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Cost/Time Analysis for Theoretical Aircraft Production

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With the growing emphasis on affordability in aerospace systems design for future aircraft, there is a need for new techniques to predict accurate system and life cycle costs (LCCs). The prediction methods must be capable of quantifying cost differences resulting from material and manufacturing process alternatives. Existing cost models are primarily weight based. While these models have been used successfully for predicting the costs of conventional aircraft, they are not sufficient for many modern or future aircraft that are produced using advanced manufacturing processes and materials. A high-fidelity production cost model was developed and presented that accepts data from multiple levels of product design analysis. The use of cost/time analysis (CTA) for aircraft production is demonstrated for the evaluation of production alternatives. The production-cost model and CTA techniques are included in a LCC simulation. Numerical results are presented for a CTA evaluation of advanced wing structural concepts for a supersonic transport.

Nomenclature

$\bar{f}$ = average annual percentage inflation rate
Q_0 = prespecified production quantity
v = learning-curve slope
w = material weight
w_0 = prespecified finished-material weight
x = production unit number
x_b = learning-curve breakpoint unit
y = current year
y_0 = base year
γ_{cx_l} = cumulative labor cost through xth unit
γ_x = xth unit cost
γ_{x_l} = xth unit labor cost
λ_{cx_m} = cumulative material cost through xth unit
λ_{x_m} = xth unit material cost
ξ_l = generalized labor theoretical first unit cost
ξ_m = generalized material theoretical first unit cost
ρ = labor rate
σ = raw material cost
ϕ = material buy-to-fly ratio
ψ = material burden rate
ω = weight-sizing curve slope

I. Introduction

TO evaluate product designs in terms of their processing characteristics a process evaluation metric is needed. The most logical metric is cost. Many product design metrics can be used to evaluate structural concepts, but process metrics are necessary to show the implications of design decisions on production, operational, and life cycle costs (LCC). Design and manufacturing decisions are tightly coupled; decisions made about manufacturing processes or material selection are rarely independent of the decisions made during the aircraft preliminary design process. The material selection and the choice of a processing method are closely related decisions affecting part producibility. Because system cost is an indicator of producibility, the use of a cost model as a procedural model of a synthesis process was one approach proposed by Calkins et al.[1] for assessing producibility in design.

Understanding and modeling factors related to economics, learning, risk, and uncertainty can enable designers to develop cost-effective systems. The importance of developing comprehensive LCC models cannot be overemphasized with respect to affordable systems. In addition to component cost estimation, usually the focal point of most cost models, accurate modeling of the factors related to production, operations, and support is necessary to generate calibrated LCC profiles. Basic engineering economics can be used for determining a price once the costs have been estimated. Interest formulas are available for predicting rates of return and other indicators of profitability. However, the complex models used for LCC prediction must utilize algorithms for simulating additional factors such as organizational learning and manufacturing process costs. LCC, when included as a parameter in the systems design and development process, provides, for economic feasibility, the opportunity to design an implicitly important objective function for the development of new aircraft concepts. To design for LCC, models of the production and operation of the aircraft must be used to estimate the nonrecurring and recurring production costs plus the operations and support (O&S) costs.

A broad range of cost models exists today, from detailed-design part-level models, based on direct engineering and manufacturing standard factors, to conceptual design system–level life cycle models. Several models exist as commercial, academic, or industry packages. Additionally, many emerging methods have been presented or published that are not software packages. For example, Resetar et al.[2] present a method for determining the cost effects of using advanced materials on airframe structures. Mujtaba[3] describes modeling and simulation of a manufacturing enterprise for verifying impacts of process changes and generating enterprise behavior information.

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While most conceptual level models for aerospace applications are parametric and weight/complexity-based, much research is being conducted to develop activity- and process-based models. For manufacturing enterprises that produce a diverse array of products, conventional costing methods have been shown to distort product costs.[4] Activity-based costing (ABC) systems allocate costs to the activities performed to produce products during the manufacturing process. The allocation bases, or cost drivers, used in ABC are, therefore, indicative of the activities performed, as opposed to only the products produced. ABC has been used by Turney[5] to simulate the effect of continuous improvement efforts on cost estimates. Greenwood and Reeve[6] describe a comprehensive architecture that supports ABC for operational decision making. Methods for determining which measures of cost performance are most useful for decision making are found in Dolinsky and Vollman.[7] Riemann and Huq[8] have developed a model for ABC to assess the potential impact of implementing innovative techniques on business performance.

A relatively newer model, described by Lee,[9] is called a process-oriented, parametric cost model. Lee's model has been used to determine the recurring production costs of rocket-engine hardware in the Rocketdyne Division of Rockwell International.

Another group of models are the top-level, parametric cost-estimating models. Two commercially available computer-aided parametric estimating (CAPE) tools are General Electric's PRICE (programmed review of information for cost estimation), and system evaluation and estimation of resources (SEER) by Galorath Associates, Inc. PRICE has been used by Solverson[10] for design-to-cost and by Apgar[11] for design-to-life-cycle-cost applications. Because many of the algorithms used within the CAPE models are not published and source codes are unavailable, it is not possible to make direct modifications for improvements or research.

Most companies consider their cost data and models highly proprietary. Many of the models and tools are based on relationships originally developed through NASA funding and have been updated with company-specific complexity factors, labor rates, learning curves, etc. Anderson[12] developed a series of computer program subroutines that can be used to predict commercial aircraft return on investment. The routines were based on engineering economic theories. NASA funds later provided the support for development of cost-estimating relationships (CERs) for transport aircraft costs.[13] A computer code that uses the CERs from Ref. 13, in an extended version of the program developed by Anderson,[12] is described by Bobick et al.[14] This more complex code was funded through NASA's analysis of the benefits and costs of aeronautical research and technology (ABC–ART) program.

The NASA/Boeing advanced technology composite aircraft structures (ATCAS) program is funding development of composite optimization software for transport aircraft design evaluation (COSTADE). Mabson et al.[15] describe the COSTADE package, one of the most comprehensive models under development; it was specifically developed to assess the effects of advanced composite materials in commercial transport fuselage structure. Detailed design-level cost-estimating relationships are being developed to support COSTADE analyses.[16,17]

The role of integrated engineering and cost models for space applications is described by King.[18] Cost engineering was used for development of the "brilliant eyes" element of the Strategic Defense System. King describes the relationship between heuristics and architecting complex systems. The heuristics provided by cost engineers can be used to aid an architect in selecting design options evaluated for affordability or cost-effectiveness criteria.

No existing cost model incorporates the ideas found in all of these methods. The weight/complexity-based model has proven most functional to date for individual aerospace applications because its cost drivers are representative of a designer's technical parameters. A high-fidelity production cost model is developed and presented that accepts data from multiple levels of product analysis. The utilization of a hierarchical LCC model was proposed by Meisl[19] as a method for enabling costs to become a design variable in an integrated architecture of engineering and cost models. Marx et al.[20] developed a specialized hierarchical LCC model for including bottom-up production cost estimates in a top-level LCC analysis that included both manufacturer and operator, i.e., airlines. The lowest level of that hierarchical LCC model consisted of the cost estimation for an aircraft wing, based upon the direct engineering and manufacturing estimates for its major structural components. Detailed estimates of direct materials and labor hours used for fabrication, assembly, inspection, and tooling of the major structural components (accommodating the many and varied material types; product forms such as sheets, extrusions, fabrics, etc.; and construction types utilized in advanced technology aircraft structures) replaced a single weight/complexity-based algorithm for estimating the wing cost in the top-level, parametric, LCC simulation model. Hence, differentials in the wing cost estimate resulting from fabrication and assembly alternatives propagate via the system roll-up cost through the life cycle for production, operation, and support for the entire system. The highest level includes determination and distribution of the nonrecurring and recurring production costs, as well as the operational and support costs over the entire life cycle of the aircraft.

The analysis of the cost and time data output from the detailed, bottom-up production cost model is a complex task in itself. Given the techniques and algorithms for generating production cost data early in the design process, one must have a suitable means for interpreting the results in a logical and systematic manner. MIL-HDBK-727, the design guide for producibility,[21] suggests the use of cost/time analyses (CTA) plots.

II. CTA

Figure 1 illustrates a generic plot of a CTA for a theoretical production operation. The x axis is the unit cost whereas the y axis represents the cumulative production time. The steps that comprise a process model for a manufacturing function are time based and can be mapped to production costs. For a given production quantity the sum of the steps traces a path on the plot, shown with the dashed line, to the end point, represented with a small circle.

Learning-curve effects are reflected in the CTA plot. The farthest point on the lower right of the cost/time curve represents the theoretical first unit cost (TFUC). The TFUC has the highest cost per unit of any unit produced. As the production quantity increases and learning curve effects are realized, the cost per unit decreases along the cost/time curve. Different process alternatives, learning curves, labor rates, production quantities, etc., will produce noticeable effects on the cost/time curves. Families of cost/time curves can be generated with the appropriate analysis tools to 1) show the effects of process changes at any level of the production, 2) determine the most significant cost drivers so that efforts can be focused to lower production costs, and 3) serve as process constraint curves for product/process design trades. Before cost/time analysis techniques can be used, a high-fidelity production cost model must be formulated.

A theoretical model for detailed production cost estimates was developed and is presented in Sec. III. The model includes variables that represent the labor hours required for fabrication, assembly, inspection, and tooling. It also includes a detailed calculation of structural concept material costs. The detailed production cost model and parallel implementation of CTA necessitated use of a LCC simulation model. An existing commercial aircraft LCC simulation, described in detail in Sec. IV, was modified extensively such that a low-fidelity algorithm for wing cost estimates was replaced with the detailed model generated in Sec. III. The data structure required for CTA was implicitly developed at the same time.

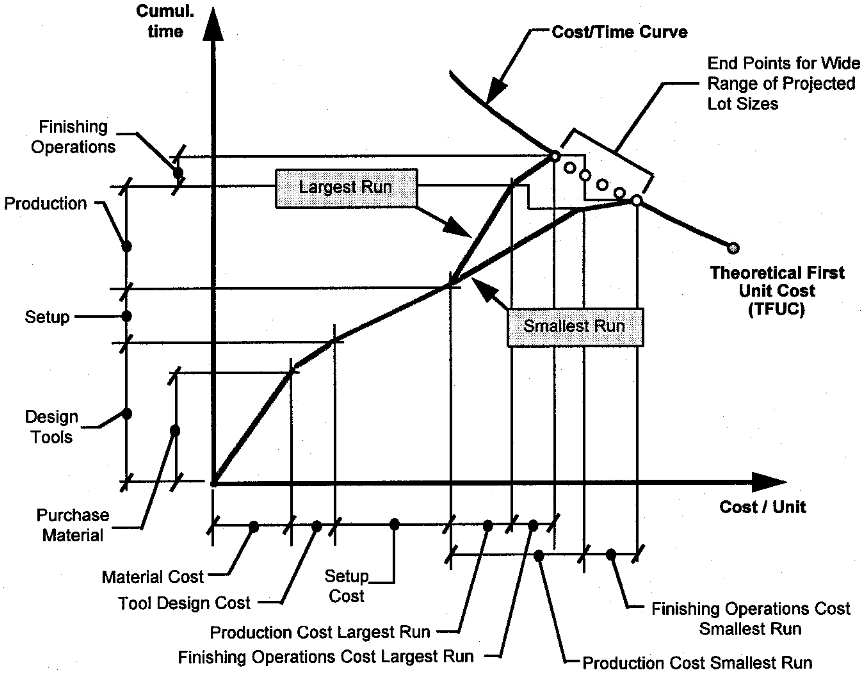

Fig. 1 CTA for theoretical production.[21]

III. Theoretical Model Formulation

The form of the original weight-based wing cost equation in the commercial aircraft LCC simulation is shown in the following equation:

$$\text{cost}_{\text{wing}} = a \cdot cf \cdot (\text{weight}_{\text{wing}})^{b \cdot ef} \tag{1}$$

where a and b are based on a historical database of aluminum aircraft wings, and cf and ef are complexity factors used to adjust the costs for titanium or composite wings. This wing cost is summed with the costs of all other major structural components to compute the airframe cost. The airframe cost is added to the cost of all other major systems, such as avionics and engines, to determine the total aircraft cost.

For a complex, integrated structure like the wing of a supersonic transport, such a model is not sufficient. Because lower weights do not always signify reduced costs, a model based only on component weights will not show the correct trends for many advanced materials and manufacturing processes. Several examples of this trend exist, including the use of thermoplastics vs thermosets. Thermoplastic materials are often selected by the product design teams, but are replaced as soon as more realistic cost/time manufacturing information is obtained, particularly for large thermoplastic components.

The comprehensive model that was developed includes terms for all recurring labor hours and material costs. The variables are based on the materials and processes used to produce specific wing structural concepts. The model was formulated in a general manner such that it can accommodate all commonly used types of production cost data. Though it is later used to evaluate alternative structural concepts for the wing of a supersonic transport aircraft, it can be used for any structural component of an aircraft.

A. Unit Learning-Curve Theory

The model is formulated using a basic learning-curve theory. As the cumulative production quantity increases, manufacturing costs decrease. This can be a result of an increase in workers' skill levels, improved production methods, and/or better production planning. This effect can be quantified in production cost estimates using a product improvement curve, commonly referred to as a learning curve. An example 90% learning curve signifies the following: Each time the cumulative production quantity doubles, the production time (or, comparatively, the production cost) will be 90% of its value before the doubling occurred. The learning curve is normally expressed as a power function

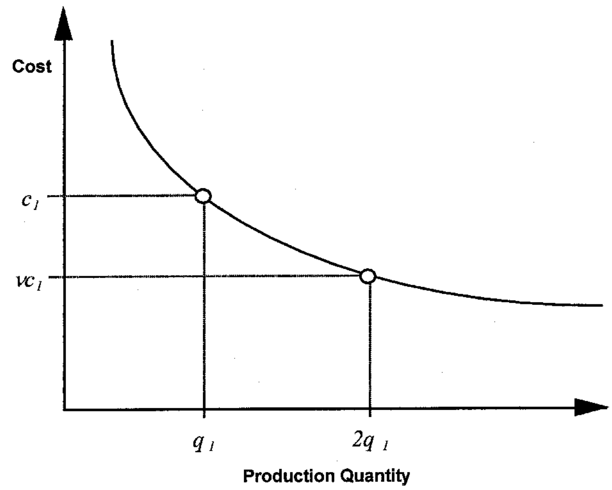

Fig. 2 Relationship between production cost and quantity.

$$\gamma_x = \alpha x^{\beta} \tag{2}$$

where γ_x is the number of direct labor hours required to produce the xth unit, α is the number of direct labor hours required to produce the first unit, and β is a parameter measuring the rate labor hours are reduced as cumulative output increases. An expression for β can be derived based on the following explanation.

The number of direct labor hours required to produce a complex product tends to decrease significantly as production experience is gained, as shown in Fig. 2.

A learning-curve formulation typically expresses how costs change as cumulative production doubles, say from an initial quantity, q_1, to $2q_1$; the cost of unit q_1 is c_1; let the cost of unit

$2q_1$ be some fraction of the cost of unit q_1, say vc_1. With that, rewrite Eq. (2) as

$$\log[\gamma_x] = \log[\alpha(x^{\beta})] \tag{3}$$

which simplifies to

$$\log[\gamma_x] = \log[\alpha] + \log[x^{\beta}] \tag{4}$$

Substituting the production quantities and costs from Fig. 2 into Eq. (4) yields the following set of equations:

$$\log[c_1] = \log[\alpha] + \log[q_1^{\beta}] \tag{5}$$

$$\log[vc_1] = \log[\alpha] + \log[(2q_1)^{\beta}] \tag{6}$$

Solving Eqs. (5) and (6) for $\log[\alpha]$ and setting the results equal gives

$$\log[c_1] - \log[q_1^{\beta}] = \log[vc_1] - \log[(2q_1)^{\beta}] \tag{7}$$

Simplification results in Eq. (8).

$$\log[c_1] - \beta\log[q_1] = \log[v] + \log[c_1] - \beta\log[2] - \beta\log[q_1] \tag{8}$$

Equation (8) can be solved for β in terms of v

$$\beta = \frac{\log[v]}{\log[2]} = \log_2[v] \tag{9}$$

The constant, v, represents the amount (fraction) that costs decrease as the cumulative production quantity doubles. It is commonly known as the learning-curve slope.

It is clear that γ_x has a dependency on production quantity. The standard measure of organizational experience in a learning-curve formulation is, indeed, the cumulative number of units produced. However, for large complex structures like major aircraft components, there may also be a dependence on the weight of the structure. The size of the structure being produced can affect the rate at which cost reductions occur. Large structures frequently result in more cost reductions than small structures as the cumulative production quantity increases.

Hence, the model formulated here is generalized to account for production quantity dependencies and structural size, i.e., weight, dependencies that separate it from previous formulations for production cost models. An equation of the following form will be developed:

$$\gamma_{x,w} = \alpha x^{\beta} w^{\eta} \tag{10}$$

where α, in general, will characterize the effects of a prespecified production quantity, x_0, and a prespecified finished-material weight, w_0

$$\bar{\alpha} = f(x_0, w_0) \tag{11}$$

With such a general formulation, the most common types of production cost data can be accommodated in the model.

B. Production Quantity Dependencies

First, the production quantity dependency of $\bar{\alpha}$ will be determined. Consider the case in which the cost to produce the x_0th unit and the learning curve of that production run are known

$$\gamma_{x_0} = \alpha(x_0)^{\beta} \tag{12}$$

Solving for α, the first unit cost, gives

$$\alpha = \gamma_{x_0}(1/x_0)^{\beta} = \gamma_{x_0}\alpha_x \tag{13}$$

$$\alpha_x \equiv (1/x_0)^{\beta} \tag{14}$$

Substituting in the original form of the learning curve, Eq. (2), gives

$$\gamma_x = \gamma_{x_0}(1/x_0)^{\beta}x^{\beta} \tag{15}$$

which can now be used to calculate the cost of the xth unit in terms of a known x_0th unit cost and learning curve.

C. Structural Size Dependencies

Similarly, the dependency on the structural size can be developed. Consider the case in which the cost to produce a structure that weighs w_0 pounds is known. A weight-sizing factor, which functions exactly as a learning-curve factor, is represented in Eq. (16) as η

$$\gamma_{w_0} = \alpha(w_0)^{\eta} \tag{16}$$

where

$$\eta = \frac{\log[\omega]}{\log[2]} = \log_2[\omega] \tag{17}$$

and ω represents the amount (fraction) costs decrease with respect to the size (weight) of the structure. Solving for α the theoretical first pound cost (TFPC) gives (TFPC is not the same as cost per pound, it is simply a mathematically derived quantity; as opposed to the TFUC, the theoretical first pound cost is not a useful metric. This formulation is, however, useful for adjusting the costs to weights other than the prespecified finished-material weight)

$$\alpha = \gamma_{w_0}(1/w_0)^{\eta} = \gamma_{w_0}\alpha_w \tag{18}$$

$$\alpha_w \equiv (1/w_0)^{\eta} \tag{19}$$

The production quantity and structural size dependencies of the generalized TFUC have now been identified. The generalized form of α is then assumed to be

$$\bar{\alpha} = \lambda\alpha_x\alpha_w \tag{20}$$

where λ represents costs in terms of hours or dollars. Because the cost of a structural component is composed of both labor and material costs, λ_l and λ_m will be formulated next.

D. Labor and Material Costs

Detailed, bottom-up labor-cost estimates usually relate production hours to pounds of material produced. They are based on actual data measured from the production floor or are based on proprietary company standards. Hence

$$\lambda_l = \mu w, \text{ h} \tag{21}$$

where λ_l is the labor cost in hours for w pounds of structure. The variable μ represents hours per pound for labor components such as fabrication, assembly, quality assurance, i.e., inspection, and tooling. Equation (21) can be transformed to labor costs in dollars by multiplying by an appropriate labor rate, ρ

$$\lambda_l = \mu\rho w, \text{ dollars} \tag{22}$$

Bottom-up material cost estimates are functions of four main variables: w, σ (per pound), ϕ (this is the ratio of the amount of material purchased to the amount of material that constitutes the finished structure) and ψ. Equation (23) relates these variables to λ_m, the material cost

$$\lambda_m = \sigma\phi\psi w, \text{ dollars} \tag{23}$$

The generalized first unit cost now accounts for prespecified production quantities and finished-material weights, learning and weight-sizing curves, bottom-up labor hour estimates, labor rates, raw material costs, material buy-to-fly ratios, and material burden rates. The expanded form of the labor and material cost equations thus far is

$$(\gamma_{x,w})_{\text{labor}} = \mu\rho w(1/x_0)^{\beta}(1/w_0)^{\eta}x^{\beta}w^{\eta} \tag{24}$$

$$(\gamma_{x,w})_{\text{materials}} = \sigma\phi\psi w(1/x_0)^{\beta}(1/w_0)^{\eta}x^{\beta}w^{\eta} \tag{25}$$

E. Inflationary Effects

Equations (24) and (25) implicitly correspond to dollar costs in a particular base year, y_0. They are expressed in constant dollars and must be converted to actual dollars for the desired year, y, of the cost estimates. Recognizing that the effects of inflation compound like interest, it is evident that a dollar value can be escalated for inflation as follows.

First year:

$$C_1 = C + Cf = C(1 + f) \tag{26a}$$

Second year:

$$C_2 = C(1 + f) + fC(1 + f) = [C(1 + f)](1 + f) = C(1 + f)^2 \tag{26b}$$

Third year:

$$C_3 = C(1 + f)^2 + fC(1 + f)^2 = [C(1 + f)^2](1 + f) = C(1 + f)^3 \tag{26c}$$

nth year:

$$C_n = C(1 + f)^n \tag{26d}$$

where C is the cost in base year dollars, and f is the inflation rate. The assumption that inflation compounds like interest implies that f is constant over the years between the base year and the given year. It would be more correct to say that

$$C_n = C\prod_{i=1}^{y-y_0}(1 + f_i) \tag{27}$$

for the nth year, where f_i is the inflation rate for each year of the period from y_0 to y. However, it is common practice in LCC modeling to use an average rate for inflation effects. Thus, the general form of the labor and material cost equations can be modified for inflation with the following multiplication:

$$\gamma_{x,w} = \bar{\alpha}x^{\beta}w^{\eta}(1 + \bar{f})^{(y-y_0)} \tag{28}$$

F. Cumulative Production Costs

Up to this point only the unit production costs have been discussed. The cumulative production costs are also needed to generate CTA data and LCC profiles. Equation (28) represents the average cost per unit, if x units are produced. Intuitively, the cumulative production cost can be found by multiplying Eq. (28) by the cumulative quantity produced, x

$$\gamma_{cx,w} = \bar{\alpha}x^{\beta+1}w^{\eta}(1 + \bar{f})^{(y-y_0)} \tag{29}$$

Equations (28) and (29) are the unit and cumulative production costs based on the learning-curve theory for a single production lot.

G. Multiple Production Lots

Production functions are not always best represented by a single learning curve. The following formulation further develops the production cost equations for labor and materials for a double learning curve.

The double learning-curve formulation implies two distinct learning curve slopes, v_1 and v_2. This leads to two values for β; let

$$\beta_1 = \log_2[v_1], \qquad \beta_2 = \log_2[v_2] \tag{30}$$

and let the learning curve breakpoint, i.e., the first lot quantity, be x_b. Then, for cumulative production quantities up to x_b

$$\gamma_{x,w} = \bar{\alpha}x^{\beta_1}w^{\eta}(1 + \bar{f})^{(y-y_0)}, \qquad x \le x_b \tag{31}$$

and after x_b

$$\gamma_{x,w} = \bar{\alpha}(x_b)^{\beta_1}(x/x_b)^{\beta_2}w^{\eta}(1 + \bar{f})^{(y-y_0)}, \qquad x \ge x_b \tag{32}$$

Because the decrease in hours or costs as a result of cumulative doubling in production is now following the second learning-curve slope, v_2, with respect to a new first unit point, namely, x_b, Eq. (32) must include the ratio x/x_b to have the doubling occur with respect to the cumulative number of units produced after x_b. Equation (32) can be simplified to

$$\gamma_{x,w} = \bar{\alpha}(x_b)^{\beta_1-\beta_2}x^{\beta_2}w^{\eta}(1 + \bar{f})^{(y-y_0)}, \qquad x \ge x_b \tag{33}$$

Using a basic property of the natural log function, Eq. (33) can be stated as

$$\gamma_{x,w} = \bar{\alpha}e^{\delta}x^{\beta_2}w^{\eta}(1 + \bar{f})^{(y-y_0)}, \qquad x \ge x_b \tag{34}$$

where

$$\delta = (\beta_1 - \beta_2)\ell n(x_b) \tag{35}$$

The cumulative production costs for a double learning curve are thus

$$\gamma_{cx,w} = \bar{\alpha}x^{\beta_1+1}w^{\eta}(1 + \bar{f})^{(y-y_0)}, \qquad x \le x_b \tag{36}$$

$$\gamma_{cx,w} = \bar{\alpha}e^{\delta}x^{\beta_2+1}w^{\eta}(1 + \bar{f})^{(y-y_0)}, \qquad x \ge x_b \tag{37}$$

Multiple lots can be accommodated with x_{b1}, x_{b2}, x_{b3}, etc.

H. Summary of Developed Equations

The extended forms of the detailed production cost model equations are given in Table 1. The detailed production cost model equations account for many factors that are not considered when using a single equation that is based on the weight of the entire wing and a historical database of wings on existing aircraft. For the large, complex wing of a supersonic transport, it is necessary to accommodate all of the parameters from bottom-up cost studies to predict costs that are representative of the actual structure being produced.

IV. Aircraft LCC Simulation Model

A simulation model based on the ABC–ART models[14] that were developed for analyzing the economic viability of applying advanced technology to transport aircraft was used for the implementation of the production cost equations given in Table 1. There were three original ABC–ART modules: fleet accounting, airframe manufacturer, and air carrier. The simulation model does not have the fleet accounting module. The

Table 1 Production cost equations

Lots	Quantity	Type	Equation	Range
Single	UPC	Labor	$(\gamma_{x,w})_{\text{labor}} = \mu\rho w(1/x_O)^{\beta}(1/w_O)^{\eta}x^{\beta}w^{\eta}(1+\bar{f})^{(y-y_0)}$	——
		Material	$(\gamma_{x,w})_{\text{materials}} = \sigma\phi\psi w(1/x_O)^{\beta}(1/w_O)^{\eta}x^{\beta}w^{\eta}(1+\bar{f})^{(y-y_0)}$	——
	CPC	Labor	$(\gamma_{cx,w})_{\text{labor}} = \mu\rho w(1/x_O)^{\beta}(1/w_O)^{\eta}x^{\beta+1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	——
		Material	$(\gamma_{cx,w})_{\text{materials}} = \sigma\phi\psi w(1/x_O)^{\beta}(1/w_O)^{\eta}x^{\beta+1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	——
Double	UPC	Labor	$(\gamma_{x,w})_{\text{labor}} = \mu\rho w(1/x_O)^{\beta}(1/w_O)^{\eta}x^{\beta_1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \leq x_b$
		Labor	$(\gamma_{x,w})_{\text{labor}} = \mu\rho w(1/x_O)^{\beta}(1/w_O)^{\eta}e^{\delta}x^{\beta_2}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \geq x_b$
		Material	$(\gamma_{x,w})_{\text{materials}} = \sigma\phi\psi w(1/x_O)^{\beta}(1/w_O)^{\eta}\, x^{\beta_1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \leq x_b$
		Material	$(\gamma_{x,w})_{\text{materials}} = \sigma\phi\psi w(1/x_O)^{\beta}\,(1/w_O)^{\eta}e^{\delta}x^{\beta_2}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \geq x_b$
	CPC	Labor	$(\gamma_{cx,w})_{\text{labor}} = \mu\rho w(1/x_O)^{\beta}(1/w_O)^{\eta}x^{\beta_1+1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \leq x_b$
		Labor	$(\gamma_{cx,w})_{\text{labor}} = \mu\rho w(1/x_O)^{\beta})(1/w_O)^{\eta}e^{\delta}x^{\beta_2+1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \geq x_b$
		Material	$(\gamma_{cx,w})_{\text{materials}} = \sigma\phi\psi w(1/x_O)^{\beta}(1/w_O)^{\eta}\, x^{\beta_1+1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \leq x_b$
		Material	$(\gamma_{cx,w})_{\text{materials}} = \sigma\phi\psi w(1/x_O)^{\beta}(1/w_O)^{\eta}e^{\delta}x^{\beta_2+1}w^{\eta}(1+\bar{f})^{(y-y_0)}$	$x \geq x_b$

module formulations and capabilities are briefly explained in the next two sections. This is necessary to present a clearer illustration of how the production cost effects can propagate through a LCC analysis.

A. Airframe Manufacturer's Model

The manufacturer's analysis begins with a calculation of the unit production costs (UPC). The UPCs are estimated with a series of exponential equations for generating airframe component manufacturing costs for various classes of aircraft. The aircraft TFUC is calculated by summing the respective component first unit costs of the airframe, propulsion, avionics and instrumentation, and final assembly. The price of the engine can be specified or estimated. Another series of exponential CERs is used to calculate the research, development, testing, and engineering (*RDT&E*) and recurring production costs for the total number of vehicles produced. The sum of the nonrecurring and recurring production costs is divided by the number of aircraft produced to give an average unit airplane cost.

The average aircraft manufacturing costs vs the production quantity are calculated. The elements of the total vehicle cost are eroded with user-specified learning curves for the airframe, avionics, propulsion, assembly, and fixed equipment. Double learning curves can be defined and input for several components. A learning-curve breakpoint can be specified, after which subsequent production follows a second-lot learning curve.

For a specified production rate, quantity, and average aircraft selling price, the manufacturer's cumulative and annual cash flows are calculated. The annual and cumulative aircraft deliveries are calculated first, based on an input production rate schedule. The *RDT&E* costs, manufacturing and sustaining costs, and the annual income are then calculated and distributed over the preproduction and production years as outlined in Marx et al.[20] The four major constituents of the manufacturer's cash flow are the *RDT&E* costs, the manufacturing costs, the sustaining costs, and the income payments. The manufacturer's net cash (*MNC*) flow is the net income (*NI*) minus the sum of the *RDT&E*, manufacturing (*Mfg*), and sustaining costs (*Sust*), as given in the following equation:

$$MNC = NI - \sum (RDT\&E + Mfg + Sust) \tag{38}$$

Negative (−) cash flow signifies costs exceeding income; while positive (+) cash flow signifies receipts exceeding disbursements.

An iterative technique is used to calculate the internal (discounted) rate of return for each cash flow generated. The discounted rate of return (or marginal efficiency of investment) is defined as the interest rate that renders the discounted present value of its expected future marginal yields (income) equal to the investment cost of the production project. Mathematically, this can be stated as

$$0 = PV(i^*) = \sum_{t=0}^{n} F_t \frac{1}{(1+i^*)^t} \tag{39}$$

where PV is the discounted present value of the cash flow, n is the number of years, F_t is the annual net cash flow, and i^* is the internal rate of return.

The total dollar value of the profit is the net cumulative cash flow for the given production run at a given selling price. The break-even unit is the aircraft for which the sign of the cumulative net cash flow changes from negative to positive. The aircraft price that is necessary to give the desired return on investment for the manufacturer is also calculated.

B. Air Carrier Module

The price at which the aircraft must be sold to earn the required return on investment (ROI) for the manufacturer is, in turn, the price that becomes the acquisition cost in the airlines' analysis. In addition to the mission for which the aircraft was designed, several economic missions can also be analyzed. This allows the quantitative evaluation of the direct, indirect, and the total operating costs for an aircraft that was designed for a particular range, but may be operated at various stage lengths.

The direct operating costs (DOC) are calculated first. Basic speed, time, and distance variables needed to determine the operating costs are calculated; these are mission-dependent parameters. Cash DOC are composed of general flight operating costs (flight crew, fuel, and oil) and direct maintenance costs (airframe and engine labor and materials). Ownership DOC calculations include determination of the depreciation, financing payments, i.e., interest on the undepreciated balance, and insurance. Simple, straight-line depreciation is used; the annual cost of depreciation is amortized over all flights made each year. The finance cost calculations are more complex. Equal annual payments are assumed over the economic life of the aircraft. The annual payment is calculated with the standard equation for capital recovery

$$A = P \cdot \left[\frac{i(1 + i)^n}{(1 + i)^n - 1} \right] \tag{40}$$

where A is the annual finance payment, and P is the present value, i.e., the acquisition cost, of the aircraft. In addition, the amount of interest paid each year is computed by applying the interest rate to the outstanding principal. The amount of principal payment for a given year is the difference between A and the interest. The insurance cost is a simple function of a user-specified insurance rate.

The indirect operating costs (IOC) include base (system) and line (local) maintenance; aircraft, passenger, traffic, and cargo services; and general and administrative (G&A) costs.

The sum of the DOC and the IOC equals the total operating cost (TOC). The break-even required yields are calculated in terms of dollars per revenue passenger mile ($\$/RPM$) for user-specified load factors. The following relation is used to determine the $\$/RPM$ given the \$/available seat mile ($\$/ASM$):

$$(\$/RPM) = \frac{(\$/ASM)}{\text{load\_factor}} \tag{41}$$

where $\$/ASM$ is the TOC per trip divided by the stage length, divided by the total passenger capacity of the aircraft.

The annual revenue for the airline is calculated using Eq. (42):

$$A_{\text{rev}} = (AVGY_{\text{cc}} \cdot NP_{\text{cc}} \cdot LF_{\text{cc}} + AVGY_{\text{fc}} \cdot NP_{\text{fc}} \cdot LF_{\text{fc}}) \times SL \cdot (U/BT) \tag{42}$$

with $AVGY_{\text{cc}}$ and $AVGY_{\text{fc}}$ representing the average yields for the coach and first class, respectively; NP_{cc} and NP_{fc}, the number of passengers; LF_{cc} and LF_{fc}, the load factors; SL, the stage length in nautical miles; U, the annual utilization in hours; and BT, the block time in hours. Because these variables do not have temporal dependencies (BT is constant for the given mission), the annual revenue remains constant throughout the economic life of the aircraft.

The salvage value is added to the airline net cash flow only in the final year of the aircraft's economic life and is treated as a capital gain. The initial investment is incurred in the first year of the economic life of the aircraft; it is the purchase price of the aircraft, assumed to be paid in full before operations begin.

The annual earnings before taxes are the annual revenues minus the operating costs. The annual income tax is calculated by multiplying a user-defined tax rate (default 34% for corporate and individual incomes over \$350,000/year, as required by the 1986 Tax Reform Act) by the earnings before taxes. The airline net earnings are the earnings before tax minus the income tax.

The airline net cash (ANC) flow is defined as

$$ANC = A_{\text{rev}} + S_{\text{value}} - Inv_{\text{init}} - \text{TOC} + D + I - Tax \tag{43}$$

where A_{rev} is the annual revenue, S_{value} is the salvage value, Inv_{init} is the initial investment, D is depreciation, I is the annual interest, and Tax is the annual income tax. The airline ROI calculation is again based upon the net present worth of the cumulative net cash flow, just as in the manufacturer's ROI calculations. With capital recovery theory, the yearly annual payments account for the principle balance plus interest on the invested capital. Hence, the addition of the annual interest each year in the airline net cash flow is a bookkeeping adjustment to account for earned interest. The depreciation is also added into the net cash flow to allow for capital expenditures.

C. Simulation Developments

Application of the wing production model formulated previously required data for several of the variables in the for-

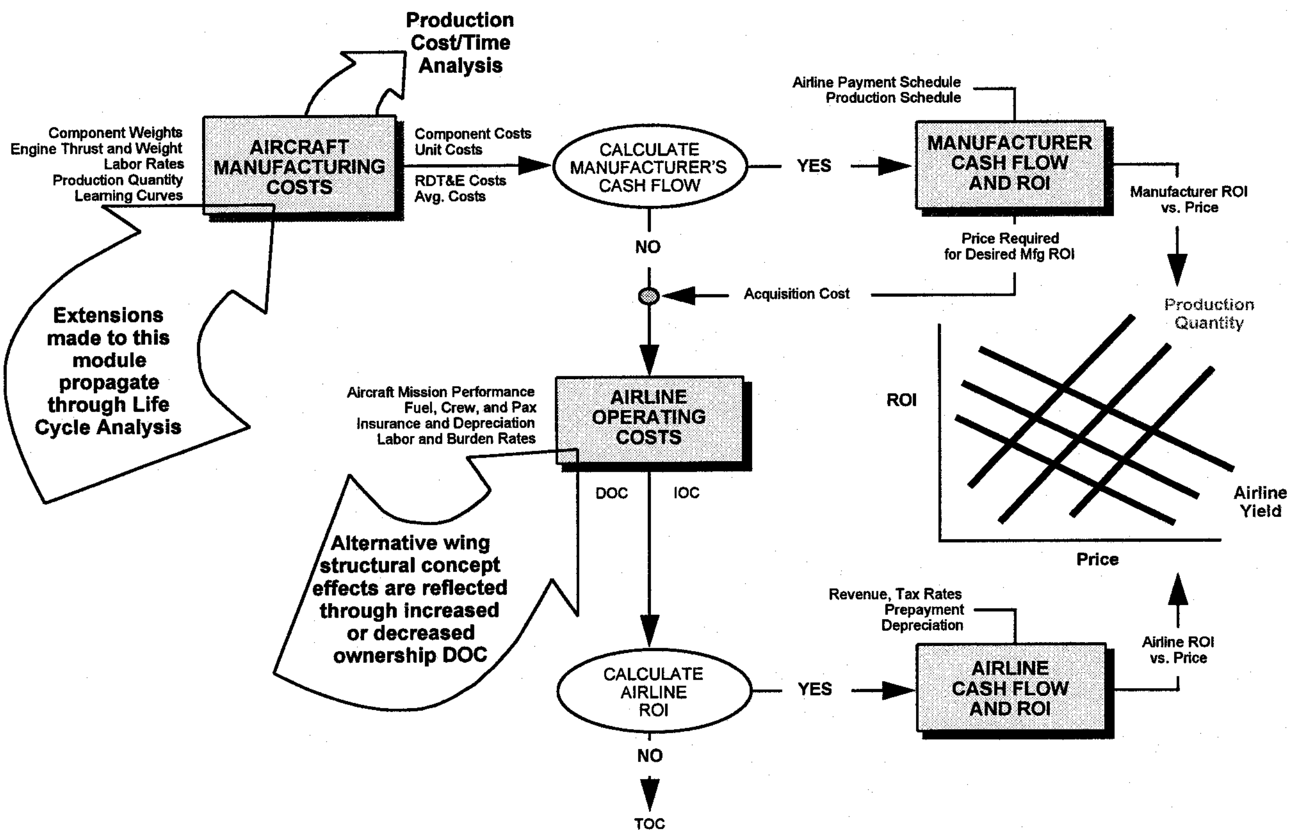

Fig. 3 ALCCA analysis schedule.

Table 2 Wing structural concept descriptions

No.	Forward strake	Inboard wing box	Wing tip box
1	SPF/DB titanium sandwich	SPF/DB titanium sandwich	SPF/DB titanium sandwich
2	PMC skin-stringer	PMC skin-stringer	PMC skin-stringer
3	PMC sandwich	SPF/DB titanium sandwich	PMC sandwich

mulation. Reference 2 provided most of the data that was used. The report included data for several nonrecurring and recurring production cost elements for advanced airframe structural materials. The cost factors presented were based upon surveys administered to several prominent U.S. aerospace manufacturers.

The study included data for recurring labor hours and costs for materials that are currently in use or are projected to be used in the future for manufacturing advanced aircraft structures. The list of materials included aluminum, aluminum–lithium, steel, titanium, graphite/epoxy, graphite/bismaleimide (BMI), and graphite/thermoplastic. Hence, in the application of the new wing production model, the variable λ is now a function of material selection. With this implementation, the direct labor hours, i.e., manufacturing, quality assurance, and tooling, and material costs are calculated for each material used to produce the wing structure and summed to calculate the total wing cost.

To generate the data required to plot unit labor costs vs cumulative labor hours for cost/time analysis, additional modifications to the LCC simulation model were required. Variables were assigned for the unit and cumulative labor cost elements (manufacturing labor cost, quality assurance labor cost, and tooling labor cost) and unit and cumulative labor hour elements (manufacturing hours, quality assurance hours, and tooling hours). Each unit or cumulative labor hour and cost element is eroded with a user-defined learning curve. Values are calculated and printed for the unit and cumulative hours and costs for different production quantities. When this is plotted it yields the cost/time curves. Approximately 900 lines of Fortran code were added to the simulation to implement the new production cost model and generate data for CTA.

D. Simulation Schedule

The analysis schedule used by the simulation is shown in Fig. 3. A simplified process flow can be stated as follows: Starting in the upper left-hand corner, first the aircraft manufacturing costs are calculated (both TFUCs and for various production quantities); the manufacturer's cash flow and discounted ROI is calculated next for several possible aircraft prices (based on the cost plus a user-defined profit margin); the airline operating costs are then calculated (based on the price calculated/required to give the manufacturer a prespecified production ROI); and finally, the airline cash flows are calculated and used to determine the airline ROIs for several possible values of \$/*RPM*. Hence, any changes to the aircraft manufacturing cost module in the upper left corner of Fig. 3 propagate throughout the entire LCC analysis. As shown in Fig. 3 the use of the detailed production model allows the effects to propagate through the LCC analysis. The scope of this paper allows only the discussion of the CTA results, but the entire simulation analysis schedule is given to illustrate the overarching economic analysis.

V. Case Study Results

The detailed production cost model and CTA implementation were included in the LCC simulation model. This section presents the CTA results for three wing structural concepts for a supersonic transport aircraft.

A supersonic transport wing can be divided into three main design regions, plus the leading- and trailing-edge structures. The three design regions are the forward strake, the inboard wing box, and the wing tip box. Three substantially different

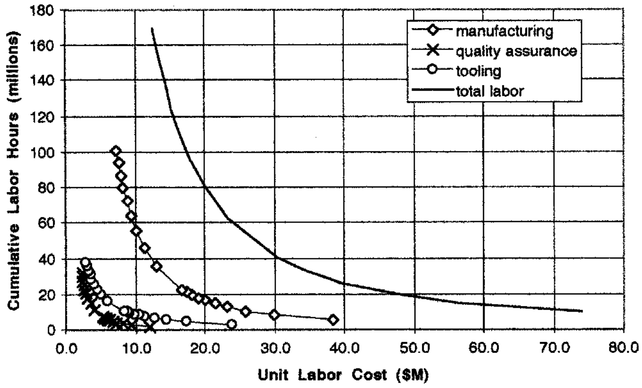

Fig. 4 CTA for wing labor: Concept 1.

wing concepts were selected to show a variety of trends in the CTA. The differences between the wings were only in the materials, process selections, and structural concepts for the three main design regions. The planform shape and size were constant. A constant weight was used for the leading- and trailing-edge structure for all three concepts because the planform shape and size did not vary. The leading-edge structure is superplastically formed/diffusion bonded (SPF/DB) titanium, whereas the trailing-edge structure is discretely stiffened polymer matrix composite (PMC) material. Two homogeneous and one hybrid wing concept were selected. Table 2 provides descriptions of the three concepts. They represent advanced concepts that could not be correctly evaluated with existing weight/complexity-based algorithms. The detailed production cost model formulated earlier can be used to evaluate these advanced structural concepts. A comprehensive cost vs performance analysis and sensitivity analysis for supersonic transport with these three wing concepts can be found in Marx.[22]

Cost/time curves are plotted for the constituents of the total direct recurring labor (fabrication and assembly, quality assurance or inspection, and tooling) for the three wing structural concepts. The sum of the three labor components yields the total labor curve. The plots in Figs. 4–7 show the costs for production quantities from the 10th unit to the 1000th unit. The farthest point on the lower right end of each curve is the 10th unit; the highest point on the left end of each curve represents the 1000th unit. The use of the CTA can help identify the key cost drivers that are not evident when only considering the individual component manufacturing costs or cost of the entire aircraft.

For all three concepts, the quality-assurance costs, both in terms of dollars and hours, are the smallest cost element of the wing labor for any production quantity. This is frequently not the case for military aircraft systems for which quality assurance costs are often one of the major cost drivers.

Close investigation of the tooling and manufacturing cost/time curves in Figs. 4–6 reveals several interesting trends. For concept 1, the all-SPF/DB titanium concept plotted in Fig. 4 and the manufacturing cost and time are greater than the tooling cost and time for all production quantities.

The high tooling cost (in terms of dollars) for low production quantities for concept 2, the z-stiffened PMC, is evident in Fig. 5. For the lower production quantities, the tooling cost is much greater than the manufacturing cost in dollars while being approximately equal in hours. As the production quantity

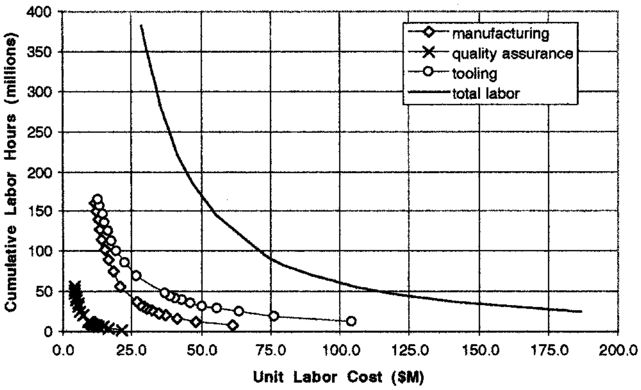

Fig. 5 CTA for wing labor: Concept 2.

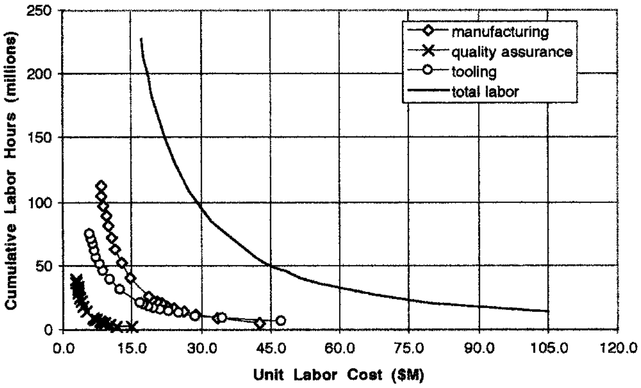

Fig. 6 CTA for wing labor: Concept 3.

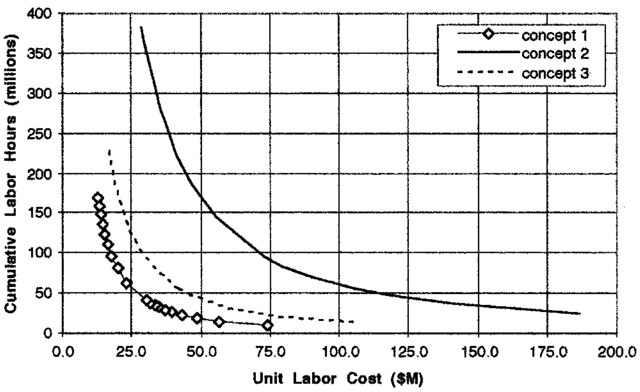

Fig. 7 CTA for wing labor: All concepts.

increases, the dollar costs of the tooling decline to be nearly equal to the manufacturing dollar costs.

The third concept has the most complex CTA plot (Fig. 6). For the lower-production quantities, the tooling dollar costs exceed the manufacturing dollar costs with the hours being nearly equal. However, as the production quantity increases, the tooling costs fall below the manufacturing costs both in terms of dollars and hours.

The total labor cost/time curves are plotted in Fig. 7 to show the relative total labor costs for the three wing concepts. Concept 2 has the highest labor cost for all production quantities, whereas concept 1 has the lowest total labor cost for all production quantities. In terms of labor costs only, the hybrid wing concept is more expensive than the all-SPF/DB titanium wing concept.

CTA, which graphically depicts the costs in terms of dollars and hours and their relation to production quantity, allows the designer to more easily interpret sensitivity analysis results for process variations.

VI. Conclusions

A detailed, bottom-up production cost model that is capable of reflecting advanced material and process selections on fabrication, assembly, inspection, tooling, and material costs for aircraft structural components was formulated. The use of CTA techniques for analyzing the production cost results in terms of time and money was discussed and implemented in a LCC simulation model. Three advanced wing structural concepts for a supersonic transport aircraft were described and evaluated in terms of their production costs using simulation model with the detailed production cost model and CTA.

The usefulness of CTA for identifying major cost drivers was exemplified with the case study. Depending on the structural concept, different labor activities may be key cost drivers. The relative importance of the cost drivers is highly dependent upon production quantity. For one concept the tooling labor cost was the major cost driver at smaller production quantities. As production of that concept increased, the fabrication and assembly labor became the major contributor to the wing costs. With a complex production cost model it is difficult to determine how economic evaluation metrics behave when subject to process variations. The usefulness of CTA for interpreting production cost estimates is invaluable for discovering the reasons economic metrics are or are not significantly affected by process variations for different production quantities.

References

[1] Calkins, D. E., Gaevert, R. S., Michel, F. J., and Richter, K. J., "Aerospace System Unified Life Cycle Engineering: Producibility Measurement Issues," Institute for Defense Analysis, Paper P-2151, May 1989.

[2] Resetar, S. A., Rogers, J. C., and Hess, R. W., "Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology," RAND Corp., Project AIR FORCE Rept. R-4016-AF, Santa Monica, CA, 1991.

[3] Mujtaba, M. S., "Enterprise Modeling and Simulation: Complex Dynamic Behavior of a Simple Model of Manufacturing," *Hewlett-Packard Journal*, Dec. 1994, pp. 80–112.

[4] Cooper, R., "ABC: A Need, Not an Option," *Accountancy*, Sept. 1993, pp. 86–88.

[5] Turney, P. B. B., "How Activity-Based Costing Helps Reduce Cost," *Journal of Cost Management*, Vol. 4, No. 4, 1991, pp. 29–35.

[6] Greenwood, T. G., and Reeve, J. M., "Activity-Based Cost Management for Continuous Improvement: A Process Design Framework," *Journal of Cost Management*, Vol. 5, No. 4, 1992, pp. 22–40.

[7] Dolinsky, L. R., and Vollman, T. E., "Transaction-Based Overhead Considerations for Product Design," *Journal of Cost Management*, Vol. 5, No. 2, 1991, pp. 7–15.

[8] Riemann, M. D., and Huq, F., "Using Activity Based Costing to Define a Quantitative Product Life Cycle Cost Model for Concurrent Engineering," *Proceedings of the 3rd International Conference on Flexible Automation and Integrated Manufacturing* (Limerick, Ireland), 1993.

[9] Lee, P., "A Process Oriented Parametric Cost Model," AIAA Paper 93-1029, Feb. 1993.

[10] Solverson, R. R., "Design to Cost with PRICE H," AIAA Paper 93-1030, Feb. 1993.

[11] Apgar, H., "Design-to-Life-Cycle-Cost in Aerospace," AIAA Paper 93-1181, Feb. 1993.

[12] Anderson, E. E., "Computer Program for Estimating Commercial Aircraft Return on Investment," Advanced Concepts and Missions Div., NASA-OART, Paper MA-71-4, Moffett Field, CA, Oct. 1971.

[13] Anderson, J. L., and Beltramo, M. N., "Development of Transport Aircraft Systems Cost and Weight," NASA TM X-73,186, Nov. 1976.

[14] Bobick, J. C., Braun, R. L., and Denny, R. E., "Documentation of the Analysis of the Benefits and Costs of Aeronautical Research and Technology Models—Volume 1: Technical Report," NASA CR-152278, July 1979.

[15] Mabson, G. E., Flynn, B. W., Ilcewicz, L. B., and Graesser, D. L., "The Use of COSTADE in Developing Composite Commercial Aircraft Fuselage Structures," AIAA Paper 94-1492, April 1994.

[16] Metschan, S. L., Wilden, K. S., Sharpless, G. C., and Andelman, R. M., "Cost Model Relationships Between Textile Manufacturing Processes and Design Details for Transport Fuselage Elements," *Proceedings of the 3rd NASA ACT Conference* (Long Beach, CA), NASA, 1992, pp. 323–340.

[17] Metschan, S. L., Mabson, G. E., Swanson, G. D., Gessel, M. H.,

Humphrey, R. J., and Tervo, D. K., ''Integration of Advanced Composite Manufacturing Trials Into a Design/Cost Database,'' *Proceedings of the 4th NASA/DoD ACT Conference* (Salt Lake City, UT), NASA, 1993, pp. 37–48.

[18]King, N. E., "Heuristics as a Design Tool for Brilliant Eyes Cost Engineering," AIAA Paper 92-1055, Feb. 1992.

[19]Meisl, C. J., ''The Future of Design Integrated Cost Modeling,'' AIAA Paper 92-1056, Feb. 1992.

[20]Marx, W. J., Mavris, D. N., and Schrage, D. P., ''A Hierarchical Aircraft Life Cycle Cost Analysis Model," AIAA Paper 95-3861, Sept. 1995.

[21]MIL-HDBK-727, *Military Handbook: Design Guidance for Producibility*, April 1984.

[22]Marx, W. J., ''Integrating Design and Manufacturing for the High Speed Civil Transport," Ph.D. Dissertation, Georgia Inst. of Technology, Atlanta, GA, 1996.