the service right the first time. 1 2 3 4 5

16. FED performs its services at the time it promises to do so. 1 2 3 4 5

Demand

17. FED should increase its support in the following areas:

a. Facilities design contract management

b. Environmental program management 1 2 3 4 5

c. Mechanical engineering design services 1 2 3 4 5

d. Electrical engineering design services 1 2 3 4 5

f. Architectural and structural design services 1 2 3 4 5

g. Construction management 1 2 3 4 5

1 2 3 4 5

18. What specific thing can FED do to increase your satisfaction with this organization?

19. What aspect of service from FED is not covered in this questionnaire?

Additional Comments:

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13. ABSTRACT ***(Maximum 200 words)***

The managers in Federal agencies are challenged to control the extensive activities in government and still provide high-quality products and services to the American taxpayers. Considering today's complex social and economic environment and the $3.8 billion daily cost of operating the Federal Government, it is evident that there is a need to develop decision-making tools for accurate resource allocation and total quality management. The goal of this thesis is to provide a methodical process that will aid managers in Federal Government to make budgetary decisions based on the cost of services, the agency's objectives, and the customers' perception of the agency's product. A general resource allocation procedure was developed in this study that can be applied to any government organization. A government organization, hereafter the "organization", is assumed to be a multidivision enterprise. This procedure was applied to a small organization for the proof of the concept. This organization is the Technical Services Directorate (TSD) at the NASA Lewis Research Center in Cleveland, Ohio. As part of the procedure, a nonlinear programming model was developed to account for the resources of the organization, the outputs produced by the organization, the decision-makers views, and the customers' satisfaction with the organization. The information on the resources of the organization was acquired from current budget levels of the organization and the human resources assigned to the divisions. The outputs of the organization were defined and measured by identifying metrics that assess the outputs, the most challenging task in this study. The decision-maker's views are represented in the model as weights assigned to the various outputs and were quantified by using the analytic hierarchy process. The customer's opinions regarding the outputs of the organization were collected through questionnaires that were designed for each division individually. Following the philosophy of total quality management, information on customers' satisfaction is presented in the model as the quality of output. The model is a nonlinear one whose objective is to maximize customers' satisfaction such that the total cost of operation does not exceed the organization's budget. This model represents a structured approach or policy mechanism, at the agency level, to make capital investment decisions based on the priorities of the agency and the quality of outputs. This procedure applied to TSD resulted in a resources allocation scheme that was reasonable and acceptable to the decision-makers and, as expected, dependent on the assumptions and accuracy of the data used in the model.

14. SUBJECT TERMS

Resource allocation; Government organization; Customer satisfaction; TQM; Mathematical model; Decision making tool

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