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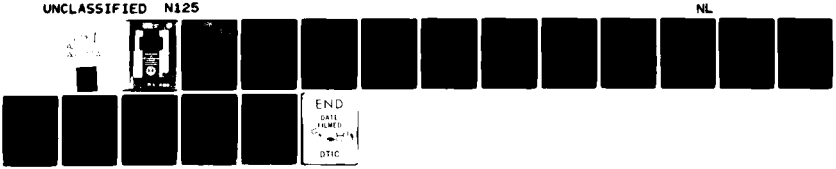

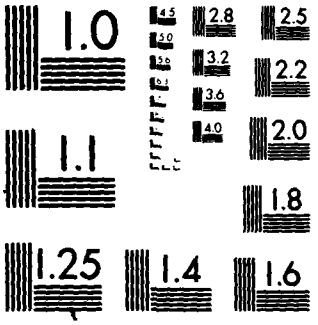

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A COST FUNCTION FOR AN AIRFRAME PRODUCTION PROGRAM

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Abstract

This research represents the expansion of previous work in the area of estimating program cost in military airframe production. The effort is unique in that it yields a model of the production process that considers the impact of learning and production rate on total program costs. To provide an empirical test of model validity the parameters are estimated for the C141 airframe program. The empirical work is instructive in that it shows how particular care must be taken in formulating models of this type. Because of data and policy considerations, each airframe program represents a unique empirical modeling opportunity. That is, data is very often not compiled by airframe per unit time. In fact, for most programs data is compiled for "lots" of airframes over varying time intervals. Batches of airframes are defined to be a quantity of airframes marked for delivery in a one month period. Previous research [14] has indicated that any time series model for predicting program costs that does not consider the special characteristics of the data can lead to serious errors in estimation and can result in bad decisions.

In this paper we make use of these data lessons in estimating the parameters of a model firmly grounded in economic theory. This model should be particularly useful as a prototype for models of on going production programs. In particular, it can be used to estimate the cost impact of exogenous changes in the program delivery schedule, the "crashes" and "stretch-outs" that frequently characterize military aircraft programs.

Introduction

The history of cost estimation in the military airframe industry is one of continuous cost overruns. Congressional concern and the need for better planning capabilities provide the impetus for new research in this area. The approach favored by the military at present is one of estimating parametric cost models. These parametric cost models explain cost as a function of only a few aircraft design characteristics. These models often yield useful planning estimates, but Large and Gillespie show that the models may produce estimates that can be off by as much as 100% [6]. However, the real limitation of these models is their inability to consider production policy changes, which may occur prior to or during the life of program. To improve upon these techniques, new models must be developed that demonstrate a better understanding of the factors and forces that determine cost.

In contrast to the parametric cost estimating approach, this research is more involved with modeling the factors that influence cost during the life of an airframe program, in particular the influence of production rate, learning, and delivery schedules on unit cost. A modeling effort with this stated purpose requires

considerable knowledge of both the planning and production stages in any airframe program.

Before production, a tentative production schedule is developed to help in labor force planning, tooling, facility needs, the ordering of long lead time items, etc. This early period of time is called the planning stage. This tentative production schedule is designed to cover the life of the project, but the formal agreement between the government and the contractor usually covers just one year. The reason is that annual congressional funding, changing national needs, or other exogenous impacts are continually varying throughout the life of the program. This period of changing situations is called the production period. The essence of this research is its ability to capture the relationship between total program cost and both endogenous and exogenous production rate changes during this program period. There is now general agreement that both learning and production rate changes impact total program costs. In the former case, it is usually assumed that production costs fall with cumulative production experience. In the latter, the direction and magnitude of the impact on total cost is less certain. Empirical studies have shown that changes in production rate may be associated with increases, decreases, and no change in total program costs.

Historical Perspective

Traditional neoclassical economic theory explores the relationship between cost and output rate. With the introduction of Wright's seminal work [17] a new dimension was added to the empirical study of cost. Wright's paper represents the foundation for many of the progress function studies that are prevelant in the engineering literature. These early engineering cost studies seemed to present a contradiction to conventional economic theory. In most of these studies, cost was explained only as a function of cumulative output. Recent research by Large shows that in many cases output rate is statistically insignificant for cost prediction purposes [7]. There is a remarkable shortage of literature that recognizes the problem or attempts to link the traditional economic approach with the industrial engineering approach. Early researchers such as Asher [3], Alchian [2, 3], Preston & Keachie [10], Oi [8], and Hirshleifer [5] considered the problem in a loose heuristical fashion, but their results, in general, lacked rigor. Rosen [11] represented the first attempt to solve the problem directly. His work included the theoretical specification of a market structure, the statement of a criterion function, and a straightforward recursive solution to the problem. Although this work is quite noteworthy, it stops short of functional forms sufficiently precise for empirical estimation.

The first real applications oriented integration of the economic and engineering approaches came with the work of Washburn [12] and Lamer [13; 14; 15; 16]. The present research effort represents the refinement of a more general model [15] for military airframes, so that it may be used to explain the production and cost behavior of a particular airframe project.

The C141 Program

The Data.

The C141 program produced 284 aircraft during the six year period from 1962 to 1968. Only one model of the aircraft was produced.

Data for this study is drawn from two sources. Orsini [9, 98-102] reports direct man-hours per quarter for each of the twelve lots in the C141 program. He also reports a delivery schedule for the aircraft by month [9, 96]. Orsini attributes these data to the C141 Financial Management Reports maintained by the Air Force Plant Representative Office located at the Lockheed-Georgia facility. The schedule of actual aircraft acceptances by month as reported in the OASD (PA&E) publication Acceptance Rates and Tooling Capacity for Selected Military Aircraft [4] was used to check the Orsini delivery data.

This data, like much data on aircraft production, provides labor hours for a period of time (quarterly) and dates and quantities of deliveries. Unfortunately, there is no available information which relates output to the period of time over which labor hours are observed.

One approach to this problem, used by Orsini, is to make some assumption about the pace of production on the program and aggregate the quarterly data across lots. In addition to being arbitrary, this approach reduces 91 potential observations to 24.

Our approach to the data problem is to construct a detailed production model of the aircraft to be delivered in any month. We then aggregate the model to explain the data rather than the other way around.

Preliminary analysis of the data revealed two additional data problems. First, there were two instances, late in the program, where a small number of labor hours were expended on a lot of aircraft after the schedule indicated delivery. This probably is a situation where deliveries were made out of sequence. To remedy this problem the labor hours for the last quarter of lots 9 and 10 were aggregated with those of the previous quarter. This reduced the number of observations by two.

Another problem is that in lots two through eight, delivery of the aircraft seems to lag the last expenditure of labor hours by an average of four months. For the other five lots labor hours are expended up to the last month of delivery. To overcome this problem, the deliveries of aircraft in lots two through eight were advanced by four months.

With these adjustments eighty-nine observations on labor hours for twenty-four quarters by twelve lots were used. These observations together with the number of aircraft delivered each month constitutes the data for the study.

The Model

The model augments a homogeneous production function with a learning hypothesis. The discounted cost of production is minimized subject to the production function constraint and the optimal time path of resource use is derived. Cost is measured in the units of the variable resource. The variables used in the analysis are:

i = an index for a batch of airframes in the same lot (j) all of which are to be delivered at time t_{ij}.

D_{ij} = the number of airframes in batch i of lot j.

E_{ij} = a measure of experience prior to beginning batch i, the cumulative number of airframes to be delivered.

$$\text{i.e., } E_{ij} = \sum_{k=1}^{j-1} \sum_{h} D_{hk} + \sum_{h=1}^{i-1} D_{hj}$$

t_j = date work begins for all the batches of lot j.

$q_{ij}(t)$ = production rate at time t on batch i.

$Q_{ij}(t)$ = cumulative production on batch i at time t,

$$\text{i.e., } \int_{t_j}^{t} q_{ij}(\tau)\, d\tau$$

$x_{ij}(t)$ = rate of resource use at time t on batch i.

δ = a parameter describing learning prior to batch i.

ε = a parameter describing learning on batch i.

γ = a parameter describing returns to the variable resources.

α = a parameter associated with decreases in labor productivity as a batch of airplanes nears completion.

ρ = the discount rate

c = discounted variable program costs

The production function is assumed to be of the following form

$$q_{ij}(t) = A\, E_{ij}^{\delta} Q_{ij}^{\varepsilon}(t)\, x_{ij}^{1/\gamma}(t)(t_{ij}-t)^{\alpha} \qquad (1)$$

where A is a constant. The input x is assumed to be a composite of many inputs whose use rate is variable throughout the production period. The output rate for any batch is related to the rate of resource use, cumulative output previous to batch i, and cumulative experience during the production of a given batch. The additional factor, $t_{ij}-t$, is included to compensate for changes in productivity due to the approaching of batch delivery date. This reflects the gradually changing tasks from part manufacturing, fabrication, assembly to testing during the production process.

This production function is assumed to be homogeneous of degree $1/\gamma$ in the resources with $\gamma > 1$. Also, it is assumed that the technological change induced by experience is Hicks neutral. This avoids having to state a different learning hypothesis for each of the variable resources.

Although the objective of the firm is a function of the wording of the contract, one goal of most contracts is to induce the firm to minimize discounted cost. The problem may be stated as:

$$\text{Min } C = \sum_{j=1}^{m} \sum_{i=1}^{m} \int_{t_j}^{t_{ij}} x_{ij}(t) e^{-\rho t} dt \tag{2}$$

$$\text{ST: } q_{ij}(t) = A E_{ij}^{\delta} Q_{ij}^{\varepsilon}(t) x_{ij}^{1/\gamma}(t)(t_{ij}-t)^{\gamma} \qquad \begin{array}{l} i = 1, 2, \ldots m \\ j = 1, 2, \ldots m \end{array}$$

$$Q_{ij}(t_{ij}) = D_{ij} \qquad \begin{array}{l} i = 1, 2, \ldots, n \\ j = 1, 2, \ldots, m \end{array}$$

$$Q_{ij}(t_j) = 0$$

Since total cost is monotone nondecreasing and the sub-problems are additive, the solution can be obtained by minimizing each of the sub problems. The problem may then be stated as:

$$\text{Min } C' = \int_{t_j}^{t_{ij}} x_{ij}(t) e^{-\rho t} dt$$

$$\text{ST: } q_{ij}(t) = A E_{ij}^{\delta} Q_{ij}^{\varepsilon}(t) x_{ij}^{1/\gamma}(t)(t_{ij}-t)^{\alpha} \tag{3}$$

$$Q_{ij}(t_{ij}) = D_{ij}$$

$$Q_i(t_j) = 0$$

This problem is an optimal control problem which may be solved directly by minimizing the Hamiltonian function. However, the problem can easily be transformed into the problem of Lagrange, which can be solved using classical variational techniques. At this point the redundant ij subscripts are dropped at the insistence of our typist.

Solving the constraint for x(t) yields

$$x(t) = q^{\gamma}(t) A^{-\gamma} E^{-\gamma\delta} Q^{-\gamma\varepsilon}(t)(t_{ij}-t)^{-\alpha\gamma} \tag{4}$$

We desire a transformation yielding one state variable and one control variable, the control variable being the time rate of change of the state variable. Let

$$Z(t) = A^{-1} E^{-\delta} Q^{1-\varepsilon}(t)/(1-\varepsilon) \tag{5}$$

This implies that

$$z(t) = A^{-1} E^{\delta} Q^{-\varepsilon}(t) q(t) \tag{6}$$

$Z(t)$ will be the new state variable and its time derivative, $z(t)$ will be the control variable. Forming the new objective functional requires absorbing the constraint, i.e., the only constraints in the problem of Lagrange are the boundary conditions. Using (4) and (6) yields an expression for $x(t)$ in terms of the new control variable.

$$x(t) = z^{\gamma}(t)(t_{ij}-t)^{-\gamma\alpha} \tag{7}$$

Substituting into the objective functional and setting the boundary conditions yields the transformed problem

$$\text{Min } C' = \int_{t_j}^{t_{ij}} z^{\gamma}(t)(t_{ij}-t)^{-\gamma\alpha}e^{-\rho t} \tag{8}$$

$$\text{ST: } Z(0) = 0$$

$$Z(t_{ij}) = A^{-1}E^{-\delta}D^{1-\varepsilon}/(1-\varepsilon)$$

Since the intermediate function does not depend explicitly on the state variable, the Euler equation is

$$\frac{\partial I}{\partial z} = \gamma z^{\gamma-1}(t)(t_{ij}-t)^{-\gamma\alpha}e^{-\rho t} = K_o \tag{9}$$

Solving for optimal $z(t)$ yields

$$z(t) = K_1(t_{ij}-t)^{\gamma\alpha/(\gamma-1)}e^{\rho t/(\gamma-1)} \tag{10}$$

This also provides a solution for the optimum time path of resource usage.

$$x(t) = K_1^{\gamma}(t_{ij}-t)^{\alpha\gamma/(\gamma-1)}e^{\gamma\rho t/(\gamma-1)} \tag{11}$$

This optimal solution to the problem is only of transient significance since the value of the constant K_1 is unknown. What is needed is an optimal expression for $x(t)$ that is in terms of the variables and parameters of the original problem.

To obtain the constants, notice that

$$Z(t) = \int K_1(t_{ij}-t)^{\alpha\gamma/(\gamma-1)}e^{\rho t/(\gamma-1)}dt + K_2 \tag{12}$$

Let $\nu = \rho(t_{ij}-t)/(\gamma-1)$ then

$$Z(\nu) = \int K_1\frac{(\gamma-1)}{\rho}\nu^{\alpha\gamma/(\gamma-1)}e^{-\nu+\rho t_{ij}/(\gamma-1)}Jd\nu+K_2 \tag{13}$$

where J is the Jacobian of the transformation.

Now $u(t_j) = \rho(t_{ij}-t_j)/(\gamma-1)$

and $u(t_{ij}) = 0$ and choosing 0 and u as the limits of integration we have

$$Z(u) = K_3\int_0^u \nu^{\alpha\gamma/(\gamma-1)}e^{-\nu}d\nu + K_4 \tag{14}$$

$$Z(u) = K_3\,\Gamma(u,\alpha\gamma/(\gamma-1)+1) + K_4$$

and Γ is the incomplete gamma function.

To satisfy the initial condition that $Z[u(t_j)] = 0$, let

$$Z(u) = -K_3\,\{\Gamma[\rho(t_{ij}-t_j)/(\gamma-1),\alpha\gamma/(\gamma-1)+1]-\Gamma[u,\alpha\gamma/(\gamma-1)+1]\} \tag{15}$$

Also let

$$-K_3 = A^{-1}E^{-\delta}D^{1-\varepsilon}(1-\varepsilon)^{-1}\Gamma^{-1}[\rho(t_{ij}-t_j)/(\gamma-1),\alpha\gamma/(\gamma-1)+1] \tag{16}$$

then Z also satisfied the final condition

$$Z(t_{ij}) = A^{-1}E^{-\delta}D^{1-\varepsilon}/(1-\varepsilon)$$

Also note that

$$z(t) = \frac{dZ(u)}{dt} = K_3\,[\rho\frac{(t_{ij}-t)}{(\gamma-1)}]^{\alpha\gamma/(\gamma-1)}\,e^{-\rho(t_{ij}-t)/(\gamma-1)}\,(\frac{-\rho}{\gamma-1}) \tag{17}$$

substituting for K_3 yields

$$z(t) = A^{-1}E^{-\delta}D^{1-\varepsilon}(1-\varepsilon)^{-1}\Gamma^{-1}\,[\,\rho\frac{(t_{ij}-t_j)}{(\gamma-1)},\,\frac{\alpha\gamma}{\gamma-1}+1\,]$$

$$[\,\frac{\rho(t_{ij}-t)}{(\gamma-1)}]^{\alpha\gamma/(\gamma-1)}\,e^{-\rho(t_{ij}-t)/(\gamma-1)}\,(\frac{\rho}{\gamma-1}) \tag{18}$$

This formulation for optimum $z(t)$ along with (10) provides a direct solution for K_1.

Substituting for K_1 in (11) yields the optimum time path of resource use

$$x(t) = A^{-\gamma}E^{-\gamma\delta}D^{\gamma(1-\varepsilon)}(1-\varepsilon)^{-\gamma}\Gamma^{-\gamma}\,[\rho\frac{(t_{ij}-t_j)}{(\gamma-1)},\frac{\alpha\gamma}{(\gamma-1)}+1]$$

$$[\rho/(\gamma-1)]^{\alpha\gamma^2/(\gamma-1)+\gamma}e^{-\gamma\rho t_{ij}/(\gamma-1)}(t_{ij}-t)^{\alpha\gamma/(\gamma-1)}$$

$$e^{\gamma\rho t/(\gamma-1)} \tag{19}$$

This is the optimum time path of resource use for any given batch of airframes.

Since the data presented in the C141 study is quarterly data, the quantity of interest would be the total amount of resource use over a quarterly period. If T_k and T_ℓ represent the beginning and ending dates for the quarterly period for some batch i, we have

$$x(T_k)-x(T_\ell) = \int_{T_\ell}^{T_k} x(t)\,dt \tag{20}$$

and using (11) the integral is

$$X(T_k)-X(T_\ell) = \int_{T_\ell}^{T_k} K_1^{\gamma}(t_{ij}-t)^{\alpha\gamma/(\gamma-1)} e^{\gamma\rho t/(\gamma-1)} dt \tag{21}$$

Let $y = \gamma\rho(t_{ij}-t)/(\gamma-1)$, then

$$X(T_k)-X(T_\ell) = -K_1^{\gamma} \int_{\gamma\rho(t_{ij}-T_\ell)/(\gamma-1)}^{\gamma\rho(t_{ij}-T_k)/(\gamma-1)} [(\gamma-1)/\gamma\rho]^{\alpha\gamma/(\gamma-1)} y^{\alpha\gamma/(\gamma-1)} e^{-y} e^{\gamma\rho t_{ij}/(\gamma-1)} (-(\gamma-1)/\gamma\rho)dy \tag{22}$$

Notice that this is a form of the incomplete gamma function. Integrating yields

$$X(T_k)-X(T_\ell) = K_1^{\gamma}[(\frac{\gamma-1}{\gamma\rho})^{\alpha\gamma/(\gamma-1)+1}] e^{\gamma\rho t_i/(\gamma-1)}$$

$$[\Gamma(\gamma\rho(t_{ij}-T_\ell)/(\gamma-1),\alpha\gamma/(\gamma-1)+1) -$$

$$\Gamma(\gamma\rho(t_{ij}-T_k)/(\gamma-1),\alpha\gamma/(\gamma-1)+1)] \tag{23}$$

Substituting for K_1 and performing the necessary algebra leaves an expression that represents the optimum amount of resource use over an interval of time.

$$X_{ij}(T_k)-X_{ij}(T_\ell) = A^{-\gamma}E_{ij}^{-\delta\gamma}D_{ij}^{\gamma\ (1-\varepsilon)}(1-\varepsilon)^{-\gamma}$$

$$\Gamma^{-\gamma}(\rho(t_{ij}-t_j)/(\gamma-1),\alpha\gamma/(\gamma-1)+1)\ (\frac{\rho}{\gamma-1})$$

$$\rho^{-\alpha\gamma/(\gamma-1)}[\Gamma(\gamma\rho(t_{ij}-T_\ell)/(\gamma-1),\alpha\gamma/(\gamma-1)+1) -$$

$$\Gamma(\gamma\rho(t_{ij}-T_k)/(\gamma-1),\alpha\gamma/(\gamma-1)+1)] \tag{24}$$

However, because of the nature of the data it is impossible to observe the quantity on the left side of equation (24). What is observable are direct man-hours per lot. This means that the observed quantity is

$$\sum_{i=1}^{n} [X_{ij}(T_k)-X_{ij}(T_\ell)]$$

where there are n batches in a lot.

Empirical Results

To explore the applicability of the theoretical specification, the parameters in (24) are estimated using Orsini's C141 data [9].

Let,

$$\beta_o = A^{-\gamma}(1-\varepsilon)^{-\gamma}(\rho/(\gamma-1)^{\gamma\alpha-\gamma-1}\rho^{-\gamma\alpha/(\gamma-1)}$$

and $\beta_1 = \alpha/(\gamma-1) + 1$

Then the model may be restated as:

$$\sum_{i=1}^{n} X_{ij}(T_k)-X_{ij}(T_\ell) = \beta_o\, E_{ij}^{-\gamma\delta} D_{ij}^{\gamma(1-\varepsilon)} \Gamma^{-\gamma}\, [\rho(t_{ij}-t_j)/(\gamma-1),\beta_1]$$
$$\{\Gamma[\gamma\rho(t_{ij}-T_\ell)/(\gamma-1),\beta_1] \qquad (25)$$
$$-\Gamma[\gamma\rho(t_{ij}-T_k)/(\gamma-1),\beta_1]\}$$

Since the monthly delivery dates for each batch within each lot are known, it is possible to estimate the parameters in (25) using nonlinear least squares.

Initially, the value of the discount rate was assumed to be 10% and the remaining parameters were estimated using Marquardts compromise. Diagnostic checking revealed that the estimates for ε and δ were extremely collinear. This suggests that an alternative specification with ε restricted to be equal to δ would be appropriate. Also, the restriction that $\rho = .10$ was relaxed, and ρ was estimated simultaneously with the other parameters in the model.

The results of both regressions are presented in Table 1. All of the parameter estimates are significantly different from zero, and the signs agree with apriori expectations. In particular, notice that the value of γ is significantly greater than one, indicating that the production function does exhibit decreasing returns to the variable factor. The learning parameter is also consistent with apriori expectations. A $\delta = \varepsilon$ value of .272 is consistent with an 83% learning curve.

However, as far as the optimum time path of resource use is concerned the estimate for β_1 yields a most interesting interpretation. Notice in (25) that β_1 is the argument in a gamma function. A gamma function with parameter $\beta_1 = 3.163$ generates a time path for resource use that is consistent with our knowledge of labor productivity patterns for "lots" of airframes. In most cases resource use rises at an increasing rate from time t_j to an inflection point, after which it continues to rise, but at a decreasing rate. Eventually resource usage reaches a maximum and declines thereafter. See figure 1 for a simulated optimal time path of resource usage. The eventual decline is because as the delivery date approaches,

there are some time consuming "testing" procedures that are not labor intensive. Therefore, there is a period of time near the end of a project where labor cost is significantly reduced.

Table 1

Parameter Estimates and Asymptotic Standard Errors

	Parameter Estimates $\rho = .10$		Parameter Estimates ρ estimated from the Data	
	Estimate	Standard Error	Estimate	Standard Error
β_o	6.073	1.0607	5.839	1.0172
β_1	3.356	.1299	3.163	.5271
$\delta=\varepsilon$	.274	.0262	.272	.0271
γ	1.080	.0004	1.041	.0004
ρ	.100	*	.049	.0096
	MSE = 3.92×10^{10}		MSE = 3.96×10^{10}	

*Standard Error is not estimated since ρ is fixed.

This research represents one step forward in the quest for a more general model of airframe production. It represents the first of several specific historical airframe production programs that will be modeled in the near future. The goal is to find more general model specifications that are useful for production planning and cost estimation in the airframe industry.

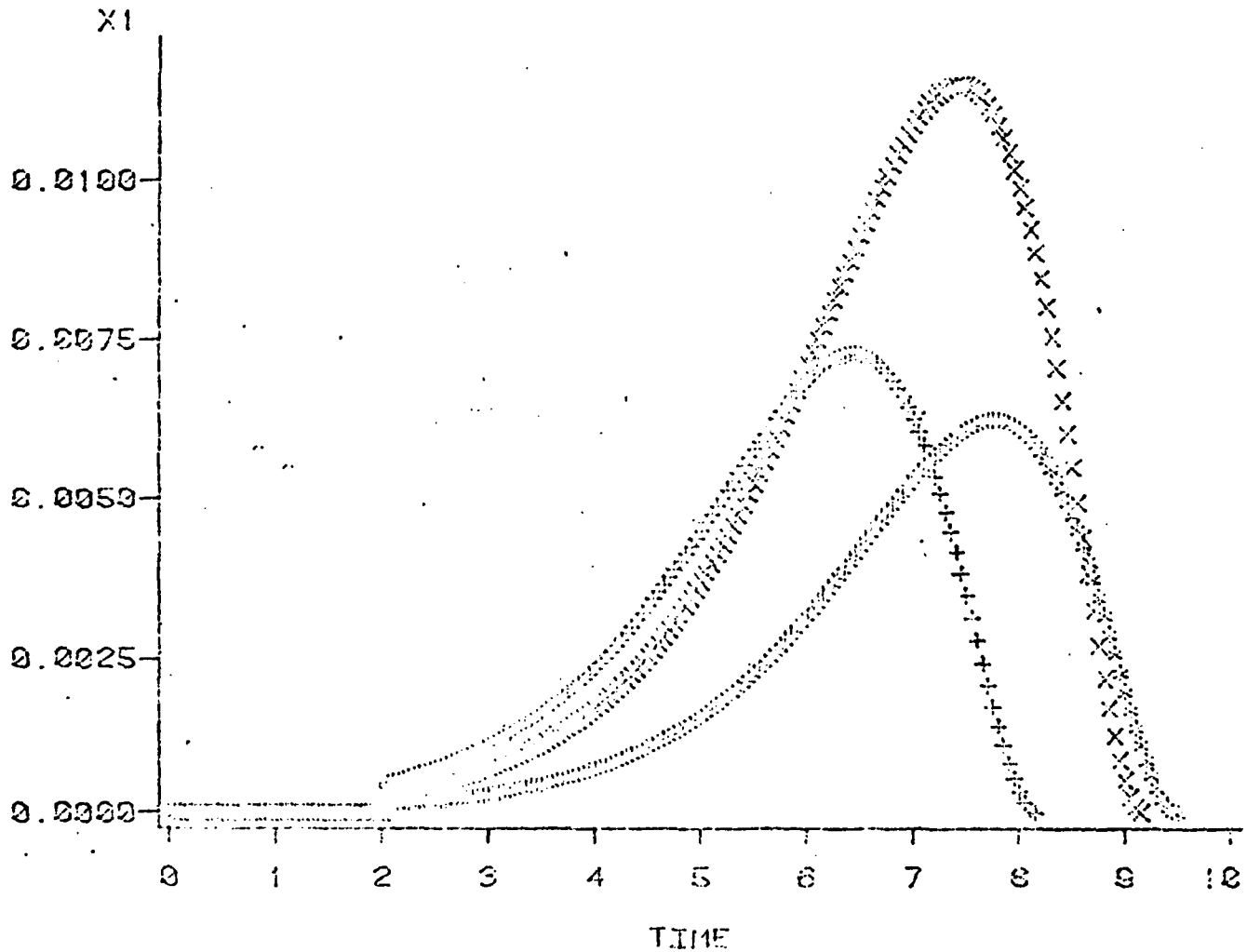

Figure 1. Simulated optimal time path of resource use for three batches of airframes within a given lot.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research represents the expansion of previous work in the area of estimating program cost in military airframe production. The effort is unique in that it yields a model of the production process that considers the impact of learning and production rate on total program costs. To provide an empirical test of model validity, the parameters are estimated for the C141 airframe program. The empirical work is instructive in that it shows how particular care must be taken in formulating models of this type. This model should be particularly useful as a prototype for models of on going

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production programs. In particular, it can be used to estimate the cost impact of exogenous changes in the program delivery schedule, the 'crashes' and 'stretch-outs' that frequently characterize military aircraft programs.

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