A HIERARCHICAL AIRCRAFT LIFE CYCLE COST ANALYSIS MODEL

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Abstract

This paper presents an exploratory study for identification and quantification of the economic benefits or implications associated with wing cost variations. A hierarchical cost model structure is used to determine life cycle effects of design and manufacturing alternatives for the major structural components of the wing of a High Speed Civil Transport aircraft concept. Preliminary results are presented relating the effects of up to a 25% variation in wing cost to overall manufacturing and operational returns on investment. It was discovered that a 25% reduction in wing costs, relative to a baseline wing, results in approximately a 3% increase in return on investment for the manufacturer. In addition, deviations in wing cost of 10% and 25% yielded acquisition price differences of 2.25% and 6.0% respectively. These relatively small percentage differences in acquisition costs produced no significant changes in operational costs of the aircraft. Small changes were evident in the costs of financing and depreciating the aircraft, but these minor differentials had a negligible effect on the airline return on investment.

Motivation

Aerospace manufacturers today are searching for techniques to gain a sustainable, competitive advantage in the global marketplace. For the United States aerospace and defense industries, a major issue is whether too much attention being paid to the "bottom line" will dull the U. S.' technological edge[1]. The many recent customer requirements emphasizing greater affordability may lead to a deemphasis of leading-edge technology. The amount of benefits that can be realized by introducing technological improvements into a new or existing program may be indeed outshadowed by economic factors over which the industry and the airlines have no control.

Accordingly, the Defense Manufacturing Council (DMC) recently established several goals[2], one of which was to have cost as a design variable on an equal level with traditional performance variables. Designing with an emphasis on economic competitiveness and cost-effectiveness must become coequal with concerns for production, finance, operations, and support. This new type of engineering paradigm reflects a life cycle orientation. It is essential that designers have both the *knowledge and freedom* to be sensitive to manufacturing and operational outcomes during the earliest stages of product development. They must assume responsibility for life cycle engineering, a largely neglected area in past aerospace systems design. Two recent initiatives, namely the Affordable Systems Optimization Program (ASOP) and the Affordable Design And Manufacturing (ADAM) program, are partially funding the development of cost models that are representative and supportive of design and manufacturing activities[3,4].

A key development strategy for which comprehensive cost modeling is required is called Integrated Product and Process Development (IPPD). IPPD is rapidly evolving within today's aerospace industry. It is built upon the foundations of product decomposition and process recomposition and encompasses the principles of Concurrent Engineering (CE) and Total Quality Management (TQM), as well as Systems and Quality Engineering. This TQM-inspired design process replaces the sequential approach with a parallel design and cost process facilitated by Concurrent Engineering. IPPD requires the development of hierarchical Life Cycle Cost (LCC) models for the cardinal process *recomposition* to occur. A hierarchical LCC model that can accept multifidelity input data and function within an integrated design environment is being developed to support programs such as ASOP and ADAM; the development of the model is the focus of this paper. The utilization of a hierarchical LCC model was proposed by Meisl[5], as a possible method for enabling cost(s) to become a design variable in an integrated architecture of engineering and cost models.

Integrated design and cost models should not be so complex such that their use is prohibitively time-intensive. Their fidelities should be high enough to

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support the required trades and optimizations at each respective level, but low enough to enable the models to be used in the conceptual and preliminary phases of design. A functional abstraction of several manufacturing technologies must become available earlier in the design process. As far as LCC modeling is concerned, this requires the development and utilization of a "bottom-up" cost model and its subsequent integration into a parametric, "top-down" cost model. The hierarchical cost model will utilize a definitive estimating method for fabrication and subassembly materials and labor, primarily used only during or after detailed design, in the conceptual design phase.

Background

Understanding and modeling factors related to learning, economics, marketing, risk, and uncertainty can enable designers to design more cost-effective systems. The importance of developing comprehensive LCC models cannot be over-emphasized with reference to affordable systems. Particular areas of concern include production cost estimating, organizational learning, pricing and marketing, subcontracting production, and predicting competitors' costs.

In addition to the component cost estimation, usually the focal point of most cost models, accurate modeling of all factors related to production, operations, and support is necessary to generate calibrated LCC profiles. Basic engineering economics can be used for determining price once the cost has 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 as organizational learning and manufacturing processes.

The importance of modeling organizational learning can be qualified with an example. The production of the Lockheed L-1011 Tri-Star commercial transport aircraft in the 1970s is an example of a production program with little indication of learning[6,7]. Lockheed lost more than $1 billion on the Tri-Star program[7]. The L-1011 production operations did not follow a typical learning curve pattern. Original estimates predicted the break-even unit would be manufactured in mid-1974[8]. However, cuts in production occurred in late 1975. Shortly thereafter, costs rose to exceed price and remained above price for the duration of the production program. Contrary to a conventional learning curve model in which unit costs decrease as a function of cumulative output, the L-1011 program costs rose as the cumulative output continued to increase. Knowledge depreciation through reorganization due to the production cuts could explain the increase in costs. While this is an exception to most production programs, the effect can be modeled with a slightly more complex formulation of the learning curve phenomena.

Another example, related to production cost estimation, dates back to the supersonic transport (SST) studies of the 1970s. The Lockheed-California Company was involved in the design of an SST concept[9]. It was discovered that a significant mass penalty was incurred in the wing tip to meet flutter speed requirements. Two of the most logical solutions were providing additional stiffening in the wing tip, or increasing the depth of the wing tip structural box. Both solutions, however, showed no significant advantages with reference to the flutter speed constraint if the baseline use of titanium was retained, since the wave drag penalties offset the savings resulting from the reduced surface panel thickness. Another option was to select a new structural material. It was found that the application of boron-aluminum composites on the baseline wing tip provided a relatively significant improvement in performance. However, the state-of-the-art at the time was not mature enough to reliably design and predict the manufacturing consequences (i.e., production and sustaining costs) for selecting such an advanced material. Hence, the wing tip flutter problem remained unsolved for the SST studies and is still one of the key technical considerations in the design of today's High Speed Civil Transport (HSCT).

Life Cycle Cost, when included as a parameter in the system design and development process, provides the opportunity to design for economic feasibility, an implicitly important objective function for the development of an HSCT concept. This paper will outline a technology-based process involving the union of engineering design and economic models to encompass all phases of the aircraft system life cycle including: Research, Development, Testing and Engineering (RDT&E); Production; and Operations and Support (O&S). The HSCT is used as the case study for life cycle model development because of its dependence upon cost-effectiveness and affordability.

Scope

Life Cycle Cost modeling, as specifically related to the research described by this paper can be defined as:

> *"The process of building abstractions or models of the three primary components of the system life cycle for the purpose of gaining insight into the interactions between these components, and their mutual interactions and interdependencies with the manufacturer and the airlines."*

Those three primary components of the system life cycle include non-recurring costs, recurring costs, and operations and support costs. Apgar[10] defines two principle objectives for an LCC trade study as the identification of the design and production process alternatives which meet minimum performance requirements, both

◊ at the *lowest average unit production cost*, and
◊ at the *lowest O&S cost* per operating hour.

The model being developed for this research will address both of these objectives. The relationship between these two objectives and the manufacturer and airlines is clear.

A full range of cost models exists today, from detailed design part-level models, based on direct engineering and manufacturing standard factors, to conceptual design level life cycle models. While most of the conceptual level models are parametric and weight/complexity-based, much research is being conducted to develop feature-, activity-[11], and/or process-based[12] models. Many of the detailed models use measured data from the shop floor for the regression analysis and algorithm development. At the other end of the spectrum are the top-level, parametric cost estimating models for life cycle estimates. Few models exist between the two ends of the modeling spectrum; no suitable methods have been demonstrated for a model that accepts multifidelity data from multiple levels of product analysis within an integrated design environment. Figure 1 shows the relation between the model types and their uses today in the phases of the design timeline.

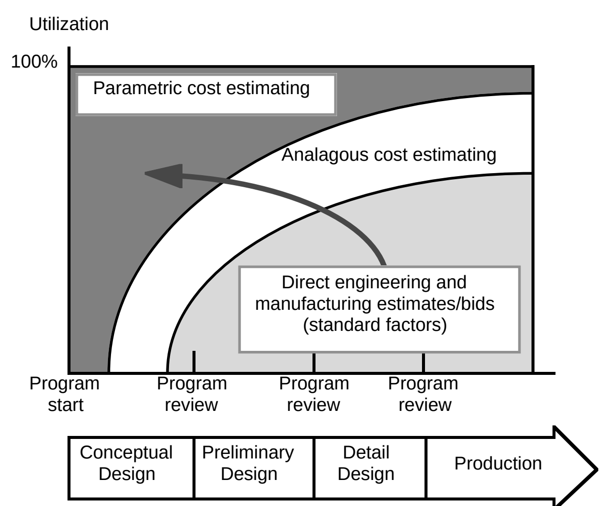

Figure 1: Estimating methods vs. phase[13]

One of the goals of this research is to provide a functional abstraction of manufacturing technology earlier in the design process. This requires the development and utilization of "bottom-up" estimating methods (to be demonstrated for a major structural component of the aircraft, specifically the wing of the HSCT) and their integration into a parametric, "top-down" LCC model. The hierarchical cost model under development for this research will utilize a definitive estimating method, primarily used previously only during or after detailed design, in the conceptual design phase, as indicated by the arrow in Figure 1.

Detailed estimates of direct material and hours used for fabrication and assembly of the wing 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) will replace the weight/complexity-based algorithm for estimating the wing cost in the top-level, parametric LCC model. Hence, differentials in the wing cost estimate due to fabrication and assembly alternatives will propagate via the system roll-up cost through the life cycle for production, operation, and support for the entire system.

With such a tool/model, the designer will be able to determine sensitivities in the top-down LCC model to changes or alternatives evaluated in the bottom-up cost model (i.e., sensitivities to manufacturing process changes). It will be possible to calculate sensitivities and design for robustness with the LCC model due to perturbations of the following factors:

◊ Entities external to the manufacturer;
◊ Functions internal to the manufacturer, but external to manufacturing; and
◊ Processes internal to the manufacturer.

The manufacturer cannot control certain factors external to the enterprise. For example, the number of aircraft ordered, the times of the orders and the corresponding payment schedules, interest rates, and projected inflation rates are not variables over which the manufacturer has complete control. The monthly or annual production rates; subcontracting decisions; learning curve effects; and distribution of RDT&E, manufacturing, and sustaining costs are factors that are internal to the enterprise, but can be categorized in a higher level than the actual material purchasing, processing, fabrication, and assembly. The sequences of activities and processes used for fabrication and assembly are assumed to be internally controlled by the manufacturer.

The lowest level of the proposed hierarchical LCC model consists of the cost estimation for the wing, based upon the direct engineering and manufacturing estimates for its major structural components as shown in Figure 1. The highest level includes determination and distribution of the non-recurring and recurring production costs, as well as the operations and support costs over the entire life cycle of the aircraft. The structure of the proposed hierarchy for the LCC model is shown in Figure 2, adapted from Meisl[5]. All constituents for each of the four levels are not shown; only the path that leads to the process/activity based estimate for the wing is illustrated. The preliminary results presented in this paper show changes in the highest level of the hierarchy as functions of assumed variations in the lowest level.

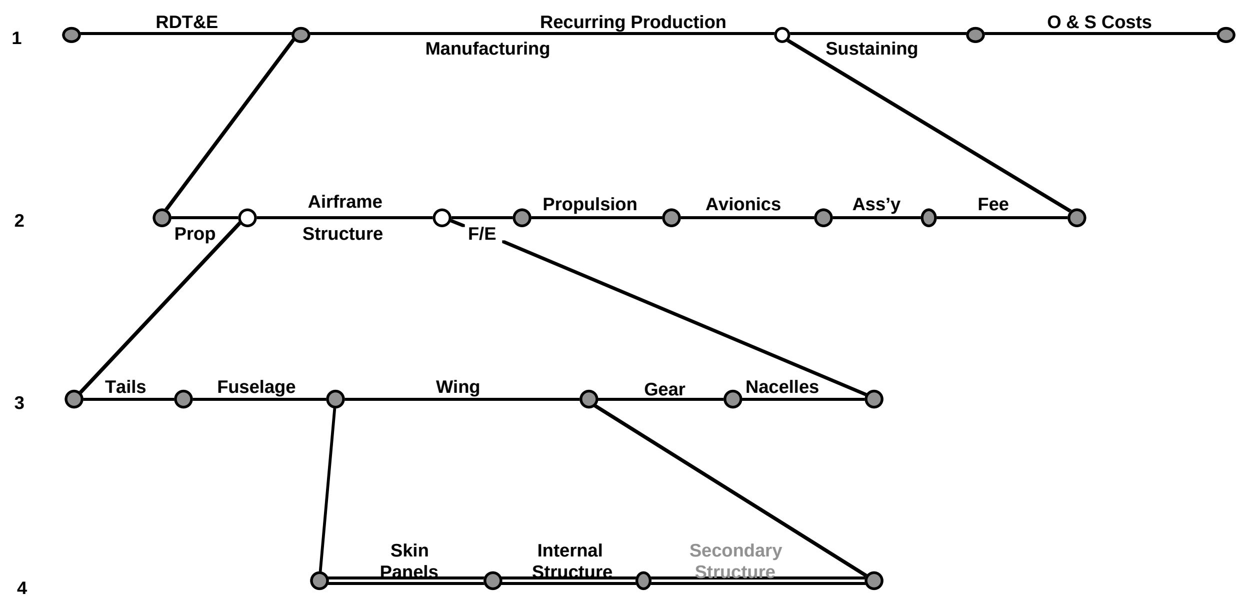

Figure 2: Hierarchical Life Cycle Cost Model

The following three sections present the mathematical theories upon which the economic analyses are based, the applications of those economic theories, and preliminary results achieved with the model. Aerospace life cycle cost modeling can be separated into two distinct, yet not necessarily independent entities, namely cost estimation and economic analysis. The emphasis of the discussions for the remainder of this paper is the economic analysis.

Economic Principles

A thorough understanding of certain economic theories must be achieved before any reasonable LCC analysis can be undertaken. Alternative investments can be compared against each other on a fair basis *only if their respective benefits and costs are converted to an equivalent economic base*, with appropriate considerations for the time value of money. Three factors are involved when determining the economic equivalence of sums of money. They are:

◊ the amounts of the sums,
◊ the times of occurrence of the sums, and
◊ the interest rate.

Interest formulas are functions of all three. These functions are used for calculating the equivalence of monetary amounts occurring at different periods of time. The following paragraphs discuss fundamental relationships that have been derived[13] for compounding interest.

Discrete Compounding Interest

The most common model used for interest calculations assumes discrete compounding interest. The compounding frequency is most often annually, but any finite period of shorter or longer duration may theoretically be used. The relationship between a present sum of money, P, and a future sum of money, F, can be expressed as a function of the interest rate, i, and the number of years of investment, n, with the following formula:

$$F = P(1+i)^n \qquad (1)$$

Solving equation (1) for P yields the present value of a future sum of money as a function of F, i, and n:

$$P = F\left[\frac{1}{(1+i)^n}\right] \qquad (2)$$

In many situations, a series of receipts or disbursements, A, occurs uniformly at the end* of each year. The sum of the compounded amount of such a series can be calculated with the following equation:

$$F = A\left[\frac{(1+i)^n - 1}{i}\right] \qquad (3)$$

Equation (3) gives a future amount, F, as a function of an equal payment series, A, an interest rate i, and n years of investment. Solving (3) for A yields the equal-payment-series sinking-fund formula:

$$A = F\left[\frac{i}{(1+i)^n - 1}\right] \qquad (4)$$

Equation (4) can be used to determine the annual payments needed to accumulate F over n years. The future amount, F, could be an initial capital investment.

* Most commonly, end-of-year payments are implicitly assumed in the model. They can be converted to beginning-of-year payments, A_b, by substituting $A = A_b(1+i)$ in these equations.

Substitution of equation (1) into (4) for F yields the equal-payment-series capital recovery formula:

$$A = P(1+i)^n \left[\frac{i}{(1+i)^n - 1} \right] \tag{5}$$

$$= P \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \tag{6}$$

As opposed to the sinking-fund formulation in equation (4), the annual payments calculated with equation (6) will not only return the initial capital investment over n years, but will also return the interest that would have been accrued on the capital investment had it been invested elsewhere at the same interest rate, i.

Periodic cash flows do not always occur in equal payments. If they increase or decrease by a constant amount, the uniform-gradient-series formula can be applied. Equation (7) expresses an equal annual equivalent amount, A, in terms of the annual cash flow at the end of the first year, A_1, an annual constant change in cash flow, G, and n and i.

$$A = A_1 + G \left[\frac{1}{i} - \frac{n}{(1+i)^n - 1} \right] \tag{7}$$

This annual equivalent amount can easily be converted to a present or future equivalent by discounting[†] backwards or forwards, respectively.

In other situations, annual cash flows may increase or decrease as functions of time by a constant percentage, g. The formula that gives the present value, P, of a constantly increasing series, in terms of the first annual flow, F_1, g, and n is given in equation (8).

$$P = \frac{F_1}{1+g} \cdot \left[\frac{(1+g')^n - 1}{g'(1+g')^n} \right] \tag{8}$$

where:

$$g' = \frac{1+i}{1+g} - 1 \tag{9}$$

is the geometric-gradient-series factor. Equation (8) can be converted to an annual or future equivalent value if desired.

Continuous Compounding Interest

Equations (1) through (5), (7), and (8) can also be applied for periods that are not annual. As long as i and n have consistent temporal variables, other compounding periods (e.g., semiannually or quarterly) may be used. In some situations, it is a reasonable assumption that continuous compounding of interest provides a better model than does annual compounding. Calculation of the limit as the number of compounding periods per year becomes infinitely large (and, correspondingly, the period of compounding becomes infinitesimally small) will yield the previous formulas converted for continuous compounding. The model that was ultimately selected for this project does not use continuous compounding; the continuous compounding equations are therefore not provided, nor discussed in detail.

[†] Discounting implies bringing values of money back or forward in time, depending on the interest rate and compounding model.

Equivalence of Money Flows

Two or more monetary amounts are economically equivalent when they have the same value for exchange. While several methods exist for generating a comparison relative to an equivalent economic basis, only three of the most pertinent are presented here.

Net Present Worth (NPW)[‡] With this technique, the cash flows through the life of the project are discounted to time zero at an interest rate representing the minimum acceptable return on capital. The project with the greatest value for its NPW is preferred. The NPW is also called the Present Equivalent Amount (PE), and can alternatively be defined as the difference between present equivalent receipts and present equivalent disbursements at a given interest rate. Values can also be calculated for Annual Equivalent (AE) Amounts and Future Equivalent (FE) Amounts.

There is some value of i, the interest rate, for which the NPW of the discounted cash flow equals zero; this value of i is, by definition, the discounted cash flow rate of return.

Discounted Rate of Return (ROI)[§] The discounted rate of return is a widely accepted indicator of profitability. The discounted rate of return is an excellent method for comparing a proposed investment opportunity with other projects. It is defined as the interest rate that causes the equivalent receipts of a money flow to be equal to the equivalent disbursements of that money flow.

Annual Equivalent Asset Cost[¶] A notable application of the Annual Equivalent formulation relates to the cost of owning an asset. The cost of an asset is comprised of two elements, the cost of depreciation and the cost of interest on the undepreciated balance. The annual equivalent cost is the *amount an asset must earn each year* if the invested capital is to be recovered with a return on the investment.

Inflation and Equivalence

The prices that must be paid for materials, labor, products, and general services fluctuate over time. Upward price movements, called inflation, should be

[‡] Depreciation is considered implicitly in NPW calculations through the definitions of the cash flows.
[§] Again, depreciation is implicit in ROI calculations through the definitions of the cash flows.
[¶] This is a particularly useful quantity when determining aircraft operating costs.

modeled in any LCC analysis that spans several years of production, operations, and support. In addition, Cost Estimating Relationships (CERs) that were developed through a regression analysis corresponding to a certain year must be modified to account for inflation.

To incorporate price-level changes, price indices must be used. Inflation rates are derived from price indices, and can subsequently be used to estimate the purchasing power of money in the future. The Department of Commerce and the Department of Labor develop the most frequently used price indices, commonly referred to as the Producer Price Index (PPI) and the Consumer Price Index (CPI). The PPI and CPI have a particular year as the base; prices and estimates are inflated or deflated depending on the number of years between the desired year of the estimate and the base year of the index. An annual percentage rate expressing the increase (or decrease) in prices over a 1-year period is defined as the inflation rate for that particular year. Most commonly, an average annual inflation rate is used for economic analyses. The single average rate represents a composite of individual yearly rates. Most life cycle cost studies depend on estimates of future inflation rates.

The importance of modeling inflation is evident if a differential exists between the interest rate and the inflation rate. The amount of money required to purchase a product today may not be enough to purchase the same product in the future if the capital were invested until a future purchase date at a given interest rate. The product's price could be more than the compounded amount earned on the investment *if* the inflation rate[#] is higher than the interest rate. This necessitates separate treatments of the earning and purchasing power of money.

Actual and Constant Dollar Analysis

To allow for the simultaneous treatment of the earning and purchasing power of money, cash flows must use consistent dollars. Money flows can be represented in terms of either constant or actual dollars.

> *Actual dollars* are defined[13] as: the dollars received or disbursed at any point in time.
> *Constant dollars* are defined[13] as: the hypothetical purchasing power of future monetary amounts in terms of the purchasing power of dollars at some base year.

Equations (10) and (11) can be used to relate constant dollars to actual dollars:

$$cd = \frac{1}{(1+\bar{f})^n} \cdot ad \qquad (10)$$

and, conversely

$$ad = (1+\bar{f})^n \cdot cd \qquad (11)$$

where *cd* represents constant dollars, *ad* represents actual dollars, and $\bar{f}$ is an average inflation rate.

Learning Curves

As the cumulative production quantity increases, manufacturing costs decrease. This can be due to 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, or 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 typically expressed as a power function:

$$\gamma = ax^{-b} \qquad (12)$$

where γ is the number of direct labor hours required to produce the x^{th} unit; *a* is the number of direct labor hours required to produce the first unit, *x* is the cumulative number of units produced, and *b* is a parameter measuring the rate labor hours are reduced as cumulative output increases. Learning curves appear as straight lines when plotted in log-log formats. The standard measure of organizational experience in the learning curve formulation is the cumulative number of units produced, a proxy variable for knowledge acquired over production. If unit costs decrease as a function of such knowledge, organizational learning in some form is said to occur. Argote and Epple[14] provide a comprehensive synopsis of the effects of learning curves in manufacturing.

Model Description

Several cost models of various fidelity levels exist as academic, commercial, or industrial products. Additionally, several emerging methods have been presented or published that are not commercial software packages. For example, Resetar presents a method[15] for determining the implications of using advanced materials on airframe structure cost. Mujtaba[16] details modeling and simulation of a manufacturing enterprise for verifying impacts of process changes and generating enterprise behavior information. In selecting the most appropriate model for this research, certain guidelines were used[13]:

- ◊ The model must represent the dynamics of the system being evaluated, and be sensitive to the relationships of key input parameters.
- ◊ The model must be flexible such that an analyst can evaluate overall system requirements as well as determine inter-relationships between various system components.

[#] Similar to the interest rate, the inflation rate has a compounding effect since the inflation rate for a given year is based on the price in the preceding year.

◊ The model must be modular so that it can be easily modified to incorporate additional capabilities or methods.

In addition, to eventually include the bottom-up cost estimate for the wing in the system Life Cycle Costs, a program had to be selected for which source code was available. The Aircraft Life Cycle Cost Analysis (ALCCA) program[17] was selected as the LCC model for this project. It has been modified by NASA Ames and the Aerospace Systems Design Laboratory (ASDL). ALCCA has been used for other research projects in the ASDL[18]. ALCCA is a powerful code that is valid for both subsonic and supersonic commercial aircraft. Inclusion of the definitive estimates for the wing component costs in the conceptual estimates for the overall system costs will constitute a pioneering framework development of a hierarchical LCC model.

ALCCA is maintained as a stand-alone program (RS/6000, AIX 3.2) and as an ASDL-developed, callable FLOPS[**] module that can be substituted for the model developed by Johnson[19].

The equations presented in the previous section of this paper provide the mathematical economic foundations for ALCCA, but they are specifically applied to manufacturer and airline economic analysis. The following paragraphs describe the capabilities of ALCCA.

Unit Production Costs

The Unit Production Costs (UPC) are estimated with a series of exponential equations for generating airframe component manufacturing costs for specific classes of aircraft. A theoretical First Unit Cost (FUC) is generated by summing the respective component costs of the airframe, propulsion, avionics and instrumentation, and final assembly. Most of the structural component cost equations are weight-based[††]. Engine costs are based on the thrust, the quantity produced, and the cruise Mach number. Alternatively, the actual price/cost of the engine can be specified as an input parameter.

RDT&E and Recurring Production Costs

Another series of exponential equations is used to calculate the RDT&E and production costs based upon the total number of vehicles produced. The average unit airplane costs, both including or excluding airframe and engine spares, are also calculated. A manufacturer's fee (profit margin) is added to the total non-recurring and recurring costs. The sum of the non-recurring and recurring production costs is divided by the number of aircraft produced to give an average unit airplane cost. Inclusion of the profit fee yields the selling price of the vehicle.

Production Quantity Analysis

A comparison of the average aircraft manufacturing costs versus the quantity of aircraft produced is provided. The elements of the total vehicle cost can be reduced with user-specified learning curves for the airframe, avionics, propulsion, assembly, and fixed equipment. Double learning curves can be defined and input for the above cost components (double or multiple learning curves could be used to model production of the L-1011 example as described earlier). The user can specify a learning curve break point, after which subsequent production will follow a second lot learning curve. Double learning curves can be used to represent reduced learning experience for a second production lot. The appropriate RDT&E and sustaining costs are calculated for different production quantities. The average cost of each aircraft for different lot sizes is calculated by dividing the sum of the cumulative UPCs, the cumulative RDT&E costs, and the cumulative sustaining costs by the total number of aircraft produced.

Manufacturer's Cash Flow

For a specified production rate (number of aircraft per month per year), shipset, 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 upon an input production rate schedule. The RDT&E costs, manufacturing and sustaining costs, and the annual income are subsequently calculated and distributed over the pre-production and production years. All costs, the income, and the net cash flow are calculated and output for 80% to 130% of the base aircraft selling price in 10% increments. The four constituents of the manufacturer's cash flow are described in greater detail next.

RDT&E Costs The RDT&E costs are calculated and distributed uniformly for five elements, mainly over the pre-production years, beginning with the first month. The five elements include: airframe development, subsystems development, avionics development, propulsion development, and development support. The initial month for cost distribution can be delayed from month one for each of the five elements. An example distribution of the five RDT&E element costs is illustrated in Figure 3.

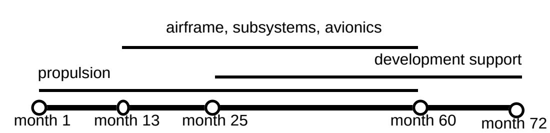

Figure 3: RDT&E Element Distributions

[**] FLight OPtimization System; a preliminary aircraft design and analysis code, NASA Langley Research Center.
[††] Several are material dependent (aluminum, titanium, or composite materials can be specified).

Manufacturing Cost   The manufacturing cost is the sum of the production costs of all operational vehicles produced each year. The costs to manufacture one vehicle include airframe cost (structure, airframe propulsion, and fixed equipment), propulsion cost (engines), avionics and instrumentation cost, and the cost of final assembly.

Based upon the monthly production rate, the total number of vehicles produced, and the number of production years, the number of aircraft produced each month (i.e., the delivery schedule) is calculated. For each vehicle, the manufacturing costs are distributed equally over the month of completion/delivery and the *preceding* 11 months. For example, for a 5-year pre-production period, it is assumed that the first vehicle will be completed/delivered in month 61. Its manufacturing costs will be distributed equally over months 50 through 61, for a total of 12 months, as illustrated in Figure 4.

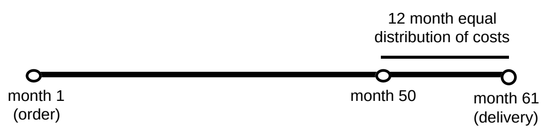

Figure 4: Manufacturing and Sustaining Cost Distributions

Sustaining Costs The manufacturer's sustaining costs are the total production costs minus the cost of the operational vehicles and the manufacturer's profit fee (27% default value). Ten elements constitute the total sustaining costs: airframe and engine spares, facilities, sustaining engineering, sustaining tooling, ground support equipment, technical data, miscellaneous equipment, training equipment, initial training, and initial equipment. The sustaining costs are distributed equally for each aircraft over the same months in which each aircraft's manufacturing costs are distributed.

Income The manufacturer's income begins in the pre-production years. A default fraction (3%) of the aircraft purchase price is paid as a down payment for each vehicle. Another fraction (77%) of the purchase price is paid upon delivery. The remaining portion (20%) of the price of the aircraft is distributed equally over the months between order and delivery. For modeling simplicity, the month of order is assumed to be the month of delivery minus the number of months in the pre-production phase. Hence, for the first aircraft produced (ordered in the first month of pre-production), again with the same 5-year pre-production period, the 3% down payment would be made in month 1, the 77% delivery payment would be made in month 61, and the remaining 20% would be distributed equally over months 2 through 60, as shown in Figure 5.

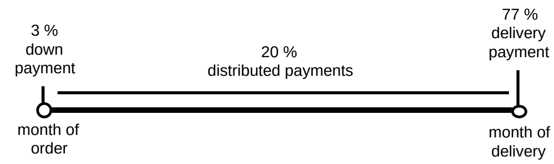

Figure 5: Payment Schedule for Income

Manufacturer's Net Cash Flow The manufacturer's net cash flow is simply the net income minus the sum of the RDT&E, manufacturing, and sustaining costs, as given in equation (13).

$$MNC = NI - \sum (RDT\&E + Mfg + Sust) \qquad (13)$$

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

Manufacturer's Return on Investment

For the same respective aircraft selling prices used for the manufacturer's cash flow analysis, the manufacturer's return on investment (ROI), the total dollar value of the profit, and the break-even unit aircraft are calculated.

The manufacturer's ROI calculation in ALCCA is based on the discounted present value of the cumulative net cash flow. A value for *i*, the rate of return, for which the NPW of the cumulative net cash flow is zero, is determined. A present value factor is calculated using equation (14):

$$PV_n = \frac{1}{(1+i)^n} \qquad (14)$$

where PV_n is the present value multiplier, and *n* and *i* are the number of years of production and the rate of return, respectively. Equation (14) is a direct application of equation (2). *PV* is simply the factor used in equation (2) for discounting a future sum of money back to the base (or present) year. *PV* is initially calculated as a function of *n*. As evident in equation (14), the later the year of production (or the greater the magnitude of *n*), the greater the discount. Therefore, when the sum of the changes in annual cash flow is multiplied by *PV*, the resulting effect is that the cumulative cash flows are discounted *more* as the cumulative year of production increases.

The sum of the changes (deltas) in annual cash flow (i.e., the cumulative net cash flow) is multiplied by *PV* to determine the discounted NPW of the cumulative net cash flow.

$$NPW_i = PV_i \cdot \sum_i (\Delta\_annual\_cashflows) \qquad (15)$$

$$NPW_i = PV_i \cdot (cumulative\_net\_cashflow) \qquad (16)$$

Changes in the value of *i* result in changes in the value of the discounted NPW. When the NPW of the cumulative net cash flow is zero, the discounted rate of return, *i*, is output as the manufacturer's ROI.

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

Operating Costs

The price at which the aircraft must be sold to earn the required ROI for the manufacturer is, in turn, the price that is used for the acquisition cost in the airlines' analysis. In addition to the mission for which the aircraft was designed, several additional "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 following paragraphs describe the operating cost components in more detail.

Direct Operating Costs (DOC) Basic speed, time, and distance variables needed to determine the operating costs are calculated first; these are mission-dependent parameters. General flight operating costs (flight crew, fuel, and oil) are calculated. Direct maintenance costs (airframe and engine labor and materials) are calculated for each mission. Investment costs are included in the DOC calculations. The investment calculations include determination of the costs associated with depreciation, financing (i.e., interest payments on the undepreciated balance), and insurance.

Simple, straight-line depreciation is used:

$$D = \frac{PR - S_{value}}{E} \tag{17}$$

where PR is the price or acquisition cost, S_{value} is the salvage value, and E is the economic lifetime in years. The annual cost of depreciation is amortized over all flights made each year.

The finance cost calculations are more complex; an *average* annual interest payment is calculated and distributed over all flights each year. The average annual interest payment is calculated as the sum of the total interest payments, calculated with the capital recovery equation (6), divided by the economic lifetime of the aircraft.

The insurance cost is a simple function of a user-specified insurance rate.

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

Total Operating Costs (TOC) The sum of the DOC and the IOC equals the 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[‡‡].

$$(\$ / RPM) = \frac{(\$ / ASM)}{load\_factor} \tag{18}$$

Airline Return on Investment

The airline return on investment is calculated for the same purchase price used in the operating cost calculations. It is also calculated for 110%, 120%, 130%, and 140% of that price. The airline ROI calculation is again based upon the NPW of the cumulative net cash flow, just as in the manufacturer's ROI calculations. The cash flow constituents are quite different, however, for the airlines. The airline net cash flow is defined as:

$$ANC = A_{rev} + S_{value} - Inv_{init} - TOC + D + I - Tax \tag{19}$$

where A_{rev} is the annual revenue, Inv_{init} is the initial investment, I is the annual interest, and Tax is the annual income tax.

Detailed descriptions of the calculations of annual revenue, the operating cost, depreciation, interest, and income tax can be found in the next section. The salvage value of the aircraft is user-specified as a percentage of the purchase price. The salvage value [by definition] is added to the airline net cash flow only in the final year of the aircraft's economic life. The initial investment is incurred in the first year of the economic life of the aircraft; it is simply the purchase price of the aircraft, assumed to be paid in full before operations begin.

The airline's cumulative net cash flow is the sum of the annual cash flows throughout the entire economic life of the aircraft. The present value factor, PV, as given in equation (14), is again used to discount the cumulative net cash flow value to zero. The rate of return for which the NPW of the airline's cumulative net cash flow is zero is the airline's return on investment. Tables of returns are given for four different average yields for both first- and coach-class fares. For unbiased estimates, all of the analyses are based upon consistent values for the stage length and annual utilization.

Operations and Support Costs

This final section provides a detailed and complex summary of the operational costs for a commercial aircraft. For a given acquisition cost, stage length, utilization, tax and interest rates, and average yields, the operations costs are calculated. The following elements of the operating costs are determined for each year in the economic life of the aircraft.

[‡‡] $/Available Seat Mile is the TOC per trip divided by the stage length, divided by the total passenger capacity of the aircraft.

Annual Revenue The annual revenue is calculated for the airline based upon the average yields for the coach- and first-class sections, the respective load factors, and the passenger capacity of the aircraft. It is also dependent upon the stage length, the annual utilization of the aircraft, and the block time of the flights. The annual revenue for the airline is calculated using equation (20):

$$A_{rev} = (AVGY_{cc} \cdot NP_{cc} \cdot LF_{cc} + AVGY_{fc} \cdot NP_{fc} \cdot LF_{fc}) \times SL \cdot \frac{U}{BT} \quad (20)$$

with $AVGY_{cc}$ and $AVGY_{fc}$ 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. Since these variables do not have temporal dependencies (BT is constant for the given mission), the annual revenue remains constant [as modeled] throughout the economic life of the aircraft.

Operating Cost As discussed previously, the total operating costs are the sum of the direct and indirect operating costs. The direct operating costs included finance charges which were based upon an *average* annual interest rate. For the more detailed analysis of the operating costs in this section, the DOC reflect the decreasing annual interest payments (due to the remaining declining yearly principle balance).

Interest The annual payments for capital recovery are calculated using equation (6). Application of that equation results in uniform values for these annual payments. These constant annual payments include payments for both the interest *and* the remaining undepreciated principle balance. Since the outstanding principle decreases annually, the interest payments decline as well. The actual declining annual interest payments and the declining principle balance are calculated. Each annual interest payment is calculated using equation (21):

$$I = PB \cdot i \quad (21)$$

where I is the annual interest payment, PB is the remaining principle balance, and i is the interest rate. The total principle paid is the cost of the aircraft.

Depreciation The depreciation is calculated using equation (17); it is constant for all years.

Earnings Before Tax The annual earnings before taxes are the annual revenues minus the operating costs.

Income Tax The annual income tax is calculated by multiplying a user-defined tax rate (default 34% for corporate and individual incomes over $350,000 per year, as required by the 1986 Tax Reform Act) by the earnings before taxes.

Net Earnings The airline net earnings are the earnings before tax minus the income tax.

Net Cash Flow The airline net cash flow was given in Equation (19). 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.

Discounted Cash Flow The present value factor, PV, for discounting back to the first year of operations, is again calculated using equation (14). PV is now calculated as a function of the economic lifetime as defined by the airlines. PV decreases as the year of operations increases. Hence, the later the year of operation, the greater the discount. The annual cash flows are multiplied by PV to determine the value for the discounted cash flow. Since the discount increases as the year increases, the magnitude of the discounted cash flow decreases as the year of operations increases.

Capital gains considerations are also modeled; however, the only capital gain incurred in the operational life of the aircraft is in the last year, with the residual or salvage value of the aircraft. Capital gains taxes are calculated appropriately for this amount (at the same rate as corporate income as per the 1986 Tax Reform Act).

The discounted rate of return, i, for which the NPW of the airline's cumulative net cash flow is zero, is output as the airline's ROI.

Preliminary Results

An implicit step in any modeling process is the calibration and validation of the model. Since no HSCT exists, there is no economic data for model calibration. However, pricing and economic data exist for the Boeing 747 commercial transport aircraft. It has been modeled in ALCCA for calibration of the manufacturer's production analysis and the airline's O&S analysis. The results of the 747 modeling are not presented in this paper.

The CERs used for component cost estimation represent the most up-to-date algorithms that are not proprietary to any particular company or institution. In addition, as previously stated, life cycle cost modeling is comprised of two parts: the cost estimation and the economic analysis. *Regardless of the confidence in the estimated component and system costs, the theories used for the economic analysis of the life cycle can be rigorously defended.* The estimated costs can be replaced with assumed costs if desired. The economic analyst can thus proceed, with due regard to the assumed values, to evaluate profitability, affordability, and overall cost-effectiveness of the system.

The definitive CERs for the fabrication and assembly processes for the wing bottom-up model were not fully integrated into the system LCC model at the time of the composition of this paper. However, in accordance with the above accreditation for model validity, the wing costs of a baseline model were scaled +/- 10% and 25%. As can be expected with a comprehensive LCC model, variations in the cost of the wing result in complex, non-linear behavior throughout the economic analysis because of the form of the equations used to model amortization, cost and income distributions, learning curves, compounding interest, inflation, etc.

The following paragraphs summarize the most significant effects as the variations propagated throughout production, operations, and support. While estimates are given for the costs and prices associated with manufacturing and operating a hypothetical HSCT, they are not presented as figures with 100% confidence. They are presented strictly as estimates for determining the trends and magnitudes of the cost effects associated with different design and manufacturing alternatives for the major structural components of the wing. The HSCT represents a conceptual configuration, generated by the Aerospace Systems Design Laboratory, with a range of 6500 nmi, cruise Mach of 2.4, and carries 250 passengers.

Unit Production Costs

The theoretical first unit cost for the baseline aircraft was estimated at $304.6M, with the wing first unit cost at $131.9M. Variations in the baseline first unit wing cost led to direct increases or decreases in the first unit cost estimate of the entire aircraft. Table 1 displays the first unit cost estimates for the system relative to the variations in the wing cost.

wing cost scale	First Unit Cost estimate		FUC scale factor
	wing ($M)	aircraft ($M)	
75%	98.9	271.7	89.2%
90%	118.7	291.5	95.7%
100%	**131.9**	**304.6**	**100%**
110%	145.1	317.9	104.3%
125%	164.8	337.7	110.8%

Table 1: First Unit Costs

These variations in wing costs, which are assumed to be due to design or process alternatives (i.e., different materials, fabrication, or assembly processes), translate directly to variations in the estimated system first unit cost of the same magnitude *in actual dollars*. As indicated in Table 1, the resulting system FUCs are not affected (scaled) by the same percentages as the wing costs.

RDT&E	base - 25%	base - 10%	**base wing**	base + 10%	base + 25%
Total	19991.2	20028.2	20052.8	20077.4	20114.3
Production	base - 25%	base - 10%	**base wing**	base + 10%	base + 25%
Operational vehicles	59797.6	63019.1	65166.7	67314.4	70535.8
Airframe spares	6204.6	6495.5	6689.3	6883.2	7174.1
Engine spares	5084.7	5084.7	5084.7	5084.7	5084.7
Sustaining engineering	13331.6	13331.6	13331.6	13331.6	13331.6
Sustaining tooling	3638.4	3638.4	3638.4	3638.4	3638.4
Ground support equip	8969.6	9452.9	9775.0	10097.2	10580.4
Technical data	1196.0	1260.4	1303.3	1346.3	1410.7
Misc. equipment	23.9	23.9	23.9	23.9	23.9
Initial transportation	344.0	362.5	374.8	387.2	405.7
Fee	26619.4	27720.6	28454.7	29188.8	30290.0
Total	125209.7	130389.4	133842.5	137295.6	142475.3
Price ($M)	264.5	274.1	**280.3**	286.7	296.2

Table 2: Non-Recurring and Recurring Production Costs

RDT&E and Recurring Production Costs

A summary of the estimated non-recurring and recurring production costs for the aircraft, relative to the scaled wing cost estimates, is presented in Table 2. The values are based upon a total production quantity of 550 units. The elements of the production costs that are affected by variations of the wing cost are shown in Table 2. The price is determined by summing the non-recurring and recurring production costs (including the fees and spares) and dividing by the total number of aircraft produced. The manufacturer's cash flows were calculated for this array of prices. A selling price corresponding to the desired rate of return for the manufacturer was calculated.

Manufacturer's Cash Flow

Figures 6 and 7 display the annual and cumulative cash flows, respectively, for the aircraft manufacturer for the base aircraft selling price of $280.3M, as given in Table 2. The distributions of the RDT&E, manufacturing, and sustaining costs, as defined in Figures 3, 4, and 5, are evident in Figure 6. The five year distribution of RDT&E costs is clear. The majority of the manufacturing and sustaining costs are not incurred until after production begins, assumed to be in the year 2000. The steep slope of the income receipts after the fifth year is due to the beginning of the (77%) delivery payments; the slope reverses near the end of the production as the production rate decreases. The net annual cash flow was calculated with equation (13).

The manufacturer's cumulative cash flow is shown in Figure 7. The dark square in the cumulative net cash flow indicates the transition point from negative (-) to positive (+) cash flow, signifying production of the break-even unit. The final value of the cumulative net cash flow is the total net profit.

Figure 8 shows the cumulative net cash flows for the productions as functions of the pre-enumerated variations in wing costs. The center band in Figure 8 represents the cumulative net cash flow from Figure 7. Intuitively, one might expect the aircraft with the lowest wing cost to show the highest profit. However, the band representing the aircraft with the highest wing cost (125%, compared to the baseline) has the highest cumulative net cash flow. This is due to the fact that the aircraft must be sold for approximately $16M[§§] more (the model cash flows represent this higher selling price) than the baseline aircraft (see Table 2) to account for the 25% increase ($33.0M) in wing cost; hence, more profit is generated with the higher income receipts. The reverse effect is true for the aircraft with the lowest wing cost. The effects on the rate of return are different if the alternatives are sold at the *same price*.

Manufacturer's Return on Investment

The manufacturer's discounted rate of return, as a function of price and production quantity, is shown on the primary axis in Figure 9. The secondary axis shows the break-even unit, also a function of price production quantity. The figure reflects intuition and reality: the lower the production quantity, the higher the price of the aircraft to generate acceptable returns. Similarly, the higher the price for a given production quantity, the lower the break-even unit. The desired rate of return for the manufacturer is used to determine the selling price of the aircraft for the subsequent operating cost calculations. For this example, a 12% ROI for the manufacturer results in a selling price of $266.7 M to the airlines.

Figure 10 presents the manufacturer's ROI as a function of the scaled wing costs. As expected, *for the same selling price of $266.7 M*, the aircraft with the lowest wing cost generates the highest rate of return. Quantitatively, a 25% *reduction* in wing costs results in an approximate 3% *increase* in manufacturer's rate of return. Additionally, the aircraft with the highest wing cost has a greater break-even unit, relative to the baseline, if sold at the same price. Hence, differentials in discounted rate of return and break-even points *as functions of the wing production cost* can now be objectively compared.

Operating Costs

An increase (or decrease) in the acquisition cost of an aircraft, *due to an increase (or decrease) in the production costs of the wing*, does not produce a noticeable effect on the direct or indirect operating costs of the aircraft. As mentioned earlier, the DOC includes the costs of flight operations (crew and fuel), direct maintenance, and investment costs. The investment costs include the cost of depreciation, finance, and insurance. The annual depreciation and finance payments are functions of the acquisition cost of the aircraft. However, when these costs are amortized over all of the flights made in a given year, small percentage differences in acquisition costs are virtually negligible in terms of increases or decreases in direct operating costs. Figure 11 shows the operating costs of the aircraft, purchased at the price that corresponds to the specified 12% ROI for the manufacturer, as a function of stage length. For reference, the required $/RPM to meet operating costs at each stage length (at a load factor of 0.55) is also included as the dashed line.

Airline Return on Investment

As given in equation (19), the airline net cash flow is a function of many elements. None of these elements are significantly affected by an increase (or decrease) in the production cost of the wing only. Figure 12 presents the airline discounted rate of return on the primary axis as a function of the acquisition cost of the aircraft and the average yield, one of the biggest cost drivers for airline revenue. A small change in the average yield can significantly affect the operation since the airlines have a very small margin of profitability. The total operating cost is also included on a secondary axis in the figure; differences of less than $15M in acquisition cost translate to operating cost variations of less than $0.001/ASM.

Operations and Support Costs

The detailed operations and support cost calculations that lead to the determination of the airline discounted rate of return are illustrated in Figure 13 for the baseline aircraft, purchased for $266.7 M, load factor of 0.55,

[§§] The $33M assumed increase in wing *cost* does not result in the aircraft *price* increasing by $33M. When all of the non-recurring and recurring production costs are amortized over the *total number of vehicles manufactured*, the price increases only by $16M (for this particular example).

average yield of $0.13/RPM, tax rate of 34%, and an interest rate of 8%. Again, the effects of the variations in wing cost were negligible (calculated, but not shown) with respect to the total operations and support costs.

Conclusions

The preliminary results presented in this paper were based on *assumed* design or process alternatives that change the manufacturing costs of the wing. The results are promising and warrant the future inclusion of the bottom-up cost estimates of the wing for definitively calculating the cost differences associated with various material, fabrication, and assembly procedures. As a by-product of this research, the benefits (in cost reductions or increased revenues) incurred as a result of technology improvements will be directly assessed. It will then be possible to objectively compare the magnitude of their effects to the effects of economic factors over which the manufacturer (and the airlines) have no control.

There is usually a conflict between *cost-effective* choices and *affordable* choices for alternative designs. Today, the desire for cost-effectiveness is often sacrificed to the practical considerations of the available funding. With the development of more complex and comprehensive life cycle cost models that can accept and process multifidelity data within an integrated design environment, it will be possible to better calculate the cost-effectiveness and affordability of future systems. Then it may be possible to design systems that are ultimately cost-effective, yet still affordable.

Future Work

The required knowledge and databases for the use of the CERs for the wing component fabrication and assembly costs will be incorporated into the integrated design environment in which the other design tools are being used. After the integration, cost-effectiveness and profitability trade-offs will be conducted. In addition, the Annual Equivalent Asset Cost may be encoded in ALCCA for the airlines' economic analyses. The geometric-gradient-series equation, as given in equation (8), may be modified to provide a more complex model of inflation for those elements in the life cycle for which inflation is not currently used.

Acknowledgments

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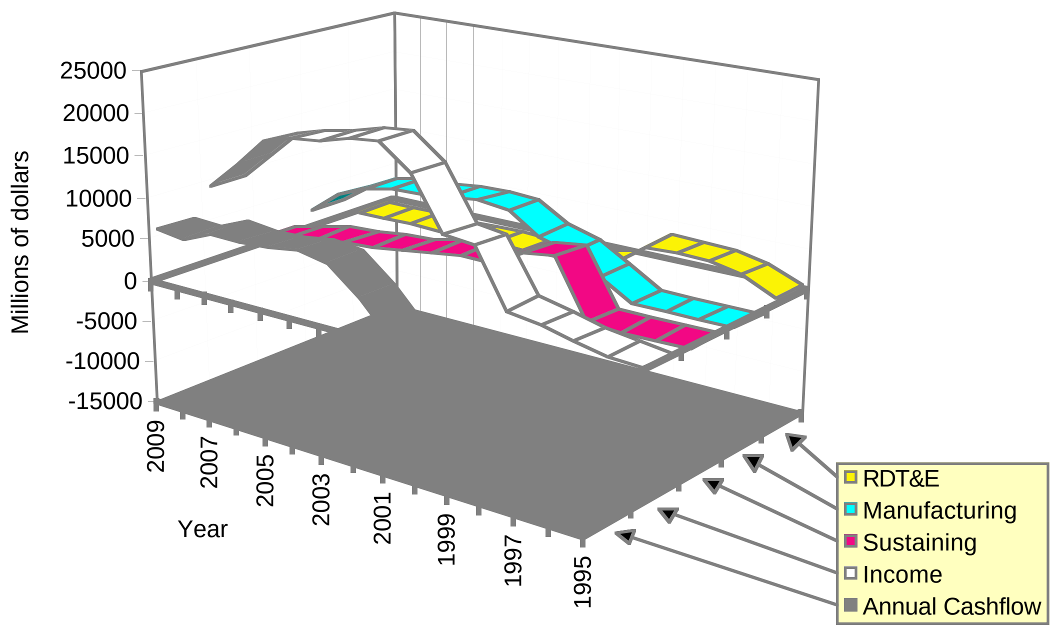

Figure 6: Manufacturer's Annual Cash Flows

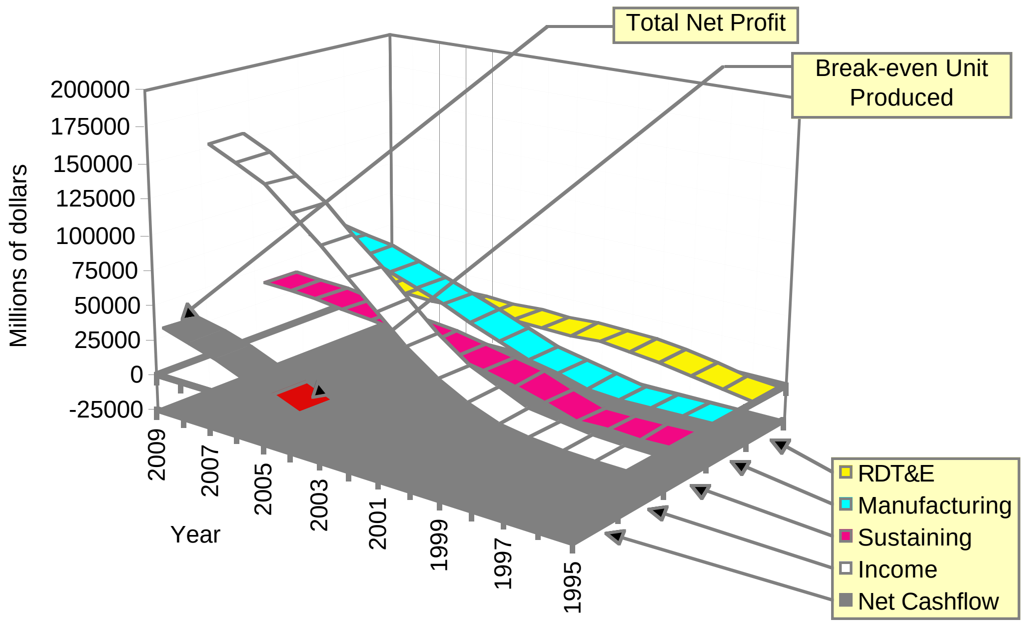

Figure 7: Manufacturer's Cumulative Cash Flows

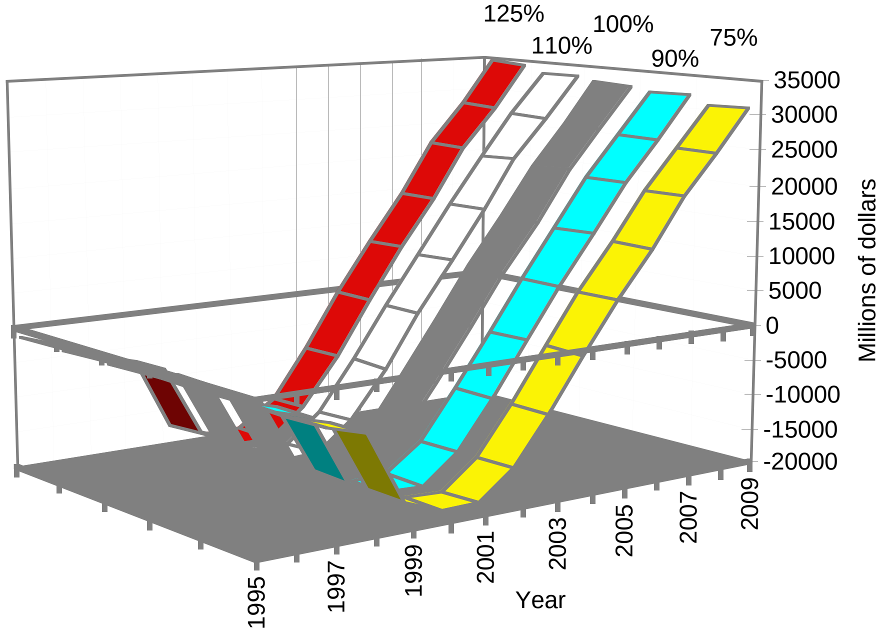

Figure 8: Manufacturer's Net Cumulative Cash Flows (for scaled wing costs)

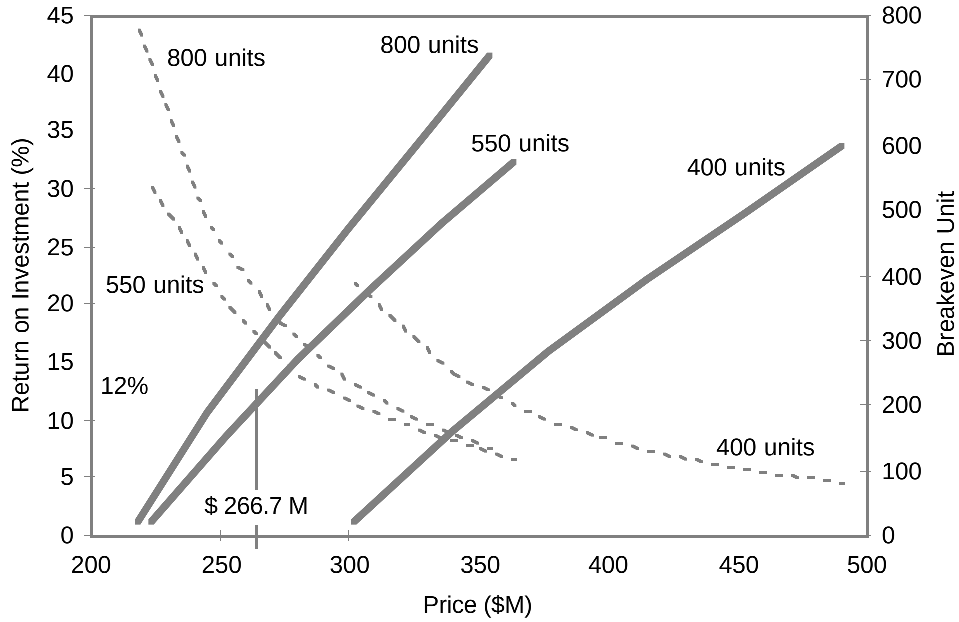

Figure 9: Manufacturer's ROI (solid lines) and Break-even Unit (dotted lines) vs. Production Quantity and Price

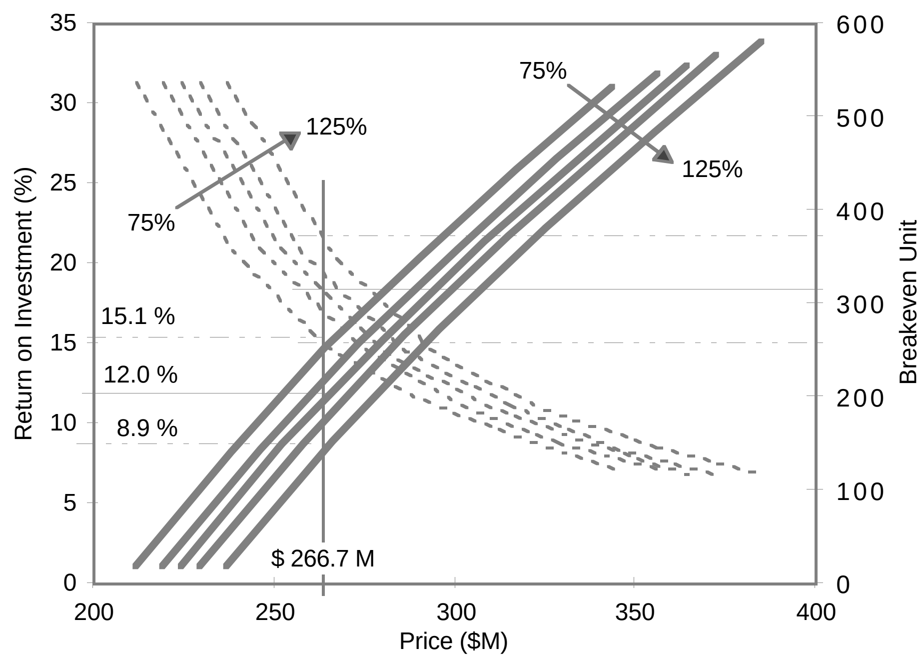

Figure 10: Manufacturer's ROI (solid lines) and Break-even Unit (dotted lines) vs. Scaled Wing Cost and Price

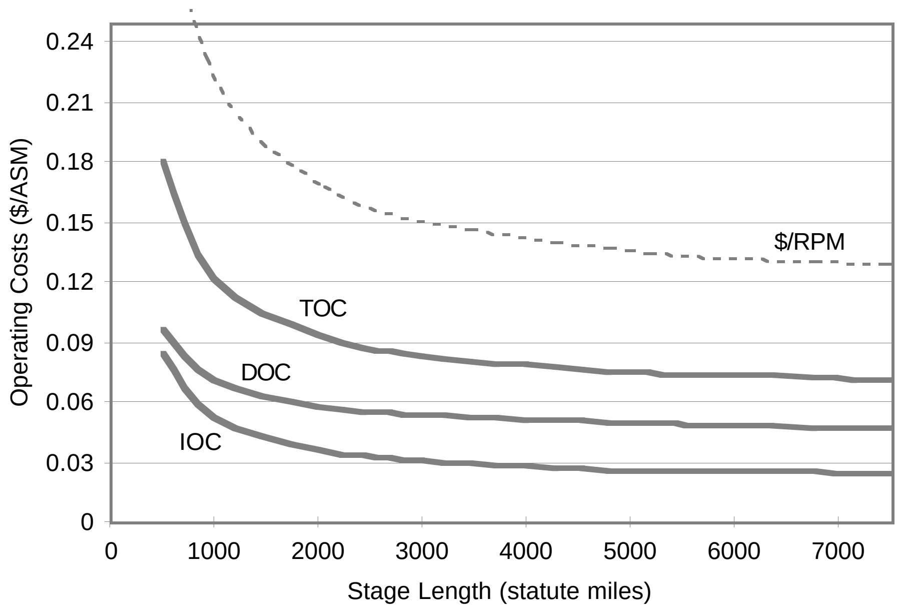

Figure 11: HSCT Operating Costs vs. Stage Length

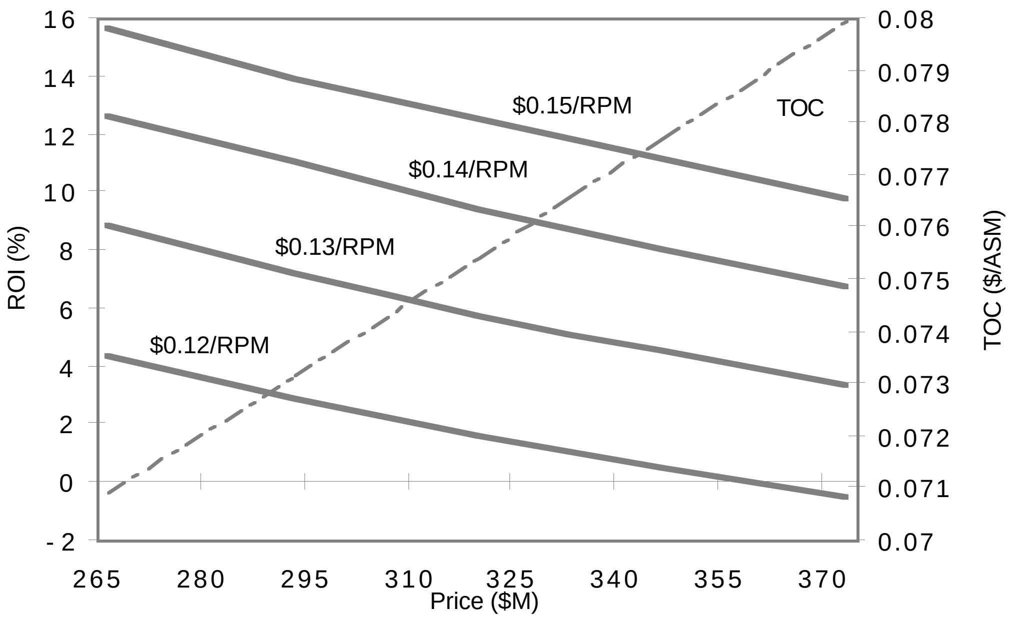

Figure 12: Airline ROI and TOC (dashed line) vs. Average Yield and Price

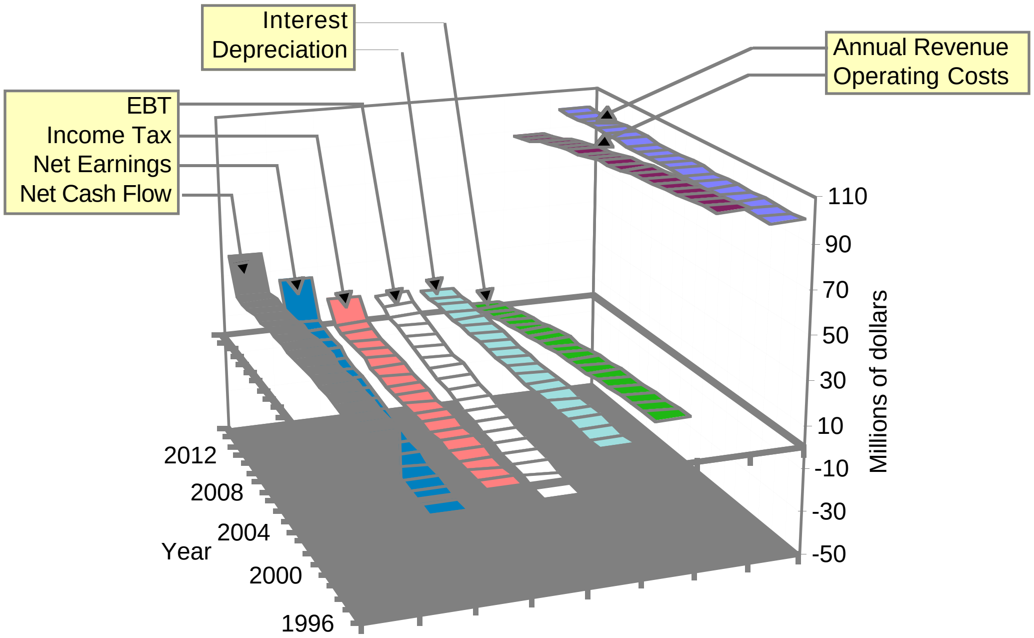

Figure 13: Operations and Support Costs