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AUDITING COST-EFFECTIVENESS ANALYSES OF TECHNOLOGICAL CHANGES

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ABSTRACT:

A methodology is developed for auditing cost effectiveness analyses of major technological changes. The methodology is applied to the Work In Process Inventory Control System (WIPICS) recently implemented at NARF, North Island. The approach involves using data on NARF operations to estimate cost functions for each major program of the NARF both before and after the change. Cost comparisons using these models do not show a clear cost savings for the WIPICS system.

Prepared by:

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and in terms of a practical use on a particular technological change. Since major portions of the report concern data and specific circumstances associated with the practical example, it is useful to detail the particular technological change involved at this point.

B. AN EXAMPLE OF TECHNOLOGICAL CHANGE

The Naval Air Research Facility at NAS North Island (NARFNI) is one of seven naval air rework facilities throughout the continental United States responsible for major maintenance, conversion and repair of United States Navy and Marine Corps aircraft and related components. To accomplish this mission NARFNI employes approximately 6800 civilian workers and spends $150 million on annual operating expenses.

Maintenance of equipment is accomplished under one of three primary programs, with two of the programs receiving inputs either directly from the customer or from the third program (see Fig. 1).

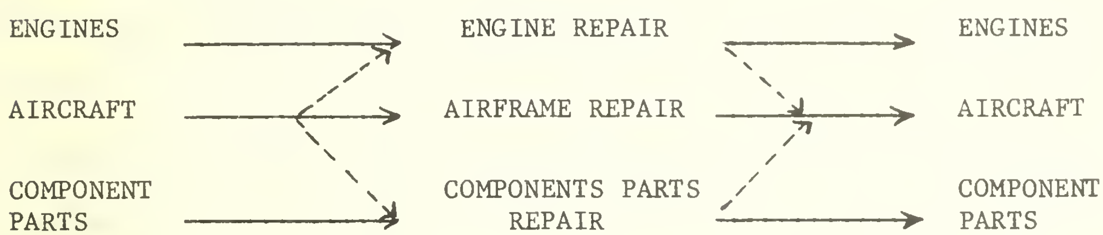

FIGURE 1. NARFNI Repair Programs

Under these programs work is further assigned to one of the six divisions of the Production Department identified in Figure 2.

I. INTRODUCTION AND BACKGROUND

A. INTRODUCTION

It is commonly accepted that technological advancements are arriving at a faster and faster pace with the state of the art generally far ahead of the functional application. One reason for this gap is the costly enterprise of transfering theory into practice. When the initial transfer is made a natural question to ask prior to extensive implementation is "Will it be cost-effective?" Current methods of cost-effectiveness analysis are tedious and usually employ a detailed analysis of the process which incorporated the change. Such analyses are inherently imprecise due to the possibilities of overlooked dependencies, double counting of costs, and external changes which may affect the effectiveness of the process and yet not be accounted for in the analysis. Thus when a cost-effectiveness analysis is completed a reviewing agency might well ask, "Are the conclusions of the analysis correct?" As mentioned, the methods employed in the analysis make this second question a difficult one to answer.

Nevertheless, it is important to answer the above question. Many technological changes are implemented on a prototype basis. Therefore, it is increasingly important that a careful audit of the cost-effectiveness analysis be made. That is, the costs, cost savings, and increased effectiveness attributable to the technological change must be carefully documented after the installation of the prototype and before similar changes are implemented at other installations.

This report provides several alternative methods of auditing cost-effectiveness analyses. It compares the methods on a theoretical basis

Weapons #1
Weapons #2
Hydraulic/Mechanical
Power Plant
Avionics
Components and Metal

FIGURE 2. Production Department Divisions

The assignment of work to various programs and production divisions can be thought of as a "job shop" operation in which each shop performs a specific task. Thus an item entering rework is subject to being dismantled, its subassemblies distributed for rework, and then re-assembled prior to returning to the customer. This type of operation places emphasis on the scheduling of rework in that ideally the shops are completing work on related parts in the same sequence to reduce the total repair time of the major end items. Scheduling is also important to the shop managers who must order material and plan personnel assignments based on the projected arrival of work from other shops. This entire scheduling problem is intimately related to the technological change to be described in the following section.

NARFNI is primarily funded by the Navy Industrial Fund (NIF) which provides a working capital fund to finance repair operations. The finished product is returned with a bill to the customer for the work done. This "debt" is then paid by transferring funds from the customer's appropriated maintenance funds to the NARF's working capital fund. Under this concept NARFNI is required to control its finances to incur zero profit at the end of each fiscal year. This control is exercised at Quarterly Planning Conferences in which representatives from the customers and NARFNI meet to plan the following quarter's work load input and prices for the work to be accomplished. NARFNI is reimbursed under basically two types of contracts, cost reimbursable and fixed price, the majority of the work being performed under fixed price contracts established at the Quarterly Planning Conference. This type of contract gives NARFNI incentive to minimize costs subject to the required work load, a fact which is instrumental to the auditing method investigated.

In January 1972, NARFNI installed an industrial information system, the Work in Process Inventory Control System (WIPICS), to assist in the location and scheduling of inventory in the rework process. WIPICS was requested and initiated by the Management Systems Development Office (MSDO) in an effort to assist the NARF's in performing their mission at a minimum cost to the government. If the prototype at NARFNI is determined to be cost-effective WIPICS will then be installed at the remaining six NARF's. Its major milestone are listed in Figure 3.

1.	Early 1969	-	ROHR Corporation studied NARFNI
2.	Late 1969	-	MSDO requested contract
3.	Early 1970	-	NAVAIRSYSCOM evaluation and approval
4.	July 1970	-	SECNAV authority for prototype
5.	Late 1970	-	Contract negotiated
6.	4 January 1971	-	Contract date, D-Day
7.	D + 9.5 months	-	WIPICS developed
8.	D + 11 months	-	WIPICS test
9.	D + 11.5 months	-	WIPICS prototype started

FIGURE 3. WIPICS Milestone

WIPICS consists of a central computer which is linked to the job shops by 164 "touch tone" telephones, 20 alphanumeric terminals, and four teletypewriters. In addition, the system is equipped with an 80 word audio-response unit to allow two-way communication through the telephones. When an item first arrives at NARFNI it is broken down into identifiable subassemblies. For each of these subassemblies a computer record is created and entered into WIPICS. This record contains information such as identification, required work, required material, location, and status. Each job shop inputs arrival and departure information through the "touch-tone" telephones. Also, an unexpected delay in work due to lack of material or some other shortcoming is inputed as it occurs. At the completion of the work day a print-out of this information is produced to aid shop managers in projecting the rate and mix of work that will be entering their respective shops in the near future.

The inauguration of the WIPICS prototype was accomplished by creating computer records for all jobs presently in the shop to preclude a lengthy start up before evaluation could begin. Simultaneously, the operational costs accountable to WIPICS were transferred as overhead to be applied to the price of jobs in shop. Thus, during January, 1972, NARFNI initiated a technological change which was to be subjected to cost-effectiveness analysis and, at the same time, provided a suitable situation to use in investigating a method for auditing cost-effectiveness analyses.

C. PREVIOUS WORK

This report documents our research in auditing cost-effectiveness analyses and summarizes several previous reports, presentations and theses generated by the research project. In particular six master's theses in Operation Analysis references [1, 2, 3, 4, 5, 6] provide much of the detail and data that underlie the report. A brief synopsis of each follows.

Spooner [1] details the general methodology to be followed in using continuous production functions of the Cobb-Douglas variety to model a multiproduct facility before and after a technological change. He also provides the initial before WIPICS data on engine and air frame jobs and a computer program to convert this information to a flow of work over time at NARFNI.

Myers [2] developes linear economic models of the air frame and engine programs at NARFNI. He also provides an estimation procedure for determining the transformation matrix from data on jobs.

Bradley [3] uses data provided by Spooner to estimate production functions for airframes, engines, and F/J components. He also does some preliminary analysis of the timing of fluctuation in workload at the NARF.

Trafton [4] extends Bradley's work by estimating cost functions of the same form as the latter production functions. He also develops and uses an estimation procedure for the cost function derived from the Constant Elasticity of Substitution Production Function.

Tye [5] continues this line of reasoning by estimating similar functions for sets of data collected after WIPICS has been implemented. He tests their significance, constructs prediction intervals and derives the first preliminary conclusions concerning the cost-effectiveness of the system.

Finally McGarrahan [6] develops models similar to Myers' for the after WIPICS data and compares the results from these models to those derived by Tye. He also reports a third type of model and compares it to the other two types.

The above theses contain data, computer programs, and specific results which support the information provided in this report.

The report is divided into several sections. The section below presents the methodology of the study and the alternative mathematical models that are employed. Section three describes the data that were used and various transformations and adjustments to that data. In section four the various estimation procedures that are employed are presented. The results of those procedures are reported in section five along with tests of hypotheses, and prediction intervals. Section six of the report contains comparisons of the various models, the conclusions of the study, and topics for further research.

II METHODOLOGY AND SCOPE OF THE PROJECT

A. INTRODUCTION

Usually the major source of effectiveness for new equipment or procedures is in terms of factor saving. That is, an analysis will frequently document expected effectiveness in term of man-days saved or decreases in wasted raw materials or replacement of several more expensive pieces of equipment.

Other contributions to effectiveness are more difficult to estimate and evaluate. However, some attempt is usually made to include effects like increased speed of production, higher quality of output, and more control over the production process.

Frequently, an attempt is made to assign dollar values to each of these measures of effectiveness and a cost-effective change is defined as one with a greater value of effectiveness than its costs.

Frequently unstated in the analysis is the assumption that these effects are expected only if nothing else changes.

After the equipment has been installed or the procedure implemented, one can gather data on the changes that have taken place. For example, we know what has happened to factor usage, we can measure the new speed of the production process, and perhaps we can determine quality changes in output. Here the important questions are not what changes have taken place, but why the changes have occurred. In particular are the changes due to our new equipment or procedure ?

Notice that after the fact, many other things may have changed as well. In particular, the outputs of the organization may have changed in both quantity and type, prices of factors, many have changed or new constraints may have been placed on the organization or old ones relaxed. Finally, the manager of the enterprise may not have acted exactly as the cost-effectiveness analysis expected. For example, suppose a new piece of equipment replaces old equipment and several men, instead of laying off the men the manager re-assigns them as trouble shooters. As a result, output increases dramatically with no increase in costs. Here costs did not decline as expected, instead the manager chose to increase output.

Current methods of auditing cost-effectiveness analyses involve looking at factors by categories and determining if their usage has changed. A portion of the change in factor usage is directly related to the new equipment by verbal argument and a dollar value is assigned to that portion of the change in factor usage. Thus the relation between the factor savings and the new equipment frequently is a verbal argument constructed by an outside observer. These allowed effects are then compared to costs. Other effects like quality changes are handled separately.

Our proposal for auditing CE analyses recognizes that an outside observer cannot effectively trace second order effects though a massive enterprise. Thus the proposal is to look at aggregated summary measures of the organization's behavior in each of several areas before and after the technological change.

In particular our approach to determining the effectiveness of WIPICS is to develop a model of the production behavior of the NARF both before and after the implementation of the system. These production models are then compared for several sets of circumstances and conclusions are drawn from the comparisons. Three different production models have been used for these purposes and each of them is described below.

B. THE CONTINUOUS PRODUCTION FUNCTION OF A MAJOR PROGRAM

A production function is frequently used to describe the relations between factors and the homogeneous output that is produced by their use. Ordinarily, the function describes this relation for a specified period of time. In addition the function typically possesses the following characteristics:

1. $W = f(Z_1, Z_2, Z_3)$ where W is output, Z_1, Z_2, Z_3 are quantities of factors used, and f is a single valued, continuous function whose first and second derivatives exist. f represents the maximum output that can be produced with a given vector of factors.
2. $\frac{\partial f}{\partial Z_i} > 0$, the marginal product of each of the factors is possitive.
3. The matrix $\left[\frac{\partial^2 f}{\partial Z_i \partial Z_j}\right]$ is negative semidefinite. This requires the rate at which one factor may be substituted for another while producing a given quantity of output diminishes as the second factor is substituted for the first.

To elaborate on this last property, it may be possible to produce a PAR Repair on an A3B with input combinations one and two below, but one would hardly expect that the possibilities of substituting labor for material at the same rate would extend to situation three.

	Situations		
Variables	1	2	3
PAR Repairs A3B	1	1	1
Direct Man Hours	12,600	12,000	10,200
Material Costs	11,400	15,000	25,800

FIGURE 4. Production Tradeoffs

By estimating a production function for an entire program we are not involved with modeling the detailed relations among shops or the exact relation between WIPICS and the cost producing variables (factors) or the effectiveness generating variables (outputs). This eliminates the need to conduct expensive and time consuming measurements of many variables and also prevents the possible double counting problems that are difficult to avoid in a cost-effectiveness analysis.

On the other hand, the production function is sufficiently detailed to permit the analysis of the NARF's opportunities for tradeoffs among factors. For example, the trade-off between man-hours and repairable airframes given some level of output and material usage is measured by the production function. Thus, the opportunity to take cost savings due to WIPICS in the form of reduced man hours or reduced inventory of repairable airframes is measured.

The basic information embodied in the production function may be combined with some additional assumptions concerning the organization to determine a cost function for a program.

For example, it may be assumed that the NARF attempts to minimize the cost of producing a given quantity of output from the program. In addition, if the NARF has no control over the prices it pays for factor then a cost function may be derived from the program:

$$\text{Min} \quad C = C_0 + P_1 Z_1 + P_2 Z_2 + P_3 Z_3 \tag{1}$$

$$\text{s.t.} \quad W = f(Z_1, Z_2, Z_3)$$

$$\text{as,} \quad C = C_0 + g(W, P_1, P_2, P_3) \tag{2}$$

In the above program C_0 is fixed cost; P_1, P_2, and P_3 are the prices of factor; and W is a measure of output for the program.

It is important to notice that the costs of production are thus related to several variables which influence the environment of the organization. The relation between program costs and prices and outputs is thus captured.

Two functions of the same form as g may be estimated by econometric techniques one each for the before WIPICS program and the after WIPICS program. Finally, the hypothesis that these functions are significantly different from one another may be tested for some level of confidence and we may determine if the relation which describes costs in the program, has changed significantly with the implementation of the WIPICS system.

Assuming the cost functions are different from one another, they may be used to describe changes in the situation after the technological change. Whether the changes are beneficial or not, may depend on the environment of the enterprise at a particular point in time. For example, Figure 5 shows projection of two cost functions on the cost, quantity axes. Suppose function B describes the before WIPICS situation and function A the after situation. Then whether the technological change is beneficial or not, depends on the expected level of output of the program. That is, the cost functions allow one to compare the before and after situation at alternative levels of output and the conclusions may very well depend on the level of output chosen.

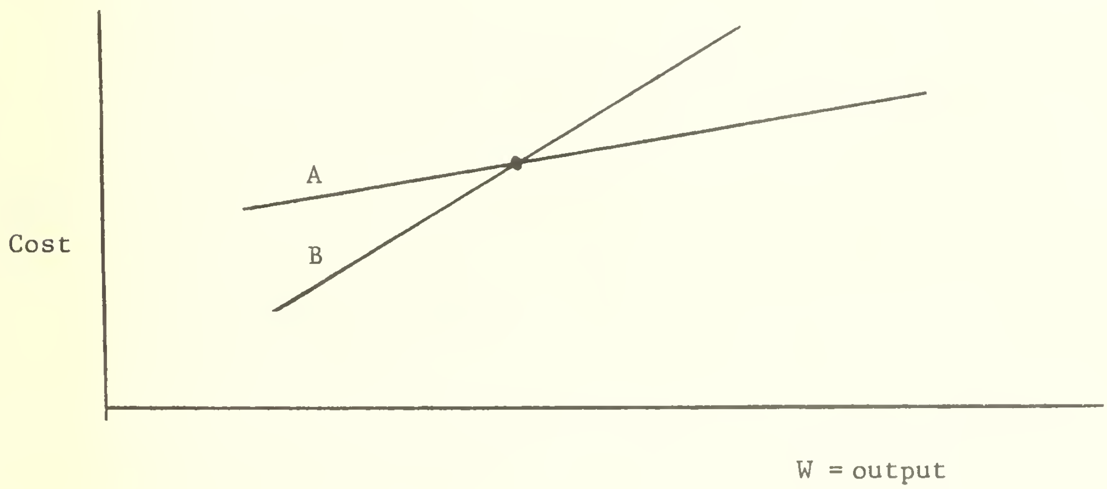

FIGURE 5. Illustrative Cost Curves

This approach to auditing cost-effectiveness analyses of technological change will permit one to compare before and after situations even if other things do change. In particular, changes in output and and prices of factors are automatically accounted for in the model. In addition any action which the manager of the organization takes to minimize the cost of producing a given level of output is compatible with the model and consistant with a valid interpretation of the results.

Finally, anticipated changes in the constraints on the manager or his enterprise may be incorporated into the programming problem at (1) and these changes also may be handled if data on the constraints are collected and used in the estimation procedure.

Two alternative production functions have been used in the study so far. The first of these is the Cobb-Douglas production function:

$$W_1 = A_1 Z_{11}^{\alpha_1} Z_{12}^{\beta_1} Z_{13}^{\gamma_1}$$

$$W_2 = A_2 Z_{21}^{\alpha_2} Z_{22}^{\beta_2} Z_{23}^{\gamma_2}$$

Here W_1 and W_2 measure output of programs one and two respectively.

Solving the programming problems at (2) yields:

$$C = C_0 + C_1 + C_2$$

where

$$C_1 = A_1^* W_1^{\frac{1}{\alpha_1+\beta_1+\gamma_1}} P_1^{\frac{\alpha_1}{\alpha_1+\beta_1+\gamma_1}} P_2^{\frac{\beta_1}{\alpha_1+\beta_1+\gamma_1}} P_3^{\frac{\gamma_1}{\alpha_1+\beta_1+\gamma_1}}$$

$$C_2 = A_2^* W_2^{\frac{1}{\alpha_2+\beta_2+\gamma_2}} P_1^{\frac{\alpha_2}{\alpha_2+\beta_2+\gamma_2}} P_2^{\frac{\beta_2}{\alpha_2+\beta_2+\gamma_2}} P_3^{\frac{\gamma_2}{\alpha_2+\beta_2+\gamma_2}}$$

and A_1^* and A_2^* are constants. The properties of production functions require that:

$$A_1^* > 0, \quad A_2^* > 0$$

$$0 < \alpha_1, \beta_1, \gamma_1, \alpha_2, \beta_2, \gamma_2 < 1$$

The second production function used in the study is the C. E. S. production function. Here an additional specification is imposed, that one of the inputs is determined by forces outside the organization's control so that there are only two decision variables in the production function. Here:

$$W_1 = \gamma_1[\delta_1 Z_{11}^{-\rho_1} + (1-\delta_1)Z_{12}^{-\rho_1}]^{-\sigma_1/\rho_1}$$

$$W_2 = \gamma_2[\delta_2 Z_{21}^{-\rho_2} + (1-\delta_2)Z_{22}^{-\rho_2}]^{-\sigma_2/\rho_2}$$

Now letting $C_0' = C_0 + P_3(Z_{13}+Z_{23})$ a programming problem similar to (2) may be solved to yield.

$$C = C_0' + C_1 + C_2$$

where

$$C_1 = (P_2+P_1\left(\frac{Z_{11}}{Z_{12}}\right))\left(\frac{W_1}{\gamma_1}\right)^{\frac{1}{\sigma}}(1-\delta_1+\delta_1(Z_{11}/Z_{12})^{-\rho_1})^{1/\rho_1}$$

$$C_2 = (P_2+P_1\left(\frac{Z_{21}}{Z_{22}}\right))\left(\frac{W_2}{\gamma_2}\right)^{\frac{1}{\sigma}}(1-\delta_2+\delta_2(Z_{21}/Z_{22})^{-\rho_2})^{1/\rho_2}$$

$$\frac{Z_{11}}{Z_{12}} = \left[\frac{(1-\delta_1)P_1}{\delta_1 P_2}\right]^{-\frac{1}{\rho_1+1}}$$

$$\frac{Z_{21}}{Z_{22}} = \left[\frac{(1-\delta_2)P_1}{\delta_2 P_2}\right]^{-\frac{1}{\rho_2+1}}$$

The properties of production functions require that the C.E.S. parameters conform to the following restrictions:

$$\sigma_1, \sigma_2, \gamma_1, \gamma_2 > 0, \quad 0 < \delta_1, \delta_2 < 1,$$

and $$\rho_1, \rho_2 > -1.$$

It may be noted in passing that either production function may be used to investigate returns to scale. For the Cobb-Douglas production function decreasing, constant or increasing returns to scale obtain as $\alpha + \beta + \gamma$ is less than, equal to, or greater than one respectively. For the C.E.S. production function decreasing, constant, or increasing returns to scale obtain as σ is less than, equal to, or greater than one respectively.

Finally, it may be noted that the C.E.S. function is much more general that the Cobb-Douglas as it approaches the latter as a special case as $\rho \rightarrow 0$.

C. THE CONTINUOUS PRODUCTION FUNCTION FOR A JOB

This production model is very similar to the above model. It does, however, overcome one troublesome assumption above, namely the requirement that the output of a program be homogeneous. Here the production function is applied to a job defined as a particular type of repair on a particular airframe or engine. Since the time to complete the same job may vary over the period analysed, the number of days a particular job was in shop is introduced as an explicit variable in this case.

These cost functions for each job type may be derived and the parameters estimated. The functions may then be estimated again for the after WIPICS situation. The two sets of functions may then be compared directly as above. Also, the total costs for some representative distribution of work load may be predicted by each as a further test of significant change between the before and after WIPICS situation. This production model for a job enjoys similar characteristics to the production model for a major program.

The mathematical model used for the continuous job production function is also a production function of the Cobb-Douglas variety. Here however, the function applied only to a single job and as a result output was measured by a constant (W_{ij}), where the subscripts refer to the type of engine or airframe being reworked and the type of repair being done respectively. This has the effect of including a dummy variable in the cost function associated with the job and for all practical purposes makes it impossible to measure returns to scale for either program. The detailed cost functions used are discussed in section four of the report. The advantage of this model is that it does not require a homogeneous output measure to be defined. The disadvantage is that it requires more data and more judgement in determining an appropriate distribution of workload for comparison. In addition, if a job occurs in the before situation that is not represented in the after situations or vice versa, the effect on this job cannot be compared.

D. THE LINEAR ECONOMIC MODEL

Linear programming is a mathematical technique for solving constrained optimization problems of a special type. A linear economic model is a specific type of linear program consisting of the maximization (or minimization) of a linear function of n variables subject to m linear inequality constraints. Linear programs (and their close mathematical relative the input-output models) have become increasingly important to microeconomic theory in recent years.

In the linear economic model being constructed it is necessary to define a process. A linear production process is an activity by which one or more outputs are produced in fixed proportions by the application of one or more input factors in fixed proportions. In this case there is at least one process per job type. The production process as defined is homogeneous of degree one which implies constant returns to scale. For example, if all inputs to a process are doubled then the output will also be doubled. A linear production function is formed from a collection of linear production processes that may be used simultaneously.

The optimal solution to a linear economic model as described above consists of finding the combination of m processes from n available processes such that a linear objective function is maximized (or minimized).

The following assumptions are made in the formulation of a linear economic model:

(1) The estimated processes (reworking of engines and aircraft) are linear functions and therefore these processes exhibit constant returns to scale.

(2) The above linear processes may be estimated by the aggregation of a finite set of observations over some time period.

(3) The management objective of the NARF will be assumed to be minimization of costs subject to completion of all work demanded by the

operational forces of the Navy.

(4) Prices used in the model are constant and may be estimated from the production data furnished by the NARF.

To present the model, it is necessary to have some mathematical notation available. Definitions will be as follows:

m = number of output constraints

n = number of production processes

$(n > m)$

R = column vector of available resources = $\begin{bmatrix} R1 \\ R2 \\ R3 \end{bmatrix}$

P = column vector of prices associated with R1, R2, and R3 respectively

Z = column vector of activity levels $= \begin{bmatrix} z_i \end{bmatrix}$

$i = 1,\ldots,n$

T = Technology matrix of observed processes at NARF $= \begin{bmatrix} T_1 \\ \hline T_2 \end{bmatrix}$

$[(m+3) \times n \text{ matrix}]$

where

T_1 = units of output

(mxn matrix)

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & \ldots & 0 \\ 0 & 1 & 1 & 0 & & \ldots & 0 \\ 0 & 0 & 0 & 1 & 0 & \ldots & 0 \\ \cdot & & & & & & \\ \cdot & & & & & & \\ \cdot & & & & & & \\ 0 & \cdot & \cdot & \cdot & \cdot & 0 & 1 \end{bmatrix}$$

and

T_2 = resource matrix $= \begin{bmatrix} r_{ij} \end{bmatrix}$

$i = 1, 2, 3$

$j = 1,\ldots,n$

with r_{ij} = amount of $i^{\underline{th}}$ resource used per unit output of $j^{\underline{th}}$ activity.

Y = column vector of production output desired $= \begin{bmatrix} y_i \end{bmatrix}$

$i = 1,\ldots,m.$

T_3 = diagonal matrix of number of days in shop for each process per unit of output $= \begin{bmatrix} t_1 & & & & \bigcirc \\ & \ddots & & & \\ & & t_i & & \\ & & & \ddots & \\ \bigcirc & & & & t_n \end{bmatrix}$

C = column vector of penalty costs $= \begin{bmatrix} c_i \end{bmatrix}$

$i = 1,\ldots,n$

where c_i = penalty cost in dollars incurred for each day in shop associated with the $i^{\underline{th}}$ process.

Now that a basic mathematical vocabulary exists for the variables, processes and costs, the linear economic model will be presented and discussed:

objective function: minimize $P^T T_2 Z + C^T T_3 Z$

constraints:

subject to: $\begin{bmatrix} -T_1 \\ \hline T_2 \end{bmatrix} \cdot \begin{bmatrix} Z \end{bmatrix} \leq \begin{bmatrix} -Y \\ \hline R \end{bmatrix}$

The objective function consists of two terms:

$P^T \cdot T_2 \cdot Z$ = actual cost in dollars of resources used for activity level vector Z

$C^T \cdot T_3 \cdot Z$ = penalty cost in dollars for activity level vector Z.

The constraint set may also be separated into two parts for discussion:

$-T_1 \cdot Z \leq -Y$ is a set consisting of the first m rows of the constraints which force the activity level vector Z to choose a set of processes which satisfy the production vector Y.

$T_2 \cdot Z \leq R$ consists of the last 3 rows of the constraint set and ensures that actual resources used do not exceed available resources.

It is clear that the size of the resource vector R is highly dependent on the production vector Y. In fact, these two vectors must be chosen carefully to avoid an infeasible linear program. The easiest approach to avoiding an infeasible linear program is to make the resource vector R very large, therefore the optimal solution to the model will not be constrained by an active resource constraint. In economic terms, this means that the "customer" is willing to pay the NARF as much as necessary to accomplish the work specified by production vector Y. If the NARF is assumed to be efficiently operated, then the costs incurred will be minimized.

In summary, the objective function of the model will be a minimum when the model is not constrained by the resource vector R. In other words, the costs are minimum when the resource constraints are inactive constraints. The value of the objective function represents the total cost incurred to accomplish production vector Y based on past performance data of the NARF.

It should be noted that the linear economic model presented in this chapter is not a production management tool in the sense that the model chooses "processes" by which the NARF should rework aircraft or engines. The model only provides a budget cost plus a penalty cost for a specified amount of work to be done. Some information is available from the model concerning tradeoff values among the three resources. The model can also determine the minimum amount of any single resource required to accomplish the specified work.

As with the previous models, the linear economic model is estimated from both before and after WIPICS data and the two resulting models may be compared process by process and for a representative workload at the NARF. The data requirements ofthis production model approximate those of model two and the estimation procedure is not as well developed in this area as it is for the previous two models. In addition, the assumption of constant returns to scale and a small number of discrete ways to combine resources are restrictive. Nevertheless, the linear economic model does preserve more detail about the production process at the NARF and for this reason it is used and compared to the previous models. It also permits changes in prices, and the level and distribution of output requirements to directly affect costs in a program.

III. DATA AND ITS USE

A. DESCRIPTION OF AVAILABLE DATA

The preceding mathematical production models are defined in terms of physical measures of inputs and outputs and well defined prices for these quantities. In fact, data on these variables cannot be obtained in most large organizations and NARFNI is no exception. The data obtained from NARFNI consists of information on 837 aircraft and 1865 engine reworks performed during the period March 1970 to March 1973. For each rework the following information was available:

(1)	Type of engine or aircraft	
(2)	Identification number	
(3)	Type of work done	
(4)	Induction date	
(5)	Production date	
(6)	Production load norm (man-hours)	(NORM)
(7)	Airframe change man-hours	
(8)	Direct labor hours expended	(DMHR)
(9)	Direct labor cost	(DLB$)
(10)	Direct material cost	(DML$)
(11)	Applied overhead cost	(DOH$)
(12)	Navy Industrial Fund (NIF) rate	(NIFR)

The manner in which the above statistics are accumulated and used by NARF North Island are enumerated in [7]

In order to keypunch the basic data it was necessary to assign codes for different types of engines/aircraft and the types of work done. These codes are listed in Tables I and II. The coded data is listed for reference purposes in Spooner [1] and McGarrahan [6].

One additional item of information concerns a penalty cost assigned to aircraft and engine down time at the NARF. These penalty costs per day were calculated from average flyaway unit procurement costs for each engine and aircraft. The particular penalty costs used are reported by McGarrahan [6].

These data were used to form several proxies for the variables of Section Two. A brief description of each follows:

TABLE I

Codes Assigned to the Engine Program

Engine Type	Code	Engine Type	Code
T58-GE-1 (A/F)	51	T64-GE-3 (A/F)	63
T58-GE-3 (A/F)	53	T64-GE-6B	65
T58-GE-5 (A/F)	55	T64-GE-6B (PAWN)	66
T56-A-8P	56	T64-GE-7 (A/F)	67
T58-GE-5 (C/G)	57	T64-GE-413	69
J57-P-4A/22	71	T58-GE-8F	81
J57-P-10	72	T58-GE-8B	82
J57-P-20A	73	T58-GE-8B/F	83
J57-P-22	74	T58-GE-8B (C/G)	84
J57-P-420	75	T58-GE-8B (HH2)	85
		T58-GE-8B/F (CONV)	86
J79-GE-8B	91	T58-GE-10	89
J79-GE-8B/C	92		
J79-GE-8B (RDTE)			
J79-GE-10	95		

Work Type*	Code
OVHL	01
OVHL/CONV	02
PAR/REP	03
SUP/REP	04
SUP/REP/CONV	05

* Abbreviations are defined as follows

OVHL	=	overhaul
CONV	=	conversion
PAR	=	Planned aircraft repair
SUP	=	Supply
REP	=	Repair
SEA	=	South East Asia
CONUS	=	Continental United States

TABLE II

Codes Assigned to the Aircraft Program

Aircraft Type	Code	Aircraft Type	Code
C-2A	10	Ch-3B	31
E-2A/B	11	RH-3A	32
		SH-3A	33
F-4J	21	SH-3A/G	34
F-4B	22	SH-3D	35
F-4G/B	23	CH-46A	41
F-8J	25	CH-46D	42
F-8H	26	CH-46F	43
RF-8G	27	UH-46A	44
		UH-46D	45
		CH-53A	48
		CH-53D	49

Work Type*	Code
OVHL	01
PAR	02
PAR/CONV	03
PAR/MOD	04
PAR/MOD/REP	05
PAR/REP	06
PAR/SEA	07
PAR/CONUS	08

*See Table I for Work Type abbreviations.

1. Output. Physical measures of output of the NARF would require hundreds of variables on numbers of aircraft and engines of various types with several different kinds of repair work done. Furthermore, there is no obvious common denominator of the repair work. So many different measures of output would be extremely difficult to handle and would require many more observations to produce statistical significance. Hence, a proxy variable of production load norm, N, was chosen to measure output. Production load norm has the advantage that across jobs it is measured in the same units, expected man-hours required to complete the job. In addition, it is, in many cases, what determines the cost to the fleet of having the repairs made. That is, the fixed price of a job is negotiated as two components, the production load norm, as a measure of the difficulty of the job, and the expected NIF rate, as the expected cost per man hour on the job. These might usefully be thought of as measures of the quantity of repairs to be completed and the price per unit of the repairs.

2. Input one - Labor. Direct man-hours expended, L, are used as a measure of labor used. This variable excludes indirect man-hours and fails to distinguish among alternative types of labor used. In spite of these drawbacks, it is the most accurate of the proxy variables.

3. Price of input one - Wage rate. The ratio of direct labor costs, L$, to direct man-hours expended, L, is used as a proxy for the wage rate P_ℓ. Because this variable is averaged over all types of labor it may be influenced by factors other than a general increase in wages. For example, an airframe that requires very technical work and uses high priced labor exclusively will be associated with higher

values of this proxy. Also, periods of time that involve large quantities of overtime labor will show high values of the variable. Still, this variable is thought to be a reasonably accurate measure of the wage rate.

4. Input two - Items to be repaired. It seems clear that if output is to be a measure of repairs on engines or airframes then one input must be repairable engines or airframes. Unfortunately, these items have many different descriptions and are in various states of disrepair. As a crude proxy for this variable the unweighted number of items in ship at any point in time, I, is used as a measure of items to be repaired.

5. Price of input two - Penalty cost per item. The NARF does not pay for items to be repaired nor does it provide "loaners" to the fleet while the repairs are being undertaken. Nevertheless, from the point of view of the Navy this pipeline of repairable items is costly and both the NARF and the Navy are concerned with reducing the size of the pipeline. Hence, the models that we are using include as costs of the NARF a penalty cost for each repairable item held by the NARF on any day. Our proxy measure of penalty cost per item per day is procurement cost of the item divided by expected service life, P_I. This measure tends to overstate the true costs because it ignores scrap value of the item. However, this is more than compensated for by its understatement of cost due to ignoring the time value of money. The particular penalty costs used are listed in McGarrahan [6].

6. Input three - Material. Because many small items of material and parts are consumed no attempt has been made to construct a quantity index of material. Instead, the dollar value of material consumed, M$,

is used as a proxy for this variable.

7. Price of input three. Since the quantity of material is measured in dollars the price of material is defined to be one. Over time periods long enough for inflation to be a problem an appropriate price index would be used for the price of material.

In addition to the definition of proxy variables, one further adjustment was required to use the available data from NARF NORIS to estimate production and cost functions. The available data consisted of observations on expenditures for each job with different jobs lasting varying lengths of time. On the other hand, the continuous program production functions describe the entire program over some given length of time. Thus, the data were aggregated in the following manner: For each job, the values of norm, man-hours, labor cost, material cost, overhead cost and penalty cost were prorated equally over the days for which that job was in the shop. Then, for each day in the period under consideration, the prorated values were totalled for all jobs which were in the shop on that day. The result of this aggregation is that for each day in the period under consideration, we have an estimate of the total number of man hours (L) used on that day, the total costs of labor (L$) for that day, the total cost of materials (M$) for that day, the total cost of overhead (O$) for that day, the total penalty cost (P$) incurred on that day, and the total hours of norm (N) produced on that day. In addition, the number of jobs in the shop (I) on each day was tabulated. All of the prorating and aggregating was done separately for the two programs--aircraft and engines. A computer program to perform this task is included in Spooner [1].

CORRELATION FOR RAW DATA - ENGINES

	NORM	DMHR	DLB$	DML$	DOH$	NIFR	NDAY
NORM	1.00000	0.94832	0.94945	0.67620	0.93864	-0.04526	0.47849
DMHR	0.94832	1.00000	0.99695	0.65128	0.99032	-0.10610	0.54876
DLB$	0.94945	0.99695	1.00000	0.65169	0.98909	-0.10374	0.54283
DML$	0.67620	0.65128	0.65169	1.00000	0.65288	0.54323	0.45987
DOH$	0.93864	0.99032	0.98909	0.65288	1.00000	-0.09700	0.55224
NIFR	-0.04526	-0.10610	-0.10374	0.54323	-0.09700	1.00000	0.04808
NDAY	0.47849	0.54876	0.54283	0.45987	0.55224	0.04808	1.00000

	MEAN	STD DEV
NORM	534.25	367.59
DMHR	534.12	376.91
DLB$	3230.61	2258.22
DML$	5764.03	5396.77
DOH$	4045.30	2911.78
NIFR	2515.00	1021.30
NDAY	33.06	10.61

Table III. Correlation Coefficients for Engine Raw Data

CORRELATION FOR RAW DATA - AIRCRAFT

	NORM	DMHR	DLB$	DML$	DOH$	NIFR	NDAY
NORM	1.00000	0.97123	0.96585	0.60199	0.95801	-0.32822	0.86055
DMHR	0.97123	1.00000	0.99633	0.62193	0.97562	-0.36636	0.87527
DLB$	0.96585	0.99633	1.00000	0.61766	0.96923	-0.36199	0.87298
DML$	0.60199	0.62193	0.61766	1.00000	0.61041	0.38659	0.57975
DOH$	0.95801	0.97562	0.96923	0.61041	1.00000	-0.32157	0.84932
NIFR	-0.32822	-0.36636	-0.36199	0.38659	-0.32157	1.00000	-0.29888
NDAY	0.86055	0.87527	0.87298	0.57975	0.84932	-0.29888	1.00000

	MEAN	STD DEV
NORM	8357.50	4043.53
DMHR	8558.26	4385.91
DLB$	52886.70	27281.99
DML$	21155.59	11208.13
DOH$	54912.00	27878.43
NIFR	1529.10	132.64
NDAY	83.58	34.39

Table IV. Correlation Coefficients for Aircraft Raw Data

These aggregated data were used as described in section 4 to estimate the parameters of the cost and production models.

B. PRELIMINARY DATA ANALYSIS

As a first step in determining the relationships among the raw data elements, the matrix of correlation coefficients was calculated for each program. These results for the engine and airframe programs are reported in Table III and IV, respectively.

It is perhaps important to note the relatively low correlation between direct material cost and any of the other variables in both programs. This is one possible indication of the fact that material costs are thought to be the least reliable of the data obtained. It is also interesting to note the relation of number of days in shop to the other variables. In the shorter engine program, these correlations are relatively low while they are significantly higher for the longer aircraft program.

In addition, the aggregated data was used to get a preliminary view of the flow of work over time at the NARF. Conversations with NARFNI personnel indicated that it was their opinion that induction rates were fairly constant, independent of time, while production rates were low at the beginning of a quarter and high at the end of a quarter. The average daily induction and production rates were computed, using a moving block average.

These rates were computed from both the aircraft and engine programs in terms of hours of norm arriving or leaving per day, actual man hours of work arriving or leaving per day, and actual physical units arriving or leaving per day. (Figure 6 and Figure 7). The results were not sensitive to changes in the size of the moving window in the range of seven

ENGINE INDUCTION AND PRODUCTION RATES

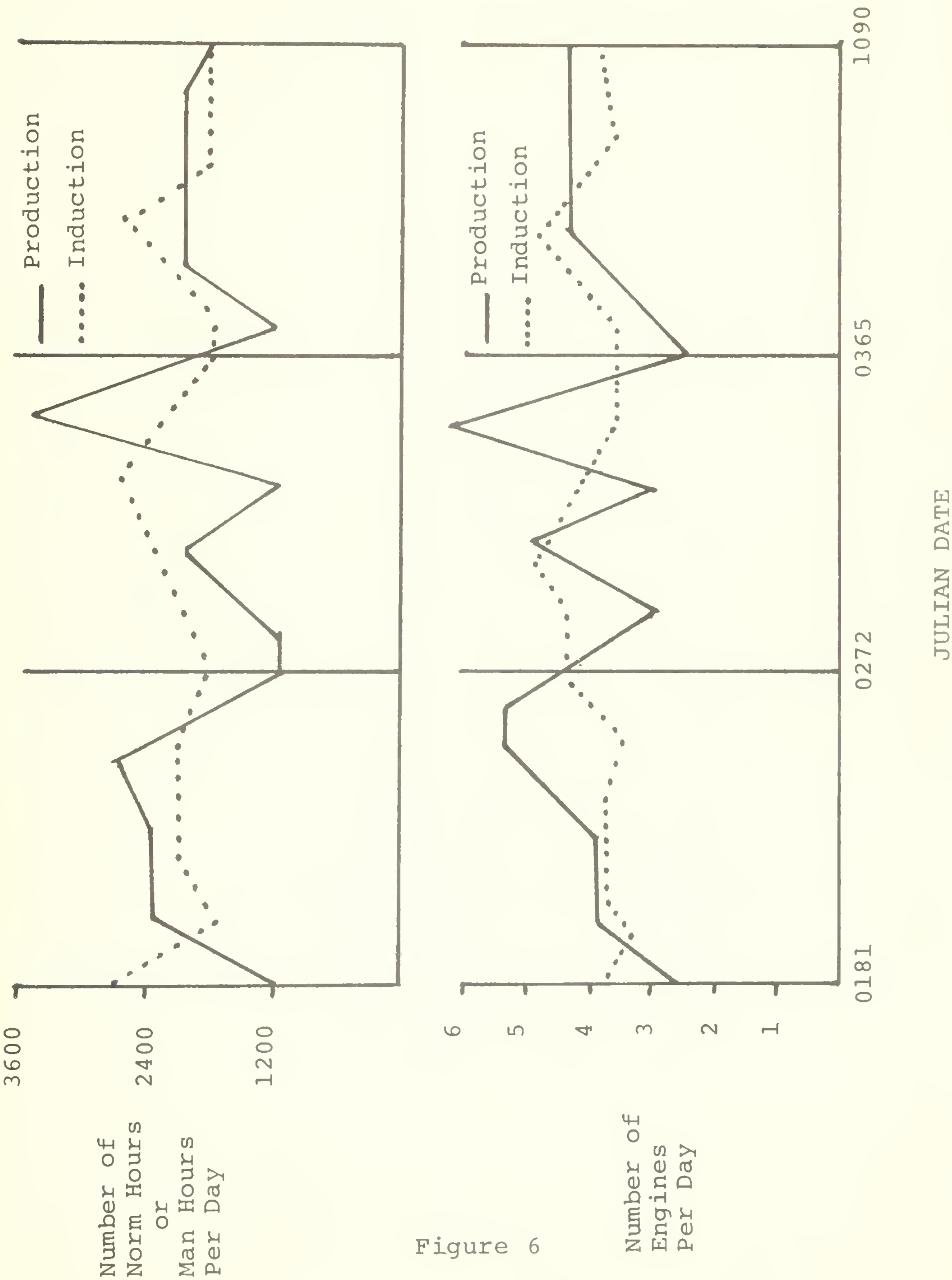

Figure 6

AIRCRAFT INDUCTION AND PRODUCTION RATES

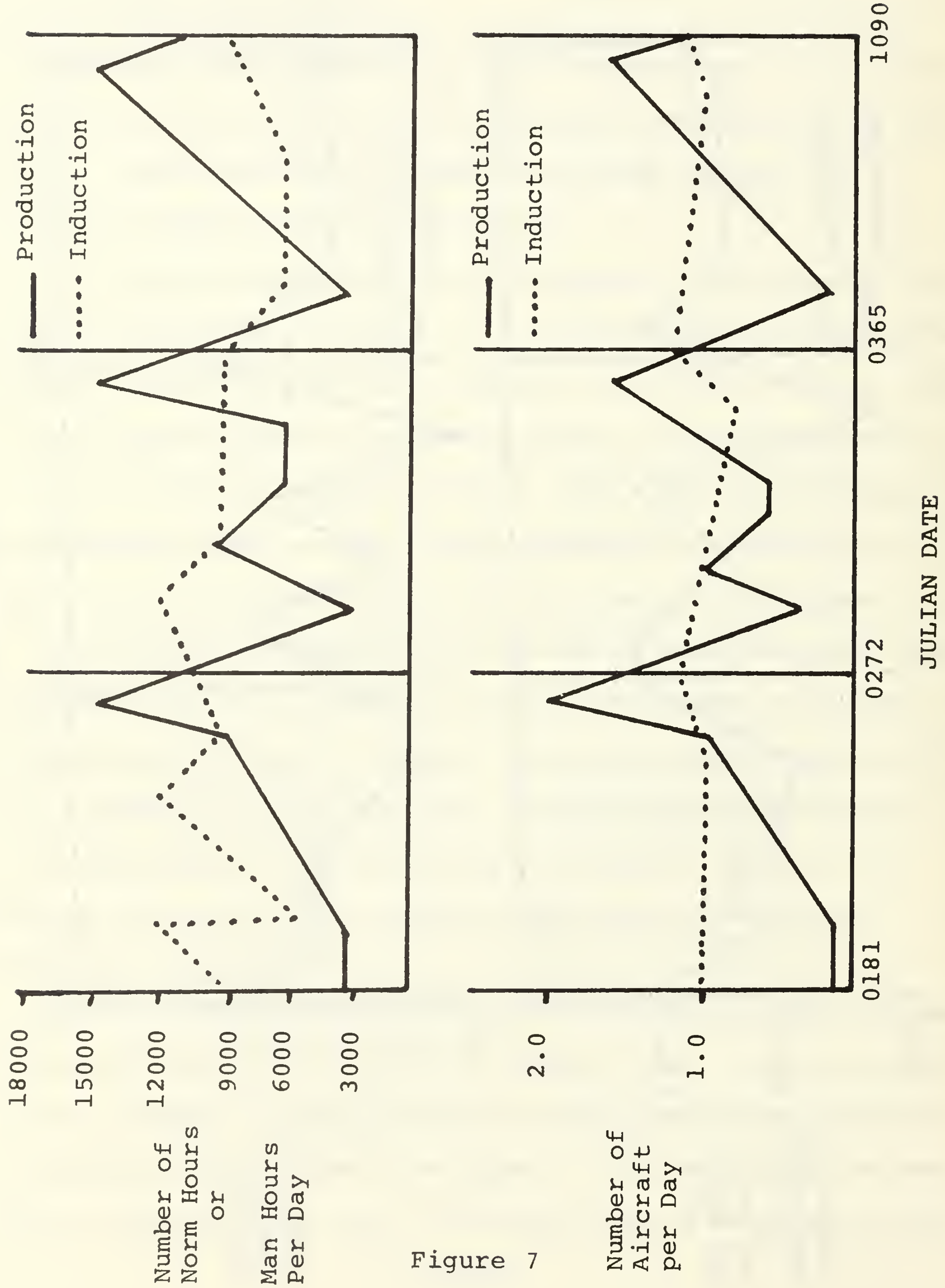

Figure 7

to twenty-one days. These plots tended to confirm NARFNI personnel in their beliefs about the production and induction rates over time. Production did increase toward the end of a quarter and did drop off sharply at the beginning of a quarter. The induction rate did have some variation over time, but it was about one-fifth as great as the variation of the production rate.

Number of jobs in shop versus time was plotted to confirm this relationship between induction rate and production rate. Number of jobs in shop should be increasing at the beginning of a quarter when production rate is less than induction rate and should be decreasing at the end of the quarter when production rate is greater than induction rate (Figure 8). This plot of jobs in shop versus time, with a maximum near mid-quarter, is consistent with the production rate and induction rate relationship described above.

The variable, number of jobs in shop (I), was considered to be descriptive of the production and induction rates and, incidentally, also descriptive of shop congestion. By using number of jobs in shop as an independent variable in the Cobb-Douglas production function, it was possible at once to describe efficiencies due to specialization of personnel, inefficiencies due to shop congestion, and work flow through NARFNI.

NUMBER OF JOBS IN SHOP

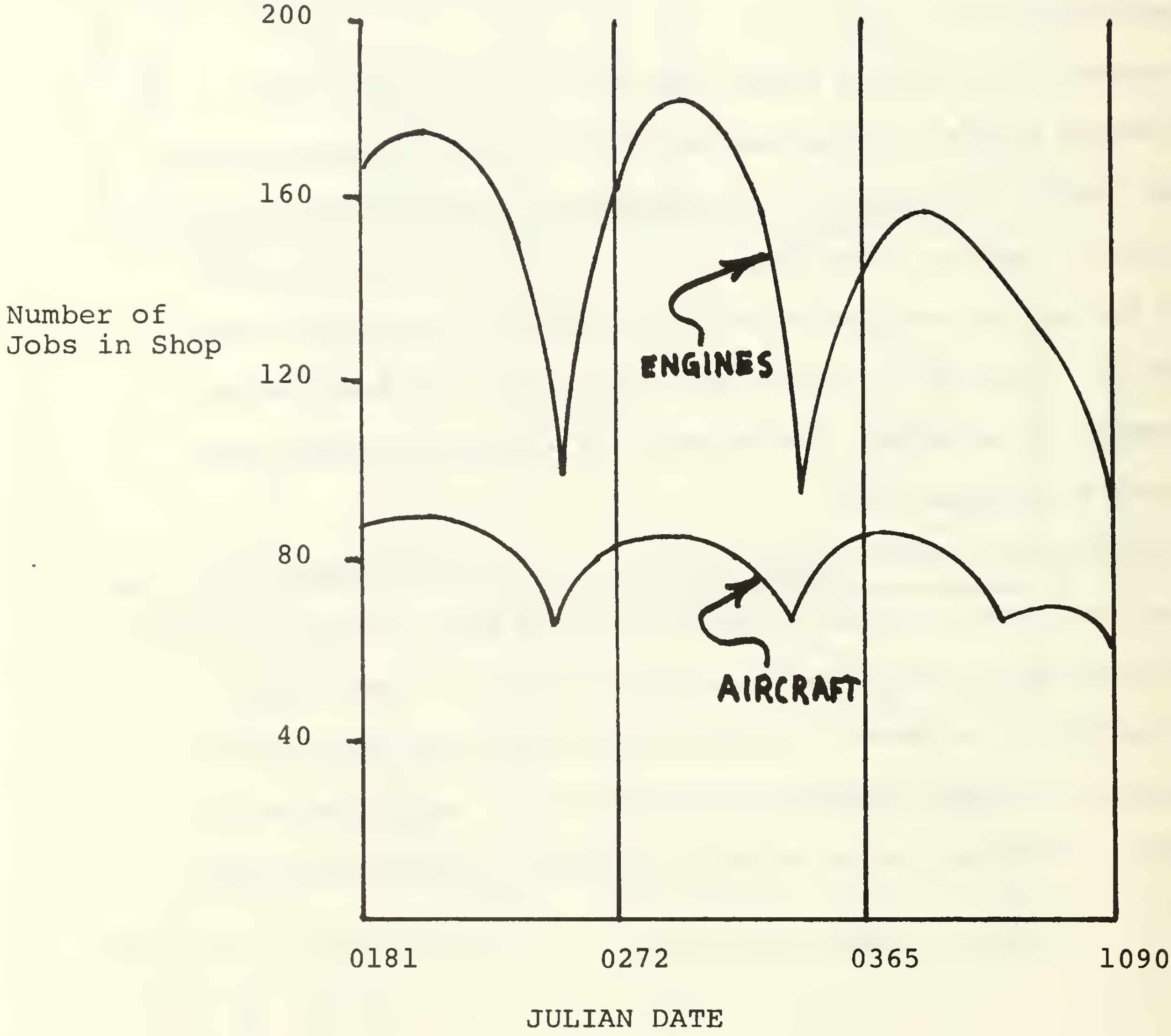

Figure 8

IV PROCEDURES FOR ESTIMATION OF MODEL PARAMETERS

A. THE LINEAR ECONOMIC MODEL

To formulate a linear economic model it is necessary to define a process. A process consists of a mathematical description of the amount of resources used (i.e. labor, material, etc.) to produce a unit amount of an output measure. The problem is how are the raw data observations used to estimate a process. The most natural way would be to estimate a process as an average amount of resources required to do a specific type of work on a certain engine or aircraft. This procedure may not be desirable because there may be alternate processes available to produce the same output. For example, to overhaul an F-8J it may be possible to use a "normal" amount of man-hours and have a low material cost. An alternate process may exist whereby the same work may be accomplished by spending <u>more</u> money on material and <u>reducing</u> the man-hours required. The essence of a linear economic model is, then, to identify these alternate processes and to use linear programming to select the most efficient processes to operate.

In an attempt to identify these alternate methods within the basic data observations a clustering algorithm was developed based on the Hierarchical Clustering Strategy of Lance and Williams [8]. The general procedure is to select a group of observations containing several different types of engines (or aircraft) and some different types of work within each engine group. These observations are then analyzed using the clustering algorithm for similarity of the vector of input/output measures. Vectors which are similar will use input resources in approximately the same fixed proportion for a unit output measure. Similar observations can then be averaged to yield a "process".

Several trial selections were made with both engine and aircraft data. The engine data was observed to cluster groups of the same engine type together with a high degree of consistency. For example, if 20 J-79 engines were selected as part of a trial run of 100 observations, a typical result would be for 17 or 18 of the original 20 to be clustered in the same group. However, the trial selection with the aircraft data were not nearly so consistent. The cluster analysis showed the aircraft data had wide variations among the input variables. The clusterings observed were highly irregular and contained a mixture of different aircraft and different work. Since the aircraft clusters which resulted from this preliminary analysis were not easily interpretable as "processes", it was necessary to do some preliminary classification before using the clustering algorithm. In particular, it seemed ridiculous to have processes which involved radically different job types even if they seemed to use resources in the same proportion, so a decision was made to form processes consisting of only similar engines (or similar aircraft) with identical types of work.

For the engine data, similar engine/work types were grouped together within each job order. The resulting raw data deck was then ordered by engine type, job type and calendar quarter in which the work was done (in special cases where a very few observations were available the engine/job types were not separated into calendar quarters). The average of the observations in each calendar quarter then provided an aggregated observation on each engine/work type worked on by the NARF during that quarter.

This observation was taken to be a potential process for that engine/ work type. At this point there were 47 different engine/work types and 103 processes by which the work could be done. A computer program was used to examine the dominance relationships among all processes with the <u>same</u> engine/work type. This computer program is described in Appendix G of Myers [2]. The dominance relationships among processes are very important in a linear program. For example, if process 1 and process 2 produce the same output but process 2 uses <u>more</u> of every required resource than process 1, then process 1 dominates process 2. In a linear program that minimizes costs, process 1 will always be selected as preferred to process 2. Therefore, if the linear programming model is to have alternate processes that reflect choices to be made then the dominance must be eliminated between all processes with the same output.

The dominance program was run with the 103 processes as previously determined based on job order numbers. The dominance relationship between each pair of processes that produced the same output was examined. If no dominance existed then that group of alternate processes was left alone. If dominance existed among any of the processes in the group then a subjective decision was made to combine two of the processes. For example, if there were five processes and dominance existed between three pairs of them, then two processes would be selected to be combined. The decision on which pair to combine was entirely subjective. The group would then have four alternate processes remaining. The dominance computer program would then be run again and the remaining alternate processes would be examined for dominance. This procedure was repeated until <u>all</u>

dominance was eliminated within process groups that had the same output (same engine/work type). Since the outputs were intended to be measured separately (as opposed to an aggregate output measure) it was not necessary to examine the dominance between processes of different outputs. The original 103 potential processes were aggregated down to 81 processes (on the 47 engine/work type) by this dominance removal procedure. The final 81 processes were used as input for the Linear Economic Model on engines described earlier.

The aircraft data consisted of 365 raw data observations. Considering each type of aircraft and type of work as a separate output meant that 70 outputs were required. This small amount of data then had to be used to estimate not less than 70 distinct processes. A decision was made to estimate only a single process for each output because of the limited data available. In this case there were no alternate processes so it was not necessary to check for dominance. The linear program in this case would not have a choice among processes and therefore the solution becomes trivial.

An important extension of this work would be to refine methods for identifying alternate processes in such small data bases. Computer programs for the data analyses described above can be found in appendices B - G of Myers [2]. The resulting linear programs for the engine and aircraft model will be compared to other models and across the Before WIPICS - After WIPICS period in Section VI.

B. THE CONTINUOUS PRODUCTION FUNCTION FOR A PROGRAM

Three alternative econometric models based on the two production functions detailed in section II are derived in this section. Each involves different specifications about how random variables enter the cost and production function and hence different assumptions concerning the behavior of decision makers at NARF North Island. Throughout this section the subscripts referring to the engine and airframe programs have been dropped. Each model is applied to both these programs.

Model one. The first and simplest of the three models assumes that the relation among inputs and output at the NARF is of the form of the Cobb-Douglas production function. Additionally, it is assumed that an unobservable error term enters the relation in a multiplicative fashion so that the production function itself is stochastic. Substituting the proxy variables and including e^{ε_i} as the random error yields:

$$N_i = A\, L_i^{\alpha}\, I_i^{\beta}\, M\$_i^{\gamma}\, e^{\varepsilon_i}$$

where i indicates the time period of the observation. Taking natural logarithms of both sides yields:

$$\ell n\ (N_i) = \ell n\ A + \alpha\ \ell n\ L_i + \beta\ \ell n\ I_i + \gamma\ \ell n\ M\$_i + \varepsilon_i$$

This equation is the econometric model associated with model one and is estimated by linear regression techniques. The results are reported in section V.

Model two. The second model also makes use of the Cobb-Douglas production function. Here, however the production function itself is assumed to hold with certainty. Random errors enter the model in the process of solving the cost minimization programming problem. Since the exact form of the production function is not known the planned quantities of inputs required to produce a given quantity of output may linearity of the C.E.S. cost function it is estimated in two stages instead of one. The first stage involves the choice of the relative quantities of the two inputs, labor and the number of items in shop. This choice is thought to be subject to a random error and is determined by:

$$\frac{L_i}{I_i} = \left[\frac{(1-\delta)P_{\ell i}}{\delta P_{Ii}}\right]^{-1/\rho+1} e^{\varepsilon_i}$$

Taking natural logarithms of both sides yields:

$$y_i = \beta_0 + \beta_1 X_{1i} + \varepsilon_i$$

where

$$y_i = \ell n\ (L_i/I_i) \qquad \beta_0 = \frac{-1}{\rho+1}\ \ell n\ \frac{1-\delta}{\delta}$$

$$\beta_1 = \frac{-1}{\rho+1} \qquad X_{1i} = \ell n(P_{\ell i}/P_{Ii})$$

This equation is the first stage of the econometric model associated with model three and is estimated by linear regression techniques.

Let the estimates derived for parameters in the first stage be b_0 and b_1 respectively so that $\hat{y}_i = b_0 + b_1 X_{1i}$ is a prediction of y_i. Also estimates of δ and ρ may be derived as:

$$\hat{\delta} = \frac{1}{e^{b_0/b_1} + 1}$$

and

$$\hat{\rho} = \frac{-1 - b_1}{b_1}$$

Finally $e^{\hat{y}_i} = e^{b_0 + b_1 X_i} = \left[\frac{\hat{L}_i}{I_i}\right]$ is a prediction of $\left[\frac{L_i}{I_i}\right]$. Substituting differ from those actually required. This leads to build ups or shortages in inventories of inputs and thus to random errors in the cost function. See Trafton [4, pp 19-20] and Dhrymes [9, pp. 232-234] for a complete derivation of this model.

Substituting the proxy variables and including the random error term yields:

$$C_i = A^* N_i^{1/\alpha+\beta+\gamma} \; P_\ell^{\alpha/\alpha+\beta+\gamma} \; P_{Ii}^{\beta/\alpha+\beta+\gamma} \; e^{\varepsilon_i}$$

where

$$C_i = L\$ + M\$_i + P\$$$

Taking natural logarithms of both sides yields:

$$\ell n\, C_i = \beta_0 + \beta_1 \,\ell n\, N_i + \beta_2 \,\ell n\, P_{\ell i} + \beta_3 \,\ell n\, P_{Ii} + \varepsilon_i$$

where

$$\beta_1 = 1/\alpha+\beta+\gamma \qquad \beta_0 = \ell n\, A^*$$

$$\beta_2 = \alpha/\alpha+\beta+\gamma$$

$$\beta_3 = \beta/\alpha+\beta+\gamma$$

This equation is the econometric model associated with model two and is estimated by linear regression techniques. The results are reported in section V.

Model three. Model three differs from the previous two models in two regards. It is based on the C.E.S. production function instead of the Cobb-Douglas function but it is also different in that material cost is no longer an input to the production process. Because of the non-these estimates into the C.E.S. cost function and supplying an error term yields:

$$C_i = \left(P_{Ii} + P_{\ell i}\left[\frac{\hat{L}_i}{I_i}\right]\right)\left[\frac{N_i}{\gamma}\right]^{\frac{1}{\sigma}}\left[1 - \frac{1}{e^{b_0/b_1} + 1} + \frac{1}{e^{b_0/b_1} + 1}\left[\frac{\hat{L}_i}{I_i}\right]^{\frac{1+b_1}{b_1}}\right]^{1/\rho} e^{\varepsilon_i'}$$

where

$$C_i = L\$_i + P\$.$$

This equation may be reexpressed as:

$$y_i' = \beta_0' + \beta_1' \ell n\, N_i + \beta_2' X_i + \varepsilon_i'$$

where

$$y_i' = \ell n(C_i) - \ell n\left\{P_{Ii} + P_{\ell i}\left[\frac{L_i}{I_i}\right]\right\}$$

$$\beta_0' = -\frac{1}{\sigma}\ell n\, \gamma \qquad \beta_1' = \frac{1}{\sigma}$$

$$\beta_2' = \frac{1}{\rho}$$

$$X_i = \ell n\left[\frac{e^{b_0/b_1} + \left[\frac{\hat{L}_i}{I_i}\right]^{\frac{1+b_1}{b_1}}}{e^{b_0/b_1} + 1}\right]$$

giving the second stage of the econometric model associated with model three and it is also estimated by linear regression. The results of model three are also reported below.

C. NONLINEAR PROGRAMMING FOR C.E.S. ESTIMATION

Because the two stage estimation procedure for the C.E.S. function described above produces parameter estimates whose properties are not known, it was considered desirable to investigate alternate estimation strategies. In particular, any least squares parameter estimation problem can be formulated as a nonlinear optimization problem. If the model is $y = f(X, \beta)$ with independent variables X, dependent variable y, and parameters β to be estimated, from the n observations (X_i, y_i) $i = 1, \ldots, n$, then the least squares solution is $\hat{\beta}$ which solves the NLP.

$$\min_{\hat{\beta}} \sum_{i=1}^{n} (y_i - f(X_i, \hat{\beta}))^2$$

If $f(X, \beta)$ is linear in β, then this is an unconstrained quadratic optimization for which standard regression produces a closed form solution. Otherwise, as in the case of the C.E.S. function, iterative nonlinear programming methods for gradually approaching the solution can be used.

Since the two stage estimation procedure sometimes yields parameters which have intuitively ridiculous signs, it may be desirable to also incorporate constraints (such as $\beta_j \geq 0$) into the nonlinear program. This approach to estimating C.E.S. cost function coefficients was investigated in some detail. The C.E.S. cost function involves the model

$$C = N^{1/\sigma} \gamma^{-1/\sigma} \left[(1 - \delta) + \delta \, (I/L)^{-\rho}\right]^{1/\rho} \left[PL + PI \, (I/L)\right] \varepsilon$$

where economic theory imposes the following restrictions on the parameters

$$\sigma \geq 0, \ \gamma \geq 0, \ \rho \geq -1, \ 0 \leq \delta \leq 1$$

By transforming the variables we can incorporate these constraints into the optimization problem. If we let $\sigma = z_1^2$, $\gamma = z_2^2$, $\rho = z_3^2-1$, $\delta = (\sin z_4)^2$ then for any value of the parameters z_i i=1, 2, 3, 4, the parameters σ, γ, ρ and δ will satisfy the above. Hence the least squares optimization problem can be formulated as the unconstrained minimization of a function of the four parameters z_1, z_2, z_3, z_4. This minimization problem was investigated for the before WIPICS aircraft program. 400 before WIPICS observations (Julian dates 0191 - 1225) were chosen as test data. Tye [5] reports the results of the two stage C.E.S. estimation procedure applied to the same data. The 400 observations were split into two subgroups consisting of the first 300 and last 100 observations so that the stability of the cost function could also be investigated. The unconstrained minimization of the least squares function was accomplished by the Conjugate Gradient method due to Fletcher and Reeves [10]. The minimizations were performed for 300, 100 and all 400 observations. In each case several different starting points were chosen including the parameter estimate from the 2-stage procedure, to test for unimodality of the least squares objective function. The results of this procedure were not promising and hence will not be reported here in detail. The following qualitative remarks will indicate some of the problems encountered:

1. Numerical difficulties were severe for the highly nonlinear C.E.S. cost function. Typical runs started with the least squares function value (sum of squared residuals) from 10^{15} to 10^{30}. Final values when the minimization terminated were on the order of 10^9. Gradient components were also frequently extremely large in magnitude. As a

result abnormal terminations due to numerical problems such as computer overflow or underflow were encountered even in double precision. Careful scaling of the variables was necessary to get any results at all.

2. The two stage C.E.S. estimates were not anywhere close to least squares solutions, having objectives in the range 10^{30}. When started at these estimates, the nonlinear programming procedure reduced the objective quickly to about 10^{9}.

3. The solutions obtained when the nonlinear minimization was started from different initial estimates had objective function values which were similar, but the parameter estimates obtained, displayed substantial variability. This indicates that there are many alternative parameter estimates all of which are approximately equivalent under the least squares criterion. We do not have other theoretical properties for these estimates (in particular their statistical properties are unknown) so the choice of which parameter estimates to use is not simple.

Due to these difficulties, it was decided not to pursue this line of investigation farther. The two estimation methods tried (2 stage, nonlinear programming) for the C.E.S. cost function gave substantially different results and neither has known properties. Thus, for the bulk of our work, the simpler Cobb-Douglas Production and Cost Functions will be used. The Cobb-Douglas functions are linear in the parameters and hence ordinary regression gives parameter estimates with known statistical properties.

D. THE CONTINUOUS COST FUNCTION FOR A JOB

The econometric model corresponding to the production model for a job is similiar to model two described above. However, to facilitate understanding of this model a complete deviation is presented here. Suppose the production function for a job of type i j is of the Cobb-Douglas form with four inputs, i.e.

$$W_{ijk} = A_{ij}\, L_{ijk}^{\alpha}\, T_{ijk}^{\beta}\, M\$_{ijk}^{\gamma}\, NIS_{ijk}^{\delta}$$

here W_{ijk} is a measure of repairs produced by completing job i, j, k, T_{ijk} is the length of time this job is in shop, and NIS_{ijk} is the average number of jobs in the shop while this job is being worked on. NIS_{ijk} is assumed not to be under the control of the NARF for any particular job and hence is not a decision variable in the following costs minimization. Also, suppose that the NARF attempts to minimize the cost of producing any given job so that its goal is to

$$\text{Min } C_{ijk} = C_{0ijk} + P_{\ell ijk}\, L_{ijk} + P_{Ii}\, T_{ijk} + M\$_{ijk}$$

$$\text{s.t. } W_{ijk} = A_{ij}\, L_{ijk}^{\alpha}\, T_{ijk}^{\beta}\, M\$_{ijk}^{\gamma}\, NIS_{ijk}^{\delta}$$

As in model two errors are expected in the attempt to perfectly meet this goal and this results in a stochastic cost function of the form

$$C_{ijk} - C_{0ijk} = A^{*}_{ij}\, W_{ijk}^{\frac{1}{\alpha+\beta+\gamma}}\, P_{\ell ijk}^{\frac{\alpha}{\alpha+\beta+\gamma}}\, P_{Ii}^{\frac{\beta}{\alpha+\beta+\gamma}}\, NIS_{ijk}^{\frac{\delta}{\alpha+\beta+\gamma}}\, e^{\varepsilon ijk}$$

Two alternative econometric models are formulated from the above equation. The first of these models is based on the assumption that output depends merely on the type of aircraft being repaired and the classification of repairs. Thus two par reworks on an F4-J would be assigned the same measure of output. Thus

$$W_{ijk} = W_{ij}^{*} \quad (K = 1, \ldots, n)$$

In this case, the variable W_{ij} is indistinguishable from the constant A_{ij}^{*} and also the variable P_{Ii} is unable to be distinguished from either of the others. Hence, all three variables must be combined into dummy variables that vary only with job description.

The first econometric model is based therefore on

$$C_{ijk} - C_{0ijk} = B_{ij} \, P_{\ell ijk}^{\frac{\alpha}{\alpha+\beta+\gamma}} \, NIS_{ijk}^{\frac{\delta}{\alpha+\beta+\gamma}} \, e^{\varepsilon ijk}$$

or taking natural logarithms and redefining variables

$$y_{ijk} = \ell n\ B_{ij} + \eta\ \ell n\ P_{\ell ijk} + \nu\ \ell n\ NIS_{ijk} + \varepsilon_{ijk}$$

where

$$y_{ijk} = \ell n\ (C_{ijk} - C_{0ijk})$$

$$B_{ij} = A_{ij}^{*} \, W_{ij}^{*\frac{1}{\alpha+\beta+\gamma}} \, P_{Ii}^{\frac{\beta}{\alpha+\beta+\gamma}}$$

$$\eta = \alpha/\alpha+\beta+\gamma$$

$$\nu = \delta/\alpha+\beta+\gamma$$

Another model formed from the above equation is due to a different measure of output. Here output is supposed to be proportinate to production load norm but the factor of proportionality depends on the job description thus

$$W_{ijk} = a_{ij} N_{ijk}$$

In this case also other variables must be combined with the constant term to form a viable model and the resulting form of the model is

$$y_{ijk} = \ell n\, D_{ij} + \delta_1\, \ell n(N_{ijk}) + \delta_2\, \ell n\, (P_{\ell ijk}) + \varepsilon_{ijk}$$

where

$$y_{ijk} = \ell n\, (C_{ijk} - C_{0ijk})$$

$$D_{ij} = A^{*}_{ijk}\, a_{ij}^{\frac{1}{\alpha+\beta+\gamma}}\, P_{Ii}^{\frac{\beta}{\alpha+\beta+\gamma}}$$

$$\delta_1 = 1/\alpha+\beta+\gamma$$

$$\delta_2 = \alpha/\alpha+\beta+\gamma$$

The results of some comparisons using this kind of cost function for a job are reported in section VI below. An alternate derivation of some similar models is given by McGarrahan [6].

V ESTIMATION AND TESTING OF THE CONTINUOUS MODELS

A. PROCEDURE

This section reports the results of applying regression analysis to estimate the coefficients of the three continous models described in Chapter IV.

1. Cobb-Douglas Production Function

$$\log N = \beta_0 + \beta_1 \log L + \beta_2 \log M\$ + \beta_3 \log I + \varepsilon$$

2. Cobb-Douglas Cost Function

$$\log C = \beta_0 + \beta_1 \log N + \beta_2 \log P_\ell + \beta_3 \log P_I + \varepsilon$$

where

$$C = \text{total cost} = L\$ + M\$ + P\$$$

$$P_\ell = \text{price of labor} = L\$/L$$

$$P_I = \text{penalty price of items in shop} = P\$/I$$

3. C.E.S. Cost Function

$$\ell n(L/I) = \beta_0 + \beta_1 \ell n \left(\frac{P_\ell}{P_I}\right) + \varepsilon$$

for stage one, and

$$\ell n\ C - \ell n \left\{P_I + P_\ell \left(\hat{\frac{L}{I}}\right)\right\} = \beta_0' + \beta_1' \ \ell n\ N + \beta_2' \ \ell n \left[\frac{e^{b_0/b_1} + \left(\hat{\frac{L}{I}}\right)^{-\frac{1-b_1}{b_1}}}{e^{b_0/b_1} + 1}\right] + \varepsilon$$

for stage 2.

Recall that for the C. E. S. cost function, total cost C does not include material cost. For each of these models the coefficients were estimated for several different sets of data both before and after WIPICS and for both the engine and aircraft programs.

First, a period of 400 days of data well before the installation of WIPICS was chosen. This data was split into two sections composed of the first 300 and last 100 days, and the models were fit to both parts to investigate the stability of the production and cost function coefficients. Since the 400 day period was well before the implementation of WIPICS, the results obtained should reveal some of the problems to look for in the estimation, that is, the expected variability due to factors other than WIPICS.

Second, data periods immediately prior to WIPICS and after installation and breakin of WIPICS were used to again estimate the coefficients. The resulting BW/AW models will be compared in section VI to see if WIPICS had an impact on the estimated costs of the aircraft and engine programs.

The results of these estimations and the stability tests will be reported in this section.

B. RESULTS FOR THE BEFORE WIPICS PERIOD

400 consecutive days of before WIPICS data covering the Julian dates 0191 - 1225 for aircraft and 0215 - 1250 for engines were split into the first 300 and last 100 observations using the regression procedures outlined in section IV, the three models were estimated for this data. The resulting coefficients are shown in tables V through X. The standard

COBB-DOUGLAS PRODUCTION FUNCTION - AIRCRAFT

	$\log N = \beta_0$	$+ \beta_1 \log L$	$+ \beta_2 \log M\$$	$+ \beta_3 \log I$	R^2	SE
First 300 observations	1.720	0.391 (0.046)	-0.244 (0.020)	0.894 (0.060)	0.920	0.010
Last 100 observations	-0.780	0.768 (0.064)	0.436 (0.056)	-0.114 (0.090)	0.995	0.003
All 400 observations	1.790	0.369 (0.040)	-0.229 (0.017)	0.872 (0.046)	0.941	0.010

TABLE V

COBB-DOUGLAS COST FUNCTION - AIRCRAFT

$$\log C = \beta_0 + \beta_1 \log N + \beta_2 \log P_\ell + \beta_3 \log P_I$$

	β_0	β_1	β_2	β_3	R^2	SE	$\hat{\rho}$
First 300 observations	0.853	0.747 (0.012)	1.847 (0.054)	0.149 (0.030)	0.960	0.017	0.924
Last 100 observations	-0.477	0.906 (0.009)	0.527 (0.118)	0.484 (0.021)	0.993	0.006	0.881
All 400 observations	0.314	0.767 (0.010)	1.822 (0.045)	0.206 (0.022)	0.961	0.016	0.936

TABLE VI

C.E.S. COST FUNCTION - AIRCRAFT

	β_0	β_1	β_2	R^2	SE
First 300 observations	2.175	0.870 (0.007)	-2.461 (0.182)	0.980	0.011
Last 100 observations	0.822	0.977 (0.006)	0.607 (.219)	0.997	0.004
All 400 observations	1.906	0.891 (0.007)	-1.908 (0.159)	0.979	0.012

TABLE VII

COBB-DOUGLAS PRODUCTION FUNCTION - ENGINES

$\log N = \beta_0 + \beta_1 \log L + \beta_2 \log M\$ + \beta_3 \log I$

	β_0	β_1	β_2	β_3	R^2	SE
First 300 observations	-0.647	1.098 (0.061)	0.123 (0.028)	-0.100 (0.031)	0.955	0.011
Last 100 observations	1.089	0.701 (0.042)	-0.171 (0.045)	0.323 (0.061)	0.936	0.009
All 400 observations	-0.227	0.855 (0.043)	0.135 (0.022)	0.058 (0.022)	0.935	0.013

TABLE VIII

COBB-DOUGLAS COST FUNCTION - ENGINES

	$\log C = \beta_0 +$	$\beta_1 \log N +$	$\beta_2 \log P_\ell +$	$\beta_3 \log P_I$	R^2	SE	$\hat{\rho}$
First 300 observations	3.046	0.877 (0.017)	0.401 (0.095)	0.032 (0.052)	0.907	0.035	0.952
Last 100 observations	3.156	1.006 (0.049)	-1.396 (0.203)	0.625 (0.126)	0.848	0.032	0.930
All 400 observations	1.465	0.894 (0.019)	0.390 (0.105)	0.429 (0.054)	0.850	0.044	0.965

TABLE IX

C.E.S. COST FUNCTION - ENGINES

	β_0	β_1	β_2	R^2	SE
First 300 observations	2.506	0.851 (0.025)	21.152 (6.113)	0.808	0.053
Last 100 observations	-5.416	1.178 (0.056)	55.511 (5.500)	0.857	0.043
All 400 observations	1.357	0.897 (0.026)	-0.135 (0.422	0.755	0.059

TABLE X

error of each estimated coefficient is shown in parentheses below the coefficient, R^2 is the fraction of the variance of the dependent variable explained by the regression equation, SE is the standard error of the dependent variable, and $\hat{\rho}$ is an estimate of the serial correlation of the random error terms in the model.

An intuitive examination shows that the coefficients do not look very similar between the 300 and 100 day data samples. A statistical measure of this difference can be obtained using a statistical technique known as the Chow test [11, pp 192-207]. Briefly, the Chow test is as follows:

Let

Q_1 = the sum of squared residuals from the regression on all 400 observations,

Q_2 = (the sum of squared residuals from the regression on the first 300 observations)

\+

(the sum of squared residuals from the regression on the last 100 observations),

$Q_3 = Q_1 - Q_2$

k = the number of coefficients estimated in each regression.

Then under the hypothesis that the coefficients are the same in all three regressions, the ratio

$$F = \frac{Q_3/k}{Q_2/(400-2K)}$$

is distributed as an F statistic with k and $400 - 2k$ degrees of freedom. If $F > F_{\varepsilon}(k, 400-2k)$, then reject the hypothesis of equality of the coefficients at the ε confidence level.

The Chow tests were performed on the Cobb-Douglas production and cost functions for both aircraft and engine programs. Details of the tests are given in Table XI. For all cases, the hypothesis that the coefficients were essentially the same for all 3 regressions was soundly rejected. This indicates that during the period considered, the coefficients of the regression models were not completely stable. Since the data on which these regressions are performed is aggregated time series data, it is wise to test for autocorrelation of the residuals. This was done for the Cobb-Douglas cost functions (since they are the models we will use the most), and in both the aircraft and engine programs the estimated serial correlation coefficients $(\hat{\rho})$ were extremely high. The standard first order autocorrelation correction [11, p 260] was made for this data and the regressions were repeated on the corrected data with the results shown in Tables XII and XIII.

Chow tests run on these corrected models still rejected the hypothesis that the three equations were statistically identical at the 95% level, but the computed F values were not nearly so large as for the uncorrected models.

C. USE OF COST FUNCTIONS AS PREDICTORS

A second approach to validation of these models involves assessing their value as predictors. This approach has been followed for the Cobb-Douglas and C.E.S. cost function models. For each of the cost function models, the data was again divided into the first 300 and the

CHOW TESTS

Reject = if $F > F\ (4,392) = 2.39$
(5%)

	aircraft	engine
Cobb-Douglas production function		
Q_1	.037	.065
Q_2	.032 + .001	.039 + .007
F	11.9	40.5
Cobb-Douglas cost function		
Q_1	.031	.143
Q_2	.024 + .001	.067 + .019
F	23.5	65.0

TABLE XI

COBB-DOUGLAS COST FUNCTION - AIRCRAFT
(corrected for autocorrelation)

	$\log C = \beta_0$	$+ \beta_1 \log N$	$+ \beta_2 \log P_\ell$	$+ \beta_3 \log P_I$	R^2	SE	$\hat{\rho}$
First 300 observations	-2.370	0.960 (0.011)	1.247 (0.123)	0.493 (0.020)	0.962	0.004	0.152
Last 100 observations	-0.252	0.907 (0.012)	0.435 (0.164)	0.474 (0.023)	0.985	0.002	o.130
All 400 observations	-1.750	0.939 (0.009)	1.072 (0.115)	0.475 (0.016)	0.966	0.003	0.159

TABLE XII

COBB-DOUGLAS COST FUNCTION - ENGINES
(corrected for autocorrelation)

$$\log C = \beta_0 + \beta_1 \log N + \beta_2 \log P_\ell + \beta_3 \log P_I$$

	β_0	β_1	β_2	β_3	R^2	SE	$\hat{\rho}$
First 300 observations	2.25	0.945 (0.015)	0.355 (0.262)	-0.089 (0.045)	0.931	0.008	-0.014
Last 100 observations	2.46	0.988 (0.029)	-0.850 (0.360)	-0.046 (0.082)	0.929	0.007	0.079
All 400 observations	3.20	0.950 (0.014)	0.211 (0.212)	-0.057 (0.040	0.926	0.008	0.071

TABLE XIII

last 100 observations. Cost functions were estimated by regression using the first 300 days data, and the resulting cost equations were used to predict the cost for each of the last 100 days of data. As a criterion for comparison, the mean squared error (MSE) was computed both for the first 300 days (upon which the cost equation is based) and for the last 100 days predicted values.

If e_i is the error of the predicted cost for the i^{th} observation a confidence interval can be empirically constructed by using the ratio of two standard errors of the function over the actual mean costs for the period. The result is a percent error in cost,

$$\% \text{ error} = \frac{2\sqrt{\sum e_i^2/n}}{\sum C_i/n} \times 100.$$

The % error approximates $\pm$ 2 standard deviations which accounts for about 90% of the mass in most probability distributions. Thus, there is approximately a 90% confidence that the predicted cost is within the percent error computed of the actual cost.

This procedure was performed on the cost functions estimated from the 300 day period, and then on the 100 day period with costs being predicted by the 300 day models. The Cobb-Douglas and C.E.S. cost functions were also compared to the "naive" models

$$C = \beta N$$

$$C = \alpha + \beta N$$

which predict cost based only on norm, to determine the improvement from using the cost function models. The results for the Cobb-Douglas cost function are given in Table XIV. The comparison indicates that the Cobb-Douglas Cost function does a substantially better job of both explaining and predicting total cost than the naive models for the aircraft program. For the engine program the differences among the three models are not so significant, and none of the models is a particularly good predictor of total cost.

For the C.E.S. cost function a similar comparison was made. Direct comparison between Cobb-Douglas and C.E.S. is not easy since the C.E.S. total cost does not include material cost while the Cobb-Douglas cost does. The results for the C.E.S. cost function are given in Table XV.

Again, the C.E.S. cost function is superior to the naive models for the aircraft program, but in the engine program this is not the case.

In summary, then, both the Cobb-Douglas and the C.E.S. cost functions do a good job of explaining and predicting total cost for the aircraft program. Neither Cobb-Douglas nor C.E.S. offers advantage over naive models for the engine program.

A similar procedure to that of the above discussion uses statistical methods outlined in Theil [12, pp 134-135] to construct prediction intervals. Let C' represent the estimated cost and accept the assumptions of the standard linear model. Then the following probability statement holds:

$$P(\ell n\, C_i' - H \le \ell n\, C_i \le \ell n\, C_i + H) = 1-\alpha$$

where

$$H = t_{\alpha/2}(SE)\sqrt{1 + V_0'\,(X'X)^{-1}V_0}$$

	aircraft	engines
Cobb-Douglas cost function		
first 300 days	$\pm$ 4.0%	$\pm$ 7.0%
last 100 days	$\pm$ 5.0%	$\pm$ 15.7%
$C = \beta \cdot N$		
first 300 days	$\pm$ 11.2%	$\pm$ 8.0%
last 100 days	$\pm$ 9.0%	$\pm$ 17.9%
$C = \alpha + \beta N$		
first 300 days	$\pm$ 11.1%	$\pm$ 7.3%
last 100 days	$\pm$ 8.4%	$\pm$ 18.0%

$2\sqrt{MSE}$ expressed as percent of actual cost.

TABLE XIV

	Aircraft	Engines
C.E.S. cost function		
first 300 days	± 2.3%	± 11.1%
last 100 days	± 3.1%	± 14.6%
$C = \beta N$		
first 300 days	± 4.8%	± 10.0%
last 100 days	± 7.2%	± 13.7%
$C = \alpha + \beta N$		
first 300 days	± 4.8%	± 9.4%
last 100 days	± 6.6%	± 14.7%

$2\sqrt{MSE}$ expressed as a percent of actual cost.

(Note total cost for this table does not include material cost.)

TABLE XV

X = matrix of independent variables used to construct the model

V_0= vector of independent variables used to predict $\ell n C_i$

$t_{\alpha/2}$ = t-statistic

This interval is in logarithms. The transformed interval in costs becomes non-symetric and non linear in the independent variable of V_0. Thus, it is more accurate to compare the extreme widths of the intervals than the mean values compared in subsection 1.

Prediction intervals were computed for the 100 day period using the 300 day models. Of the 100 prediction intervals resulting the minimum and maximum interval were transformed to dollars and then divided by the mean cost for the 100 day period to obtain a maximum and minimum width as a percentage of the average cost (parenthetical entries of Table XVI). Finally, the percentage of actual costs that fell outside their corresponding prediction interval is reported in the last column of Table XVI.

	Model	Max. Interval	Min. Interval	% Out-side Interval
Airframes	CD	6729 (8.5%)	5365 (6.8%)	4%
	CES	4480 (4.0%)	3347 (3.0%)	32%
Engines	CD	5375 (12.5%)	3783 (8.8%)	62%
	CES	6943 (20.5%)	4836 (14.3%)	29%

TABLE XVI Extreme Widths of 90% Prediction Intervals (in dollars)

The uneven prediction results between the cost functions may be indicative of the Chow Test's conclusion that the two periods of data, 300 vs. the following 100 days, are in fact different and a model of one period is a poor prediction of costs in another period. This possibility is important because the periods are not separated by a recognizable technological change. It reemphasizes the need to include the accuracy of the models in the final comparison of estimated costs.

D. ESTIMATED MODELS FOR THE BEFORE WIPICS - AFTER WIPICS COMPARISON

For the before WIPICS - after WIPICS comparison the decision was made to use only the Cobb-Douglas cost function corrected for autocorrelation. The primary reason for this, is that autocorrelation is clearly a problem for data of this type. Straightforward corrections for autocorrelation exist for linear regression models (such as the Cobb-Douglas cost function) but the effect of autocorrelation on non-linear models (such as the C.E.S. cost function) is not known.

For these regressions the time periods were chosen as close as possible to the technological change so the before and after situations would be as similar as possible except for the WIPICS system. The observations used are:

Aircraft	Number of Observations	Julian dates
Before WIPICS	400 observations	0316 to 1350
After WIPICS	90 observations	2090 to 2179
Engines		
Before WIPICS	400 observations	0247 to 1281
After WIPICS	160 observations	2158 to 2317

different periods are used for aircraft and engines since the average length of stay at the NARF is different for jobs in the two programs. The resulting Cobb-Douglas cost functions (corrected for autocorrelation) are presented in Tables XVII and XVIII. Comparison of these cost functions with each other and with other models will be the subject of section VI.

COBB-DOUGLAS COST FUNCTION - AIRCRAFT
(corrected for autocorrelation)

	$\ell nC = \beta_0$	$+ \beta_1 \ \ell n\ N$	$+ \beta_2 \ \ell n\ PL$	$+ \beta_3 \ \ell n\ PI$	R^2	SE	$\hat{\rho}$
Before WIPICS (0316 - 1350)	-.135	0.941 (0.008)	0.260 (0.132)	0.459 (0.014)	0.974	0.003	0.190
After WIPICS (2090 - 2179)	2.2[illegible]	0.907 (0.025)	-0.502 (0.346)	0.383 (0.032)	0.953	0.003	0.375

TABLE XVII

COBB-DOUGLAS COST FUNCTION - ENGINES
(corrected for autocorrelation)

	$\ell n\, C = \beta_0$	$+ \beta_1\, \ell n\, N$	$+ \beta_2\, \ell n\, PL$	$+ \beta_3\, \ell n\, PI$	R^2	SE	$\hat{\rho}$
Before WIPICS (0247-1281)	3.25	0.929 (0.013)	0.150 (0.200)	0.000	0.930	0.008	0.147
After WIPICS (2158-2317)	4.54	0.696 (0.030)	0.254 (0.161)	0.080 (0.098)	0.812	0.019	0.256

TABLE XVIII

VI COST COMPARISONS BEFORE AND AFTER WIPICS

A. PROCEDURE

The cost function models described in the previous sections of this report were used to compare costs on typical workloads for the before and after WIPICS situations. The results of these cost comparisons are reported in this section. For each cost equation the parameters were estimated twice, once using before WIPICS data and once using after WIPICS data. The resulting two cost functions will be called the Before WIPICS cost function and the After WIPICS cost function.

Applying the Before WIPICS cost function to a particular workload gives an estimate of what the cost of performing that work would have been if it had been done before WIPICS was installed. Similarly, using the After WIPICS cost function on the same workload gives an estimate of what the cost would have been if that work had been done after WIPICS was installed. The difference of these two cost estimates yields an indication of whether WIPICS was cost-saving for that particular workload. Any indicated cost savings can then be compared with WIPICS costs to see if WIPICS is cost-effective. Most of the results reported in this section will deal with the aircraft program since even though WIPICS has been in operation for some time, it has not been directly applied to the engine program. For the Cobb-Douglas cost functions, the engine program results will also be given as an indication of possible changes not due to WIPICS.

B. CONTINUOUS COST FUNCTIONS FOR A MAJOR PROGRAM (COBB-DOUGLAS)

The Before and After WIPICS Cobb-Douglas cost functions for both aircraft and engines, corrected for autocorrelation, were given in

	Before WIPICS Workload	After WIPICS Workload
Before WIPICS Cost Function	$226311.	$222440.
After WIPICS Cost Function	$241140.	$228302.
Difference BW - AW	$-14829.	$-5862.

TABLE XIX Cobb-Douglas Comparison of Average Daily Costs for Aircraft Program section V - D. The actual workloads for the NARF during the Before and the After WIPICS periods were used as representative workloads for the cost comparison. The results are given in tables XIX and XX. The costs indicated in the tables include estimated cost of labor, material, overhead, and penalty for time in rework. Since the Cobb-Douglas cost functions operate on prorated aggregated daily data, the cost estimates represent the average daily total cost for all jobs in the shop over the time period being used.

Positive values of differences indicate a cost savings while negative differences indicate that performing the same work After WIPICS would cost more than if it had been done Before WIPICS.

Detailed discussion of these results will be postponed to section VI - E, after the results from all the different cost functions are available.

C. LINEAR ECONOMIC MODEL COST FUNCTION

The linear economic model of section II - D was used to estimate Before WIPICS and After WIPICS costs for the aircraft program. 837 aircraft jobs were separated into three groups:

1. 414 jobs before WIPICS
2. 158 jobs in a buffer period
3. 265 jobs after WIPICS

The buffer period consisted largely of jobs started before and finished after WIPICS was initiated. That period included all jobs with induction dates between Julian dates 1181 and 1334 inclusive. These dates were arbitrarily chosen to allow for the long time period required for aircraft

	Before WIPICS Workload	After WIPICS Workload
Before WIPICS Cost Function	$55652.	$50586.
After WIPICS Cost Function	$54622.	$51037.
Difference BW - AW	$1030.	$-451.

TABLE XX Cobb-Douglas Comparison of Average Daily Costs for Engine Program processing plus the indeterminate period while WIPICS was being initially tested. The before and after groups were the same as those used to generate the regressions used in the job cost model.

The two groups were compared and aircraft-work categories common to both periods were selected for the cost comparison. The jobs in these 20 common categories were then selected, representing 70.4% (257/365) and 68.7% (182/265) of the original before and after WIPICS groups, respectively. In the interest of descriptive brevity, let

$\{B\}$ be the set of observations before WIPICS

$\{B_M\}$ be the subset of observations of $\{B\}$ in the 20 common categories

$\{A\}$ be the set of observations after WIPICS

$\{A_M\}$ be the subset of $\{A\}$ that matches the categories of $\{B_M\}$

Activity vectors and objective function coefficients were then estimated for both data sets $\{B_M\}$ and $\{A_M\}$ using the procedures developed by Myers [2]. The resulting linear economic models were formulated with three different objective functions.

1) Min: Total Cost = $[P^T T_2 + C^T T_3]\ Z$

2) Min: Operations Cost = $P^T T_2 Z$

3) Min: Penalty Cost = $C^T T_3 Z$

In order to compare the models, two test cases were run against both the before and after models. The test cases consisted of the actual jobs in $\{B_M\}$ and $\{A_M\}$ and the two price vectors associated with them. Activity and price vectors run against their own models simply provide actual cost determinations, but the runs against the opposite model represent

	Before WIPICS workload $\{B_M\}$	After WIPICS workload $\{A_M\}$
Before WIPICS model	46.192	40.799
After WIPICS model	51.498	45.565
Difference BW - AW	-5.306	-4.766

(millions of dollars)

TABLE XXI Linear Model Cost Comparison
Total Cost - Aircraft

predicted costs. The costs were calculated for each of the objective function versions and the results are listed in Tables XXI, XXII, XXIII. The costs in these tables are the estimated total costs of doing all the jobs in the workload in question. Figures are listed in millions of dollars. The upper right corner prediction of Table XXI, for example, is read, "If the jobs represented by $\{A_M\}$ had been accomplished during the before WIPICS period, it is predicted that the total cost would have been $40.799 million."

As the comparative results indicate, the after WIPICS period costs were estimated to be higher in each of the cost variations used. Comparison of entries in the T_2 matrices for before and after situations emphasized the increases in resources used per hour of NORM. In every process at least one coefficient was higher for the after WIPICS period, with many cases showing two and three increased coefficients. Any decreases were relatively smaller in magnitude than the increases. This model contains no inherent inflation compensation for the materials and overhead expenditures such as the DMHR price has.

Comparing the activity vectors before and after WIPICS highlighted another potential problem. The two vectors presented radically different levels of activity in many of the processes. Such differences could greatly magnify any deviation of the linear relation from the true relationship, which is more probably non-linear. The coefficients used in these linear models and the details of the $\{B_M\}$ and $\{A_M\}$ workloads can be found in McGarrahan [6].

	Before WIPICS workload $\{B_M\}$	After WIPICS workload $\{A_M\}$
Before WIPICS model	29.708	25.882
After WIPICS model	33.043	28.972
Difference BW - AW	-3.335	-3.090

(millions of dollars)

TABLE XXII Linear Model Cost Comparison

Operations Cost - Aircraft

	Before WIPICS workload $\{B_M\}$	After WIPICS workload $\{A_M\}$
Before WIPICS model	16.484	14.917
After WIPICS model	18.455	16.693
Difference BW - AW	-1.971	-1.776

(millions of dollars)

TABLE XXIII Linear Model Cost Comparison
Penalty Cost - Aircraft

D. CONTINUOUS COST FUNCTION FOR A JOB

The continuous cost function for a job was developed in section IV-D. Two versions of this cost function were estimated and compared using the same before and after WIPICS workloads $\{B\}$ and $\{A\}$ as in the linear model.

The two versions of the cost function used are:

1) $C = A_i \, P_L^{\beta_1} \, P_D^{\beta_2} \, \overline{NIS}^{\beta_3} \, N^{\beta_4}$

2) $C = A_i \, P_L^{\beta_1} \, T^{\beta_2} \, \overline{NIS}^{\beta_3} \, N^{\beta_4}$

where $\overline{NIS}$ is the average number of jobs in the shop over the time period when this job was in the shop. T is the length of time this job stayed in the shop, P_D is production date, and all other variables are as previously defined.

A total of ten relationships were estimated from the data in $\{B\}$ and $\{A\}$. These represented before and after WIPICS characterizations of the following:

1. Version 1
   a. Total Cost
   b. Operations Cost
   c. Penalty Cost
2. Version 2
   a. Total Cost
   b. Operations Cost

The estimation was done only for the aircraft program. Details of the estimated coefficients and statistical properties of these models can be found in McGarrahan [6]. The resulting cost functions were then applied to the jobs in data sets $\{B_M\}$ and $\{A_M\}$ (recall these contain job categories which are present both before and after WIPICS) to obtain cost comparisons. The resulting comparisons are given in Tables XXIV through XXVIII. Figures in the tables are estimated total cost to perform all the jobs in the given workload. Costs are in millions of dollars. Positive differences indicate predicted cost savings after WIPICS, negative differences indicate predicted cost increases after WIPICS.

The results do not seem to indicate consistent superiority of one cost function over the other. Further discussion of these results will be included in the next section.

	Before WIPICS Workload $\{B_M\}$	After WIPICS Workload $\{A_M\}$
Before WIPICS cost function	44.91	43.72
After WIPICS cost function	41.25	43.66
Difference BW - AW	3.66	0.06

(millions of dollars)

TABLE XXIV Job Cost Comparison - Version 1 - Total Cost

	Before WIPICS Workload $\{B_M\}$	After WIPICS Workload $\{A_M\}$
Before WIPICS cost function	28.95	27.81
After WIPICS cost function	23.68	28.17
Difference BW - AW	5.27	-0.36

(millions of dollars)

TABLE XXV Job Cost Comparison - Version 1 - Operations Cost

	Before WIPICS Workload $\{B_M\}$	After WIPICS Workload $\{A_M\}$
Before WIPICS cost function	15.87	15.49
After WIPICS cost function	24.55	15.22
Difference BW - AW	-8.68	0.27

(millions of dollars)

TABLE XXVI Job Cost Comparison - Version 1 - Penalty Cost

	Before WIPICS Workload $\{B_M\}$	After WIPICS Workload $\{A_M\}$
Before WIPICS cost function	46.13	45.97
After WIPICS cost function	50.62	44.12
Difference BW - AW	-4.49	1.85

(millions of dollars)

TABLE XXVII Job Cost Comparison - Version 2 - Total Cost

	Before WIPICS workload $\{B_M\}$	After WIPICS workload $\{A_M\}$
Before WIPICS Cost Function	29.59	28.98
After WIPICS Cost Function	34.87	27.82
Difference BW - AW	-5.28	1.16

(millions of dollars)

TABLE XXVIII Job Cost Comparison - Version 2 - Operations Cost

E. SUMMARY OF COST COMPARISONS

The cost difference for the various cost functions are brought together in Table XXIX. The differences reported are all predicted cost from before WIPICS cost function minus predicted cost from after WIPICS cost function. For the Cobb-Douglas models the differences are expressed as dollars per day while for the other linear and job models the differences are in millions of dollars for completing the workload. Positive values indicate cost savings negative values indicate cost increases.

AIRCRAFT COST DIFFERENTIAL COMPARISONS

Cost Function	Cost Construction	Difference of predicted costs for Before WIPICS workload	Difference of predicted costs for After WIPICS workload
Linear	Total Cost	-5.31	-4.77
	Operations Cost	-3.34	-3.09
	Penalty Cost	-1.97	-1.78
Job, Version 1	Total Cost	+3.66	+0.06
	Operations Cost	+5.27	-0.36
	Penalty Cost	-8.68	+0.27
Job, Version 2	Total Cost	-4.49	+1.85
	Operations Cost	-5.28	+1.16
Cobb-Douglas	Total Cost	-$14829./ day	-$5862./ day

TABLE XXIX

VII. SUMMARY AND CONCLUSIONS

This report has explored several alternative approaches to the problem of auditing technological change. Three distinct types of models have been documented and several versions of some types have been examined in detail and applied to the problem.

The linear economic model is the most detailed of the model types. It permits different relations between costs, inputs, and output for each different job description. This model type has several drawbacks however. Estimation procedures for the model are not well developed and the statistical properties of the estimators are unknown. The model requires large quantities of data. It also requires the restrictions of constant returns to scale and independence of production processes; two assumptions which are unlikely to hold in any given application.

The second model type is based on a continuous production function for a program. The model uses data that is aggregated over jobs and is therefore not affected by the fact that individual jobs may not be independent of one another. One of the models, based on the Cobb-Douglas production function, is able to be straightforwardly estimated by statistics with well known properties in the absence of perverse circumstances. This model also has the advantage of not imposing a requirement of constant returns to scale. On the other hand the model is not as sensitive to changes in workload as the others. It also relies heavily on production load norm as a measure of output, at best a relatively imprecise measure. The advantages of using aggregated data in the model are balanced by the fact that the aggregated data set tends to be autocorrelated. Thus a special, though not unusual, correction must be applied in using the model.

The models based on a continuous production function for a job combine some of the characteristics of the previous models. These models are able to account for changes in the mix of jobs without imposing the restriction of constant return to scale. They also permit estimation by statistics with well known properties. The models do not use aggregated data and therefore present no problem of autocorrelation. However, these models do suffer from the fact that each job is assumed to be independent of any other and as a result errors are introduced when this assumption is violated.

Several versions of each of the model types were applied to data supplied by NARFNI for periods of time both before and after the introduction of the WIPICS system. The results of the application are reported in Chapter VI and briefly summarized in Table XXIX.

The results in Table XXIX apply only to the aircraft program because the WIPICS system, while operating, had not been applied to the engine program at the time data was collected, March 1973.

Even a brief glance at Table XXIX indicates that the results are not conclusive. Only the two versions of the last model type indicate cost savings for the WIPICS system in excess of the direct costs of the system and even here there is significant disagreement when applied to the before WIPICS workload. The other model types indicate that the costs of the system exceed the cost savings generated by it.

Several general conclusions may be drawn from the study. Obviously, the evidence that now exists is insufficient to conclude that the WIPICS system is cost effective at this time. The results of the various regression analyses are too contradictory to warrant such a conclusion. This result compares quite favorably with other evidence which indicates that the system at this time had not been fully implemented on the airframe program. In addition it must be emphasized that a system like WIPICS, if it is to be useful and to generate cost savings, must be faithfully used by a large number of people in many different shops throughout the NARF. Discussions with the management of the NARF seem to indicate that during the time period involved many people were not sufficiently knowledgeable to use the system effectively. As a result, the accuracy of the data in the system was suspect and the usefulness of the system questionable. These conclusions are drawn primarily from information provided by the Naval Area Audit Service.

The lack of agreement among the various models used illustrates the effect of different underlying assumptions and differing model characteristics. There is no objective way to choose among these alternative models. However, the continuous models do present statistics which enable one to construct confidence intervals and test hypotheses about the importance of variables. Thus there is some tendency to find the results of these models more believable than the results of the linear economic model. Even among the continuous models there is disagreement however. The problems here stem mainly from the fact that the data are inherently variable. The continuous cost functions which were estimated while explaining large proportions of the variations in costs are still accurate to within only 5 to 10 percent of total costs. Differences among the alternative regression analyses are well within these bounds. This emphasizes the fact that no definitive conclusions concerning the cost effectiveness of the WIPICS system on the airframe program may be drawn at this time.

The possible sources of this unexplained variation in total costs are numerous. Some of them are discussed briefly below.

Measurement of the variables. As discussed in Chapter Three, the various regression analyses use several proxy variables to measure prices, inputs and outputs of the production activity at the NARF. This use of proxy variables to measure desired variables will of course inject unknown errors into the analyses. In particular the treatment of material cost as a quantity, thus ignoring price increases for material may have been an important source of such errors. This particular source of error was to some extent adjusted for by including the production date as a variable in version one of the job cost model.

Collection of the data. Two particular types of data collection problems are possible sources of unexplained variation. One problem arises from the fact that in some instances production load norm is renegotiated after a particular repair job is begun. While the renegotiated norm may be more representative of the actual work to be done it seems likely that the series of norms some renegotiated and some not, bear a random relationship to work accomplished. No attempt was made to isolate those jobs with renegotiated production load norms for special analysis; this may be a source of unexplained variations.

Another data collection problem concerns the allocation of material cost to jobs and impacts on the assumption that different jobs in the NARF are independent of one another. In some cases "job a" needs a part which is not available. To expedite the aircraft a used part from "job b" is placed on "job a" and a new part ordered for "job b". By this process "job a" is completed earlier than it would have been and "job b", which has many additional operations to be performed on it, is completed no later than it would have been. The problem, from the point of view of data collection, is which job gets charged for the new part. Unfortunately, the answer to this question is not uniform. In some cases the job which needed the part "job a" is charged for the new part in other cases the job which actually received the new part "job b" is charged. This problem impacts on man hour data as well. Here the question is which job should be charged the labor cost of removing the used part from "job b" and of replacing it with the new part.

The existence of backrobbing tends to argue that jobs in the shop are not independent of one another. Although backrobbing may be too infrequent to incorporate into the model explicitly, it remains a source of unexplained variation.

Assumptions and form of the relations. Any attempt to describe the behavior of a complex organization with a relatively simple relation involving only a few variables is bound to be subject to some error. The relations estimated in this report are, of course, not exceptions to this general rule and thus some unexplained variation in the data is to be expected. While it is not desirable to complicate the relations to the point of explaining every detail of the operations there are several influences on production costs which may require explicit treatment. The effects of changes in retirement policy, the impositions of personnel ceilings, and various admonitions and constraints placed on the NARF have been ignored in the cost functions which have been estimated. These omissions as well as others are also sources of unexplained variation in costs in the analyses.

Despite the fact that there are many factors left out of the regression equations, the fact that variables were measured subject to error and the fact that proxy variables were used; each of the continuous cost functions derived above explain over ninety percent of variation in total costs of production in the aircraft and engine programs at the NARF. Also, while there are differences in the prediction of total costs of production among the various continuous models an analysis of each requires the conclusion that the net cost savings of the WIPICS system at this point in time are not significantly different from the usual random variations in costs experienced at the NARF. This conclusion agrees with other observations on the system provided by independent sources.

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A methodology is developed for auditing cost effectiveness analyses of major technological changes. The methodology is applied to the Work In Process Inventory Control System (WIPICS) recently implemented at NARF, North Island. The approach involves using data on NARF operations to estimate cost functions for each major program of the NARF both before and after the change. Cost comparisons using these models do not show a clear cost savings for the WIPICS system.

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