Old Dominion University Research Foundation

Final Report
June 30, 2002

NASA Research Grant: NAG-1-2195

ODURF Project: 192991

Process Cost Modeling for Multi-Disciplinary Design Optimization

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Executive Summary

For early design concepts, the conventional approach to cost is normally some kind of parametric weight-based cost model. There is now ample evidence that this approach can be misleading and inaccurate. By the nature of its development, a parametric cost model requires historical data and is valid only if the new design is analogous to those for which the model was derived. Advanced aerospace vehicles have no historical production data and are nowhere near the vehicles of the past. Using an existing weight-based cost model would only lead to errors and distortions of the true production cost.

This report outlines the development of a process-based cost model in which the physical elements of the vehicle are costed according to a first-order dynamics model. This theoretical cost model, first advocated by early work at MIT, has been expanded to cover the basic structures of an advanced aerospace vehicle. Elemental costs based on the geometry of the design can be summed up to provide an overall estimation of the total production cost for a design configuration. This capability to directly link any design configuration to realistic cost estimation is a key requirement for high payoff MDO problems.

Another important consideration in this report is the handling of part or product complexity. Here the concept of cost modulus is introduced to take into account variability due to different materials, sizes, shapes, precision of fabrication, and equipment requirements. The most important implication of the development of the proposed process-based cost model is that different design configurations can now be quickly related to their cost estimates in a seamless calculation process easily implemented on any spreadsheet tool.

In successive sections, the report addresses the issues of cost modeling as follows. First, an introduction is presented to provide the background for the research work. Next, a quick review of cost estimation techniques is made with the intention to highlight their inappropriateness for what is really needed at the conceptual phase of the design process. The First-Order Process Velocity Cost Model (FOPV) is discussed at length in the next section. This is followed by an application of the FOPV cost model to a generic wing. For designs that have no precedence as far as acquisition costs are concerned, cost data derived from the FOPV cost model may not be accurate enough because of new requirements for shape complexity, material, equipment and precision/tolerance. The concept of Cost Modulus is introduced at this point to compensate for these new burdens on the basic processes. This is treated in section . The cost of a design must be conveniently linked to its CAD representation. The interfacing of CAD models and spreadsheets containing the cost equations is the subject of the next section, section.... The last section of the report is a summary of the progress made so far, and the anticipated research work to be achieved in the future.

List of Abbreviations

ACCEM	Advanced Composite Cost Estimation Method
AHP	Analytical Hierarchical Process
BWB	Blended Wing Body
FO	First Order (same as FOPV)
FOPV	First Order Process Velocity
LC	Learning Curves
MDO	Multidisciplinary Optimization
MTM	Motion and Time Methods
MRM	Multiple Regression Models
PBMAC	Process-based Manufacturing and Assembly Cost
PL	Power Law
QM	Qualitative Methods (of cost estimation)
RM	Regression Models
RSM	Response Surface Methods
SM	Scoring Methods
Tau	y intercept of asymptote for cost hyperbola
TS	Time Study
V_0	Process Velocity, defined as units of finished parameters per unit time
WS	Work Sampling

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Process Cost Modeling for Multi-Disciplinary Design Optimization

1.0 Introduction

Old Dominion University is pleased to submit this final report to the National Aeronautics and Space Administration (NASA) Langley Research Center to address the issue of process cost modeling for multi-disciplinary design optimization. This cost model is intended for use during the conceptual phase for the design of advanced aircraft or spacecraft.

Cost is one of the most important attributes of any design, product or service. If not cost effective, any product, design or service is bound to encounter economic failure in the long run and engineers need to pay attention to this important fact. Traditionally, 'cost' is considered as a result of various engineering and operation decisions taken at various life-cycle stages of a product, process or service. *One of the important realizations by researchers is that, almost 70% of the product life-cycle cost is committed at the early design stage and preliminary design decisions affect cost the most.* (Steward82) To make the product or service more cost effective, it is imperative then to have some reasonably accurate measure of its costs at an early design stage. The same cost estimates can be used to compare various initial designs and to select the best alternative or to select the best suitable process of manufacture for a given design. An accurate, fast and robust cost estimation technique can give a competitive advantage to an organization. Ideally the cost model should be capable of estimating cost of production, operation, maintenance and retirement at the early design stage so that they can be added up to give total life-cycle cost, and the product design should be optimized based on that total cost function. Generally, costs of operation, maintenance and retirement are born by the users and costs of design engineering and production together, the so-called cost of manufacture, are the ones that are born by a manufacturer. Within cost of manufacture, production costs are predominant in many cases, and in the case of spar fabrication it is the machining operation that is the most significant. In the context of this report it is the primary topic of discussion.

The Multidisciplinary Design Optimization (MDO) methodology exploits the synergism of mutually interacting phenomena. The readers are referred to recent review articles on MDO. (Sobrieszczanski97, Giesing98) Traditional MDO tends to ignore cost and focuses primarily on vehicle performance criteria such as lift, drag, and range. If cost is included at all, then it is typically based solely on the weight of the vehicle. But this is inadequate and could even be misleading. High manufacturing cost could easily overwhelm any incentive to improve the design to the point of forcing the cancellation of the entire project. Determining the cost of manufacturing and assembly processes has been elusive in the past because of the difficulty of correctly modeling the cost of these processes.

Typically the MDO processes focus on either optimizing the vehicle aerodynamic performance (Zang99) or minimizing its structural weight. (Walsh00a and Walsh 00b) The weight is indirectly related to the manufacturing cost, and the aerodynamic performance is related to operational cost. Both weight and performance play an important role in life-cycle cost. But they are not accurate for estimating the process-based manufacturing and assembly cost (PBMAC), which is directly related to the acquisition cost. Unfortunately it has been difficult to model the PBMAC in term of typical parameters and design variables used in a traditional MDO process. The purpose of this project is to demonstrate the use of a PBMAC modeling tool with a performance analysis tool for cost-performance optimization.

1.1 Research Objectives

The research objectives for this project are:

1- Obtain and develop improved methods for estimating fabrication and other cost categories related to airframe design
2- Develop process cost methods that are truly relevant to the multidisciplinary optimization of airframe design
3- Identify the necessary relationships required to link cost methods to multidisciplinary optimization analysis procedures, and
4- Develop and demonstrate methods and procedures to include cost methods in the multidisciplinary optimization process

1.2 Status of accomplishments

The first objective has been met with the development of the First Order Process Velocity Cost Model (FOPV) following an in-depth survey of current cost estimation techniques. The essence of FOPV is that cost estimation must be based on the process that creates the part. Furthermore, among the many dimensions or measurements of the part, there must be one that dominates the rest of the others as far as cost is concerned. For machining, it is usually the wetted area. For assembly, it is the perimeter that matters. It should also be pointed out that both of these so-called "cost driver" measurements or parameters are readily extracted from the CAD model of the part, thus providing a seamless relation between physical entities and cost estimates.

The second objective has been met with the focus of our research on parts and processes related to airframe design such as spars, ribs, frames, stringers, skins, etc… The material and construction of these parts are intimately linked to the conceptual design of aircraft and spacecraft.

The third objective is an evolutionary process. The initial focus has been on machining operations, particularly those related to milling. Riveting and hand assembly has also been studied. Current and on-going efforts are being directed at all conventional and potential processes for fabricating aircraft parts.

Finally the fourth objective has been addressed by our effort to use an integration tool such as Framework CT™ to link CAD models directly to spreadsheets that contain cost equations and an interface program that emulates the bill of materials of an assembly product from a cumulative cost stand point.

In summary, the objectives set forth at the beginning of this project have been met. The most important conclusion, or impact, of this project is the fact that a framework has been established to expand our proposed process-based cost model to cover from single component to whole product for use in multidisciplinary optimization studies. The report outlines the technical approaches and subsequent results obtained throughout the time period allocated for this project.

2.0 Review of Cost Estimation Techniques

Cost is an important parameter in all design considerations. There are numerous models discussed in the open literature. The interested readers are referred to the following texts for general purpose cost models: Oswald 92, Stewart 91, and Greer 90. The space Systems Cost Analysis Group maintains a web page where a list of cost estimating models for aerospace and advanced systems is provided. (Pine 99) Bao (Bao 00b) categorized cost models into three appropriate groups for each of the three phases in the life cycle of a product: conceptual, development, and production. Figure 2.1 summarizes the appropriate cost models for each of these three phases.

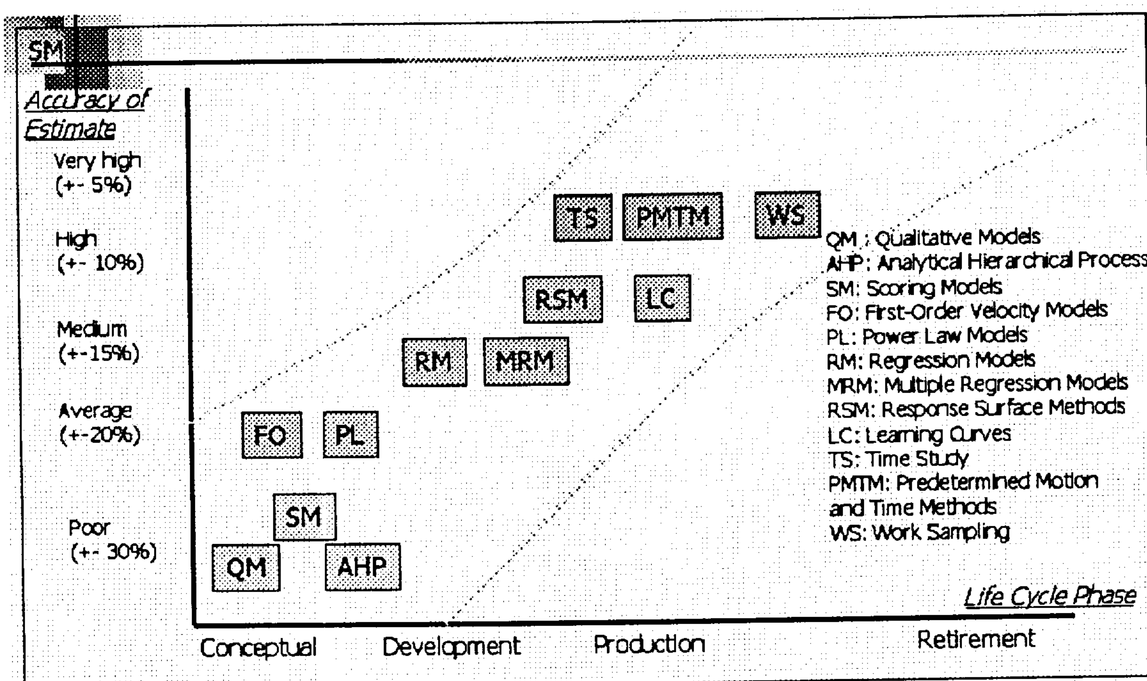

Figure 2.1. Cost models for various phases of life cycle (Bao 00b)

Since the research for this project is focused on the conceptual design phase, the following discussion is limited to the cost modeling techniques which are appropriate for this phase only. They are respectively Qualitative Methods, Scoring Models, Analytical Hierarchical Process, First-Order Process Velocity, Power Law, and Regression Models.

2.1 Qualitative Method

Qualitative methods are always useful when the following three conditions exist: 1- no historical data, 2- external factors more important than factors that governed the previous development of the technology, and 3- ethical or moral considerations overriding the technical processes. Any single or combination of the above conditions would require expert opinion. The available qualitative methods include committee decision, the Delphi procedure, cost modeling by analogy, and leading indicator.

Committee decision is the least costly approach to obtain cost estimate. The advantages of a committee include sum of information being at least as great as that available to any individual, and wide range of consideration depending on the experience of the members of the committee. On the other hand, disadvantages include potential for misinformation, pressure to agree with the majority, influence of vocal minority, and personality issues.

The Delphi procedure offers distinct advantages of group decisions while overcoming their disadvantages. It offers anonymity, controlled feedback, and statistical group response. Modern electronic meetings add further advantages to this method of forecasting or decision making in terms of time savings, distributed meeting locations, and instantaneous collaborations.

Cost estimation by analogy involves a systematic comparison of the new process with some earlier process that is similar in many respects. The difficulty is with the definition of analogies. The following dimensions may have to be addressed carefully when attempting to apply this method of cost estimation: state of technology, human interaction, economic impacts, environmental influence, ecological influence, etc...

A leading indicator for a different event or process could be used as a forecast for the process under consideration. The basic assumption is that there is a known time lag between the two events so that the occurrence of one event will predict the occurrence of the other event.

Qualitative methods of cost estimation are useful in their own right when the latter is quickly needed and when there is no historical data to rely upon. But they definitely lack the precision that many critical projects require as far as accurate cost estimation is concerned.

2.2 Scoring Model

This model is used to rank or compare several designs or products when a number of parameters or characteristics are important, and there is no analytical procedure for combining them in a composite measure.

The scoring procedure consists of three steps: 1- identify all important factors, 2- weight these factors, and 3- construct the model to obtain individual scores for each design alternative.

In the following example, there are 10 factors: 2 overriding factors (A, B); 3 factors that can be traded with each other (C, D, E); 2 factors that cannot be traded with each other but are not as overriding as A and B (H,K); and 3 factors that are detrimental (I,J,K). The overall score for any design is indicated in equation 2.1 below. Note that beneficial factors are put on the numerator side while detrimental factors are put on the numerator side, thus making the score of type "higher is better".

$$Score = \frac{A^a B^b (cC + dD + eE)^z (1 + hH)^x}{(iI + jJ)^w (1 + kK)^v} \qquad \text{(eq. 2.1)}$$

The coefficients a, b, c ,d ,e ,h , i, j, and k are such that the following relations are satisfied:

$a + b + z + x = 1$
$c + d + e = 1$
$i + j = 1$
$w + v = 1$
$0 < h < 1$
$0 < k < 1$

The score could be taken as cost estimate for a given design, thus providing a way of comparing various design alternatives as far as their relative costs are concerned.

2.3 Analytical Hierarchical Process (AHP)

The AHP process exploits the breakdown structure of a process and provides pair-wise assessment of all the factors contributing to the complexity of that process. Its application results in a figure of complexity for each process, which can then be correlated to the cost of fabrication. One crucial advantage of AHP is its tolerance for accepting a mixture of actual and judgmental data.

The following example is used to illustrate the application of AHP. 2 designs are to be compared: Design A is a known design with known cost of fabrication; Design B is the new, unknown design. Assume that the production for these 2 designs is characterized by 4 main factors: material cost, handling, versatility, and fabrication. Fabrication can be further brokeb down into 3 subfactors: labor, equipment, and tooling. A panel of experts have agreed with the following assessment of importance, or weight, for the factors indicated above: Main factors (material cost 12%, handling 38%, versatility 7%, and fabrication 43%; sub factors (labor 40%, equipment 30%, and tooling 30%). The same panel of experts have looked at the 2 designs and agreed with the following ratings (scale of 1 to 5, 1 being best):

	Design A	Design B
Material Cost	$1000	$3000
Handling	2	2
Versatility	4	1
Fabrication		
Labor	1	2
Equipment	4	2
Tooling	3	3

The complexity of design A can be calculated as:
0.12(1/4) + 0.38(2/4) +0.07(4/5) + 0.43[0.4(1/3) +0.3(4/6) +0.3(3/6)] = .4838
The complexity of design B can be calculated as:
0.12(3/4) + 0.38(2/4) +0.07(1/5) + 0.43[0.4(2/3) +0.3(2/6) +0.3(3/6)] = .5162

Based on above results, it can be stated that design B is more complicated than design A by about 7% ([.5162-.4838)/.5162]). Concurrently one can possibly say that cost of design B is about 7% higher than cost of design A.

2.4 First-Order Process Velocity Cost Model (FOPV)

This cost model is the key model advocated in this project. It is the subject of section 3 given later on.

2.5 Power Law Cost model

Power law cost models are currently the most common types of cost models being used by both industry and research communities. The popularity of power law models is probably due to their similarity with learning curve formulations. The general power law equation is:

$$t = a(\lambda)^m \qquad \text{(eq.2.2)}$$

where t : process time, or cost
λ: critical design parameter that drives process time or cost
a and m: coefficients relevant to process

Some examples of process times in the hand lay-up operation for composite material are as follows:

- Position template and tape down:
    - 0.000107 $(\text{area})^{.77006}$
- 12 inch manual ply deposition:
    - 0.05+ plies(0.001454 $\text{length}^{.8245}$)
- Transfer layup to curing tool:
    - 0.000145$(\text{area})^{.6711}$
- Stretch flange:
    - plies (length.0.064.$\text{radius}^{-.5379}$.$\text{flange}^{.7456}$)

It is obvious that power law equations have been derived from historical data. For new objects for which costs are needed, the use of these equations implies identical process and production environment. Hence the use of power law equations are quite restricted and usually not appropriate for new products or processes.

2.6 Regression Models

Like power law models, regression models are also based on historical data. Typically they appear as:

First order linear: $y = a + b(x1) + c(x2)$

Second order linear: $y = a + b(x1) + c(x2) + d(x1x2) + ex1^2 + fx2^2$

First order linear with dummy variables: $y = a + b(x1) + c(x2) + dD1 + eD2$

nonlinear: $y = a + e^{bx}$

Similar to power law models, regression models suffer from the disadvantage of being restricted to the range of original data and the same process governing these data.

2.7 Discussion

An in-depth survey of cost/time estimating models is provided in the appendix of the report to explain the different nuances among these models. From the brief presentation given above, it is apparent that cost models commonly used in the conceptual phase of a design suffer from the serious disadvantage of being derived from historical data. Some cost models, such as the Price H system, have attempted to compensate for the differences between the existing process – based upon which the power law or regression equations were derived – and the new process by the introduction of a complexity factor. A close study of how this factor was derived unfortunately reveals that it was too rough an indicator and, consequently, not accurate enough to be a reliable measure of the difference between existing process and new process. The first-order process velocity cost model (FOPV) on the other is related directly to the physical dimensions of the design, thereby offering a straightforward way to derive cost directly based on the CAD model. In the remaining portion of this report, The FOPV model is explained in detailed followed by demonstrations of its application to a generic wing. The concept of cost modulus is also introduced as a way to transcend from a known process to a related, supposedly more complicated, process. Finally an integration tool is introduced to tie in with the desire of the MDO research group to fully automate the process of cost generation for different design concepts.

3.0 First-Order Process Velocity Cost Model (FOPV)

This cost model was first proposed by the research group at the Laboratory for Manufacturing and Productivity at MIT. (Gutowski 94). Details of this cost model were further elaborated in a Ph.D. thesis. (Neoh 95). It was born out of an observation that many human and machine activities can be represented by simple dynamic models indicated by the following equation:

$$V = V_0(1 - e^{\frac{-t}{\tau}}) \qquad \text{(eq. 3.1)}$$

where V, the process velocity, has the dimension of λ/time with λ representing the appropriate variable for the process under consideration, and time t is the process time. V_0 is the steady-state process velocity, and τ is a time constant to capture the delay in attaining the full speed and should be related to the setup of that process. As indicated by Gutowski, λ could be a length, an area, or a volume, so long as it is the dominant parameter that affects process time. The process velocity, V, can be equated to the time derivative of λ, i.e. V=dλ/dt. λ can therefore be obtained by integrating V over time, resulting in:

$$\lambda = V_0[t - \tau(1 - e^{\frac{-t}{\tau}})] \qquad \text{(eq. 3.2)}$$

t is the quantity sought after. Unfortunately, equation 3 cannot be inverted explicitly for t. However two simple approximations are possible depending on the value of t relative to τ:

a. For t << τ : $t \cong \sqrt{(2\tau\lambda)/V_0}$

b. For t >> τ : $t \cong \tau + \dfrac{\lambda}{V_0}$

The above approximations could be combined into a single hyperbolic relation shown below, as suggested by Mabson (in reference Proctor 96):

$$t = \sqrt{(\lambda/V_0)^2 + (2\tau\lambda/V_0)} \qquad \text{(eq 3.3)}$$

The implication of equation 4 is that process time t is simply related to λ, the dominant geometrical feature of the part, through two parameters V_0 and τ. The accuracy of this model has been validated in the MIT study (Gutowski 94) as well as for machining data at Boeing Corporation. (Metschan 00). It has also been pointed out that equation 4 is valid for a wide range of manufacturing processes from painting to carpet laying to hand layup of epoxy fiberglass composite. Thus such an expression for process time is universal and seemingly related to one of the physical features of a part. From an MDO standpoint it means that, at the conceptual design stage, that particular feature could be easily extracted from the CAD model of the product and the cost of production could be derived directly from the equation. Thus sensitivity studies could be made to determine the impact of design features on cost.

3.1 Hyperbolic Equation

Equation 3.3 deserves further explanation, as follows. The general equation for a hyperbola is

$$\frac{(x-h)^2}{a^2} - \frac{(y-k)^2}{b^2} = 1 \qquad \text{(eq. 3.4)}$$

where (h,k) is the center of the hyperbola and the transverse axis is parallel to the x-axis. (see figure 3.1).

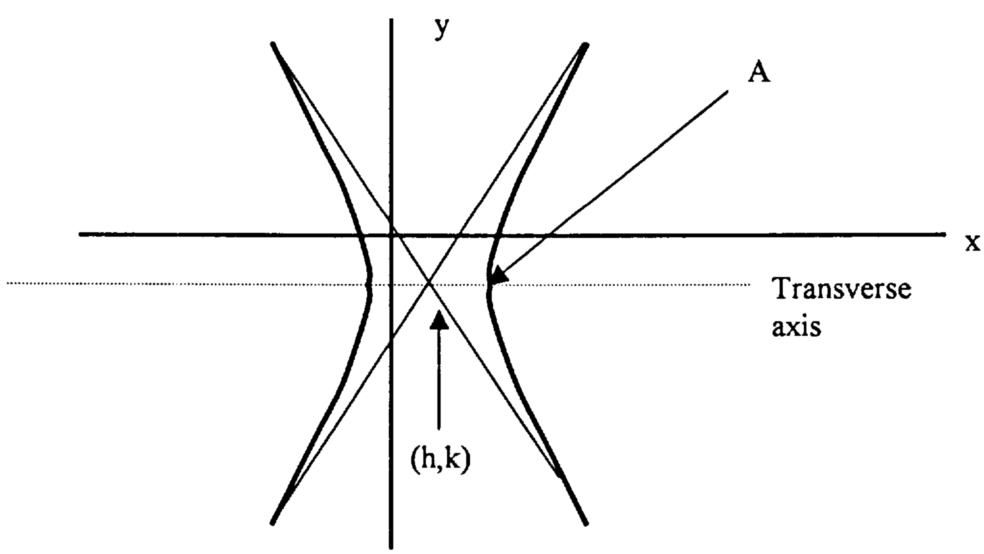

Figure 3.1 General hyperbola

If the transverse axis is coincident with x axis, then k=0. And the hyperbola equation is reduced to:

$$\frac{(x-h)^2}{a^2}-\frac{y^2}{b^2}=1 \qquad \text{(eq. 3.5)}$$

For point A to be at (0,0), eq. becomes $\frac{(x-h)^2}{a^2}=1 \rightarrow$ h=+-a $\rightarrow$ h=-a

Eq. 3.5 then becomes $\frac{(x+a)^2}{a^2}-\frac{y^2}{b^2}=1$

which leads to $y^2=\frac{x^2}{(\frac{a}{b})^2}+\frac{2bx}{(\frac{a}{b})}$ (eq. 3.6)

Let V_0 = a/b and Tau = b, then eq. 3.6 becomes

$$y=\sqrt{\frac{x^2}{V_0^{\,2}}+\frac{2\tau x}{V_0}} \qquad \text{(eq. 3.7)}$$

Eq.3.7 is, of course, identical to eq. 3.3 . Graphically it is reproduced as follows.

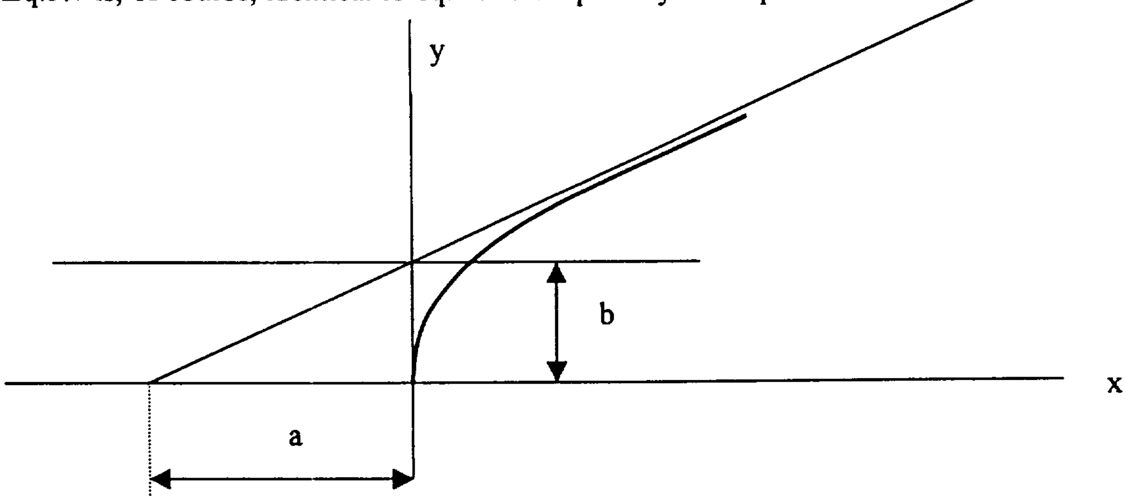

Figure 3.2 FOPV cost model

The significance of the two key parameters V_0 and τ of the FOPV cost model is indicated in the figure above:

1- V_0 is the ratio of a over b, ie the inverse of the slope of the upper asymptote; and
2- τ is the y intercept of the upper asymptote.

V_0 is interpreted as the steady state rate of change of the extensive parameter – dimension that dictates the bulk of the cost of the process - per unit time. Tau (τ) is approximately the setup cost of the process.

4.0 Application of FOPV Cost Model to Generic Wing

An aeroelastic wing known as ARW-2 is often used as a testbed for transonic steady and unsteady pressure tests in many Langley Research Center projects. (Sandford 89) The parametrerized model for this wing is shown in figure 4.1 below.

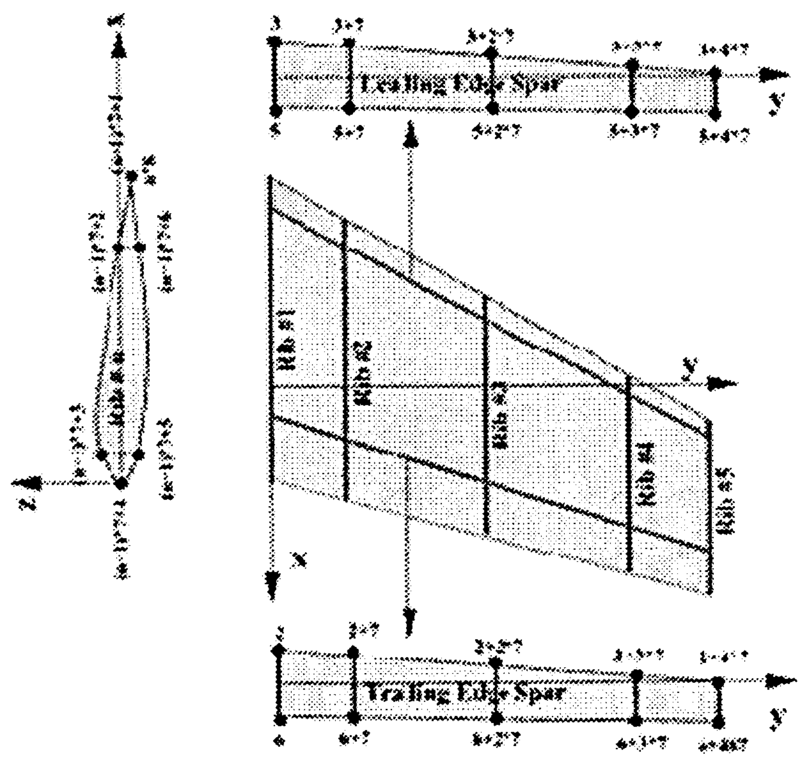

Figure 4.1 Parameterized Model of the Generic Wing

The structural components of this wing include 5 ribs, a front spar, a rear spar, and the top and bottom skin. Two types of material are considered: aluminum 7000 series, and composite. All aluminum components are fabricated by milling, while all composite components are fabricated by RTM process or lay-up process. Actual process times were collected from industry sources and indicated by corresponding V_0 and τ values as follows.

Table 4.1 V_0 and τ values for Generic Wing

Material	Components	V_0	τ	Extensive Parameter
Aluminum	Skin Fab	3.024	3.1123×10^4	Wetted area
	Rib Fab	2.059	4.1423×10^4	Wetted area
	Spar Fab	2.4624	3.6934×10^4	Wetted area
	Assembly	0.0395	2.1341×10^4	Perimeter
Composite	Skin Fab	2.1447	4.3883×10^4	Wetted area
	Rib Fab	0.8236	1.0356×10^5	Wetted area
	Spar Fab	1.4485	6.2788×10^4	Wetted area
	Assembly	0.02826	2.9877×10^4	Perimeter

The ARW-2 wing described in figure 4.1 is reproduced in SolidWorks™ and shown in figure 4.2 below.

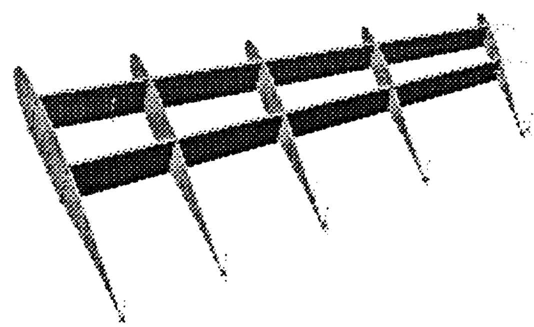

Figure 4.2 CAD representation of generic wing in SolidWorks

Typical of most contemporary CAD tools, SolidWorks can easily provide geometric data such as surface area and perimeter of individual components. These measurements can then be coupled to the respective V_0 and τ values of table 4.1 to calculate costs. A spreadsheet can be used to develop total cost of wing through a number of iterations for different geometric configurations of the wing. The calculation process is shown in figure 4.3 below. Forty-six different geometric configurations of the wing have been considered, and their costs determined as shown in figure 4.4. Cost contribution by separate elements have also been determined and shown in figure 4.5. From figures 4.4 and 4.5, it is obvious that some geometric configurations are less expensive than others. This information is extremely important for the designers to know while they are deciding on alternative designs and trying to optimize their choice from a multi-disciplinary standpoint, including cost. A broader discussion of this issue is included in the paper "Affordable Design: A Methodology...." attached in the appendix section of this report.

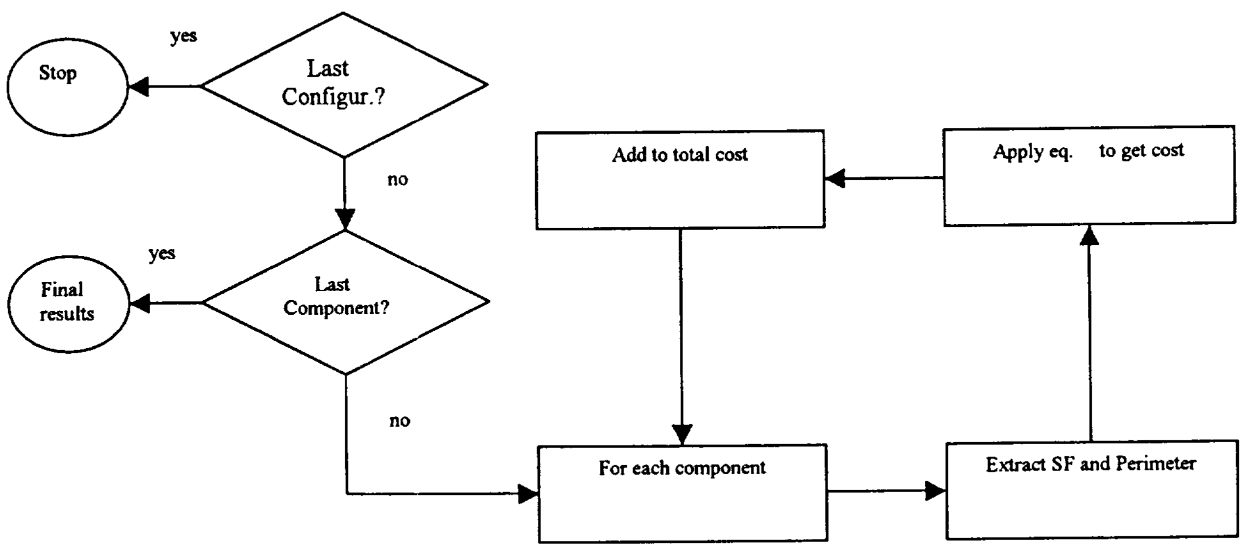

Figure 4.3 Cost calculation process

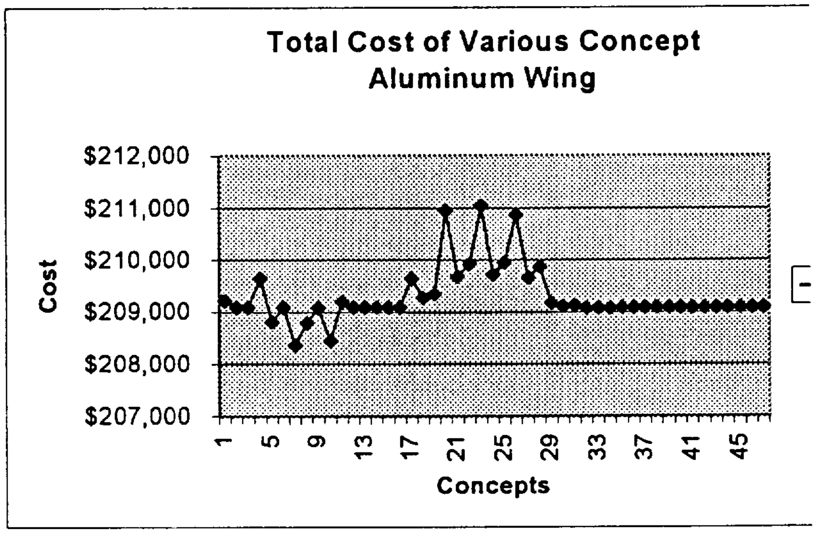

Figure 4.4 Costs for different wing geometric configurations

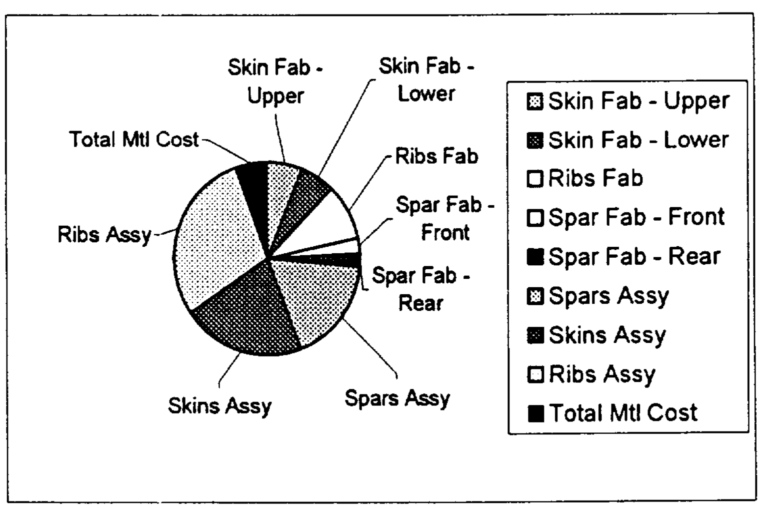

Figure 4.5 Cost contributions from various elements of the win

5.0 Concept of Cost Modulus

The First-Order Process Velocity Cost Model (FOPV) discussed in sections 3 and 4 relies on an actual process, for example milling operation, assembly of skin for the generic wing, etc..., to determine the critical V_0 and τ values for insertion into eq. 3.3 for cost to be calculated. Suppose now that a slight variation to that process is dictated for a new part. This variation may be due to a different material, a different shape , a different precision requirement, etc... Strictly speaking, a modified process must be available first before experimentation can be made to determine the new V_0 and τ values. In practice, such a modified process would be difficult and/or expensive to acquire. Short of acquiring the new process, how can one have the V_0 and τ values for that process? The solution can potentially come from the application of a Cost Modulus concept as explained in this section. For illustration purpose, the explanation is based on a machining process but, theoretically, the concept could be extended to any type of processes or operations.

5.1 Manufacturing Cost Estimation

The costs in metal cutting are of four major types and can be put together in Eq. 5.1 0:

i. Handling or Work Setup cost
ii. Machining cost
iii. Tool changing cost
iv. Tool cost

$$C_o = Mt_1 + Mt_m + M\left(\frac{N_t}{N_b}\right)t_{c_t} + \left(\frac{N_t}{N_b}\right)C_t \qquad \text{(eq. 5.1)}$$

Where;

C_o	= Production cost per piece	N_t	= Number of tools used
M	= Total machine and operator rate	N_b	= Number of components in a batch
t_1	= Work setup time	t_{c_t}	= Tool change time
t_m	= Machining time per component	C_t	= Cost of each tool

One of the most significant effects on cost of cutting comes from cutting speed choice. Much of the experimental work has been done and standards evolved to facilitate the selection of operating conditions. There are cutting conditions tabulated by the Machinability Data Center (MDC), Metcut Research Associates inc., in two volumes of Machining Data Handbook. The American Society of Metals (ASM) also publishes data on metal cutting parameter. All this information is essential to get an exact picture of metal cutting economics and estimation. The above equation suggests that the problem of cost estimation is essentially a problem of process time estimation compounded with estimation of other specifics like machine hourly rate and tooling. As one looks at current cost models, it is apparent that virtually none of them used solid process-based considerations like those indicated in equation (1), but rather one finds that statistics, fuzzy logic or some combinations of inferring tools have been used to estimate cost. The cost model proposed in this paper is a first step in a direction that attempts to eliminate the use of inferring tools and drawbacks associated with them, and to explain manufacturing or process cost on the basis of scientific and technical reasoning.

5.2 Cost Modulus

The inputs to the model are extracted directly from a CAD file and are listed as follows:

- Principal shape
- Dimensions
- Material
- Manufacturing Precision
- Equipments and Tooling
- Technical Data and Information

The design description may vary based on the stage of product development. There are two aspects of the data: details and accuracy. At an early design stage, data may be very sparse and inaccurate while at a later detail design stage the data may be more accurate. Same is the case with the available details about a design. But, whether it is an early design stage or detail design stage the data can be put in the same format as given above. Only the details and accuracy of the data will vary.

The proposed generic cost estimation system relies on relative cost estimate rather than on absolute cost estimate. The concept of relative cost estimation was necessary and important because some specific cost details, which are not available at the early design stage anyway, can be skipped. One can still proceed without those specifics and come up with the cost of a design in relation to known cost of a standard reference product or design. General manufacturing rules, principles and databases are used as a basis for comparison and evaluation of the relative cost. These rules, based on scientific data, analysis and studies are the same everywhere irrespective of the specific conditions of manufacturing setup. For example – if cutting speed of a carbide tool on 1020 steel is 180 ft/min for 60 min of tool life in turning operation, which is common and considered to be 'reference' on the basis of experimental and scientific data, then this rule holds true everywhere irrespective of time and space coordinates. Using such 'reference' practices and rules, 'reference' designs for each manufacturing process can be evaluated for their manufacturing costs, and all such 'reference' estimates can be stored in a system database for the comparison. Any new design then can be evaluated in relation to the 'reference' design based on same widely accepted principles and standard rules.

When cost is considered as a property of a design or a part from a scientific perspective, this gives rise to a concept of '***fundamental coefficient of cost***'. The coefficient is named ***'Cost Modulus'*** and it reflects the cost of the part. The Cost Modulus is an index of cost of a design compared to some standard reference design of which cost is known. By definition, a reference part or design is known to have cost index or cost modulus of 1, and other designs can be compared to the reference design to identify their cost modulus. For example, in case of milling operations, the manufacture of a 12"x12"x12" (1 cu.ft.) of solid pure aluminum block, with material equally removed from all of its six faces, with conventional milling tolerances, and with one final finish cut can be regarded as a design having milling cost modulus equal to 1. Other design with milling cost modulus of, say 3.5, would mean that that design would cost 3.5 times the cost of the previously specified reference design.

The process cost of a product or part in a given setup can be written as the summation of products of processing time and setup rate for individual processes.

$$C = \sum T \times S \qquad \text{(eq. 5.2)}$$

Where;
C = Process cost
T = Process time
S = Setup rate inclusive of equipment and manpower cost in $ per unit time

Processing time for a part is related to physical properties of a design like shape and size of the features to be manufactured, the material of construction, and the required precision. The manufacturing setup required is also a design consequence. Setup also depends on the design specifications like shape, size, type of operation, tolerance etc. So, it is clear that design specifications affect both time and setup costs and that's how manufacturing cost is a consequence of the design specs.
Applying eq. 5.2 to a Reference Object design, we get

$$C_{RO} = \sum T_{RO} \times S_{RO} \qquad \text{(eq. 5.3)}$$

Where;
C_{RO} = Cost of Reference Design
T_{RO} = Processing time for Reference Design
S_{RO} = Setup rate for Reference Design

The process cost modulus can therefore be defined as the ratio of process cost of actual design to process cost of standard design. So, taking ratio of Eq. 5.2 and Eq. 5.3 we get;

$$C_m = \sum\left[\left(\frac{T}{T_{RO}}\right)\times\left(\frac{S}{S_{RO}}\right)\right] \quad \text{(eq. 5.4)}$$

Where;

C_m = Process cost modulus

This Eq. 5.4 is a general equation and provides the way to consolidate various process time and cost effects due to design specifications. It can be seen that, process cost modulus of a part is equal to the product of relative process time and relative setup rate. So, the cost modulus has two components, one based on relative process time and the other based on relative setup cost. The design affects the decision of selecting certain setup that reflects as relative setup cost and also the processing time that reflects as relative process time. It is critical at this point to investigate how design actually affects the processing time and setup cost components and how design specifications can be used to quantify these effects.

If Cost Modulus is considered to be a design consequence, like other physical properties of a design such as weight, volume, surface area, moment of inertia etc., process cost modulus should be evaluated from the design specifications. A more intense thought to the root cause of cost reveals that the cost of a part or assembly depends on the following characteristics or specifications: size, shape, precision, equipments and material of construction.
The discussion above can be summarized in Eq. 5.5:

Cost Modulus = f (Size, Shape, Precision, Material, Equipment/Tooling,) (eq. 5.5)

Size leads to processing quantity, which leads process time
Shape leads to possible processes, which leads to process and tooling complexity
Precision leads to additional care, hence cost
Material leads to process parameters
Equipment leads to setup cost rate

Individual effects of these design specifications have been analyzed further and presented in [5]. The final Cost Modulus C_m is computed from the Cost coefficients that are declared and defined based on their individual effects on the machining characteristics and the cost thereby. These Cost Coefficients are tabulated in Table 5.1 below.

Table 5.1: List of Cost Coefficients

No	Description	Notation	Related Design Specification	Process Impact	Cost Effect Variable
1	Predominant Variable OR Size Coefficient	C_v	Change in Volume	Machined Volume	Productive Process Time – Roughing

2	Cost Coefficient - Shape, Process Velocity	C_{p_v}	Shape	Process Velocity	Productive Process Time - Roughing
3	Cost Coefficient – Shape, Tool Settings	C_{p_n}	Shape - Number of Features	Tool Setting Time	Non-Productive Time
4	Cost Coefficient – Shape, Work Settings	C_{p_w}	Shape - Faces to be Machined	Work Setting Time	Non-Productive Time
5	Cost Coefficient – Precision, Tolerance	C_{pr_t}	Precision – Dimensional Tolerance	Processing Time, and Equipment Cost	Total Cost before tolerance correction
6	Cost Coefficient – Precision, Surface Finish	C_{pr_s}	Precision – Surface Finish	Process velocity – Finish Cut	Productive Process Time - Finishing
7	Cost Coefficient – Material, Rough Cutting	$C_{mt_{rv}}$	Material	Process Velocity – Rough Cut	Productive Process Time Roughing
8	Cost Coefficient – Material, Finish cutting	$C_{mt_{fv}}$	Material	Process Velocity – Finish Cut	Productive Process Time - Finishing
9	Cost Coefficient – Material, Tool Cost	C_{mt_t}	Material	Tool Replacement	Tooling Cost
10	Cost Coefficient – Equipment Factor	C_e	Physical Size	Equipment Size	Equipment Setup Cost

Eq. 5.1 can be used to find the cost of manufacture of a reference object. The individual 'cost' terms in the same equation for computing the actual design are then calculated by using the relative Cost Coefficients tabulated above that depend on the 'law of scaling'. Once the scaled cost of the actual design is available, the cost modulus is nothing but the ratio of actual design manufacturing cost to the Reference Object manufacturing cost. The following equation represents the arrangement of Cost Coefficients that gives the Cost Modulus, C_m, which is nothing but the representation of cost of machining the actual design relative to that of the reference object.

$$C_m = \left[\frac{\left(\frac{C_v}{C_{p_v} C_{mt_{rv}}} + \frac{P_f P_s}{C_{mt_{fv}}} C_{pr_s} + (1+P_f) P_{n_t} C_{p_n} + P_{n_w} C_{p_w} \right) \left(1 + P_t C_{mt_t}\right) C_e C_{pr_t}}{\left(1+P_f\right)\left(1+P_n\right)\left(1+P_t\right)} \right] \qquad \text{(eq. 5.6)}$$

In this equation, all P's are percentage factors that can be found from detail process plan of the Reference Object manufacturing. And all C's are the Cost Coefficients that are calculated from design specification of the actual design, engineering data and Reference Object specifications as described by various equations in the previous section. The Cost Modulus equation is based totally on design specifications of actual design, engineering data related to metal cutting process and definition of Reference Object. This is the first close-loop equation that translates design specifications into a single 'Cost' related parameter called Cost Modulus. If the absolute cost of Reference Object is known, then absolute cost of Designed Object can be found out by multiplying its Cost Modulus by the Reference Object cost.

5.3 Application of Cost Modulus to Aircraft Spar Design

As discussed previously the first requirement in this cost estimation case study is to define a 'reference object' in relation to which the cost will be estimated. In the case of an aircraft spar milling cost estimation, the complete design specifications for the Reference Object can be summarized as below.

- Shape: Box type, cube
- Size: 12"x12"x12"
- Tolerance: range 0.010" all sides, straightness and flatness
- Surface Finish: 125 μin Ra
- Material: Aluminum, cast, 99.99%

A typical process plan for the standard object specified above would involve the use of an appropriate milling machine to machine each of the six sides. Every time a tool would be changed for roughing and finishing of each surface. The work piece would be set six times, one time for each side. Initial cleaning and setup as well as final cleanup would be included as a part of the process. All these details plus any additional details for the process plan could be added based on the location specific conditions. The volume to be removed from the Reference Object can be identified by considering a 10% machining allowance on each side. This means initial raw stock dimensions of 13.2"x13.2"x13.2". The difference of final object volume to raw volume is therefore 571.968 in^3, and the cost incurred in processing this on standard recommended machine with recommended tools is the cost of the Reference Object process cost. These details of reference object and its process plan are sufficient to evaluate the percentage factors, all P's in Eq. 32. The spar was designed using CAD software as shown in Fig. 5.1. The data that was extracted from this model include total volume after machining, number of features, and surface area for finishing. The methodology of implementation is explained below.

There are three major components of the implementation of the case study.

- Design Data
- Material Data
- Calculations Worksheet

These three components interact with each other. At this point of time this interaction is carried out manually but if intended for the professional use, the system needs to be automated and more sophisticated. This can be done by using OLE (Object Linking and Embedding) and API (Application Programming Interface) interfaces. Each of these components is discussed in the following sub-sections.

Design Data:

The parametric model of an aircraft spar was built in CAD system and design data such as volume, surface area, length, etc, were exchanged back and forth with the Cost Modulus calculating worksheet. The following parameters were kept independent for generating various combinations of the design so that their cost impacts can be studied. These parameters are important from the functional design point of view and they are prime consideration while designing a spar.

- Spar length
- Larger Cross-section Web height and
- Pitch of 'the holes' or pockets on the face

Material Data:

A large amount of data related to metal cutting process has been published in various sources like the Machinability Data Center handbooks, the Tool and Manufacturing Engineers Handbook. Generally, this data would be stored in a database, but because only a small set of data was needed for the demo purpose, it was directly put in the same worksheet that was used for creating the design configurations. The material data used was:

- Metal cutting parameters
- Specific Cutting power values

Calculation Worksheet:

Simple worksheets were used for the required calculations based on the design data and material data. First individual Cost Coefficients and then the final Cost Modulus were calculated. Some constants, as mentioned in the previous section, are based on actual process plan of Reference Object. These constants were identified from process based cost estimates obtained using a commercial Cost Estimation software. The worksheet interfaces with Solid model and material data and finally calculates the Cost Modulus.

Model Application and Results:

The study was conducted by varying one of the concerned parameters while the others are kept constant. The following are the results of this study.

Material Choice:

Keeping all dimensions, precision and shape the same, if designer varies material of construction of the spar, then the processing cost varies according to Fig. 5.2. It can be seen that machining the design with Titanium alloy construction was found to be 4.63 times costlier to machine compared to the one in Aluminum alloy in same case. Two things need to be mentioned here. First, this is just a processing cost and does not include material cost. And secondly, this 'relative cost ratio' is design specific. Qualitatively we know that Ti-alloys are difficult to machine compared to Al-alloys but the model allows us to quantify that fact for a given design. This graph could also be plotted against relative strength or strength to weight ratio, thus giving the designer a clear idea of deciding the correct material choice.

Surface Finish Area:

The finishing cost is affected by the amount of surface area to be machined by finishing operation. Figure 5.3 shows this effect. As the amount of finished area is increased from 0% of the total area of object to 100%, the machining cost increases by almost 5.68% in case of Aluminum as a material of construction. The same variation is of the order of 40.57% if the material is 60-40 Cr-Ni-alloy. This shows that material has a significant impact on finish machining cost.

Tolerance:

The more stringent the tolerance specification, the higher is the manufacturing cost. Considering process capability equal to 0.008 in and tolerance specification of 0.008 as a reference case, the machining cost is almost 7.96 times the reference cost if the tolerance limits are halved. This information could be of much importance to designer as well as process planners while deciding the tolerance and while deciding process respectively.

Machined Volume:

While machining 5000 cubic inch of aluminum it takes 12.7% more cost compared to machining of 2500 cubic inch of aluminum in the case of the spar design. For other materials these figures would be different.

Pocket Features:

Pockets are generally difficult features to machine compared to plain surface machining. Increased material removal from pockets would significantly affect the overall cost of machining. The study shows in case of an aluminum spar how machining cost is affected by increasing pocket volume to be machined. If the volume in pockets is 60% of the total volume to be machined then the machining cost is more by 19.16% compared to the machining cost of the same Spar without any pockets.

Number of Features:

A higher number of features mean more tools to be used initially and certainly, additional cost is associated with that. If the number of features increases from basic 3 to 11, the cost jumps 2.4 times. This shows every additional geometric feature has a significant cost in the case of a spar manufacture.

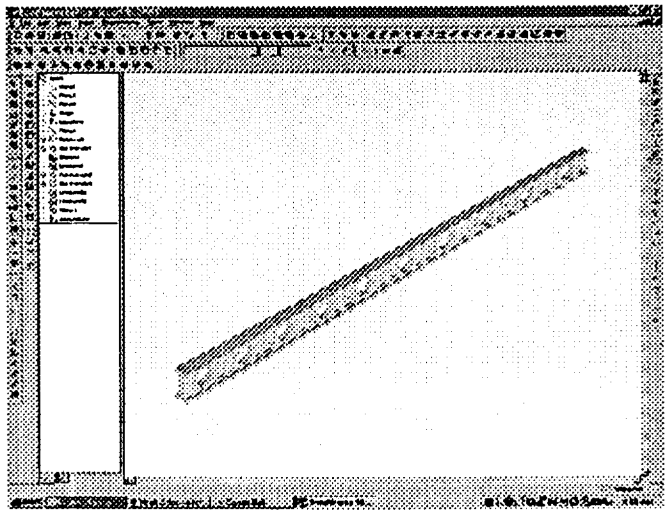

Figure 5.1 Spar design for cost estimation

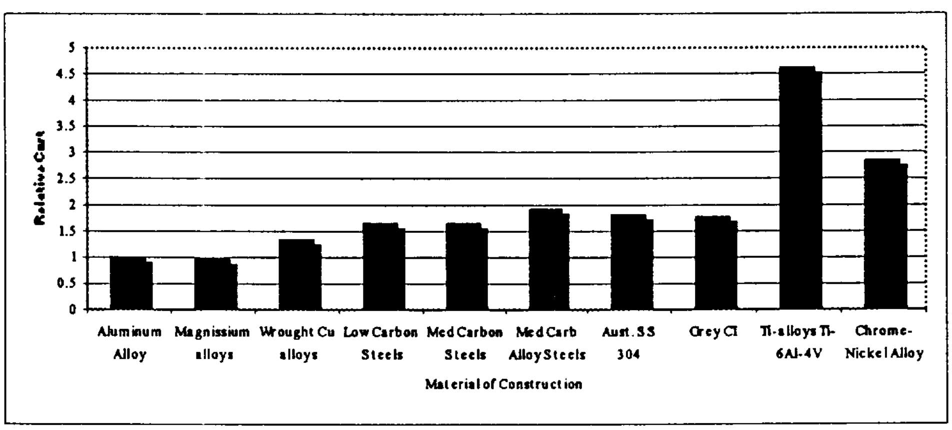

Figure 5.2 Effect of material choice on total machining cost of spar design

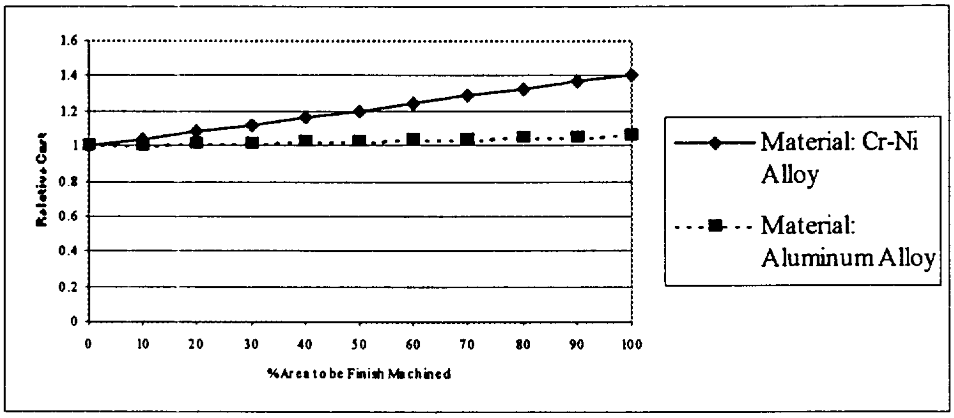

Figure 5.3 Effect of extent of surface area on total machining cost of spar design

6.0 Integration Tool

In order to link cost calculation to alternative concept designs, an integration tool must be developed to extract the critical dimensions from CAD models and pass them on to spreadsheets for cost determination. After exploring a variety of software tools, Framework CT™ from Teamvision Inc. has been selected to play the critical role of systems integrator. Teamvision, Inc. has had a long association with NASA Langley Research Center in work related to cost optimization for transport aircraft design evaluation. (Proctor96).

The base technology of Framework CT™ is the Common Object Model (COM), which is one of the core technologies for Microsoft products. It essentially allows the user to create a network of spreadsheets and common engineering applications such as SolidWorks, MS projects, and Matlab. Using Framework CT, the user can move data easily from one application program to another. Its graphic capability is superior to many common application tools, thus allowing knowledge workers to display composite data from unlimited sources. Its core elements include classes, instances, links, and analysis explorers. Class explorers are used to create or specify the behavior of attributes of each type of classes. Instance explorers are objects, or image of classes. Link explorers explore the relationships among objects using graphs, diagrams, networks, or simple mathematical relations. Analysis explorers are essentially various "what-if" scenarios composed by the user. The various explorers are shown in figure 6.1 below.

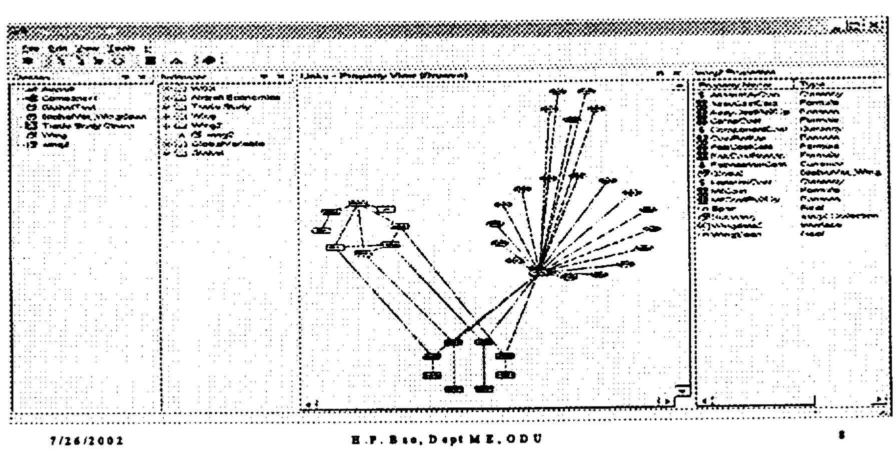

Figure 6.1 Frame CT's main screen

In the context of this project, the objective is to link a SolidWorks™ design to a spreadheet that contains cost estimation equations. To remind the readers, the data extracted from

SolidWorks include lengths, surface areas, volumes, and perimeters. The cost equations in the spreadsheet provide the values of V_0 and τ which, when applied to the physical data from the CAD model, lead to costs. Framework CT's role is to send basic, overall dimensions of the design to SolidWorks. SolidWorks passes the resulting measurements of lengths, surface areas, volumes, and perimeters to spreadsheet. Spreadsheet calculates costs. And costs are returned to Framework Ct. Framework CT repeats the cycle for as many different design configurations as needed. At the end, Framework CT displays costs as per specification form the user. Figures 6.2 and 6.3 summarize the calculation cycle.

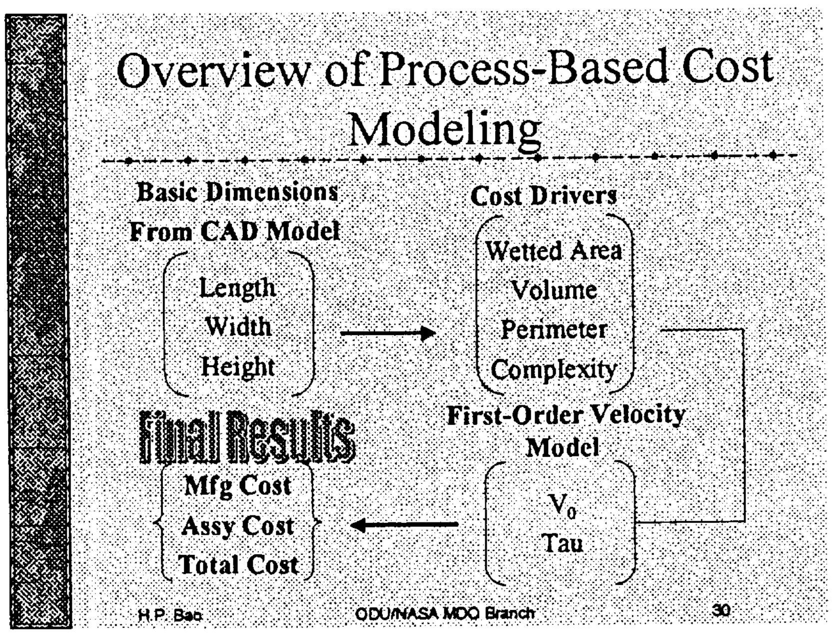

Figure 6.2 Overview of Process-Based Cost Modeling

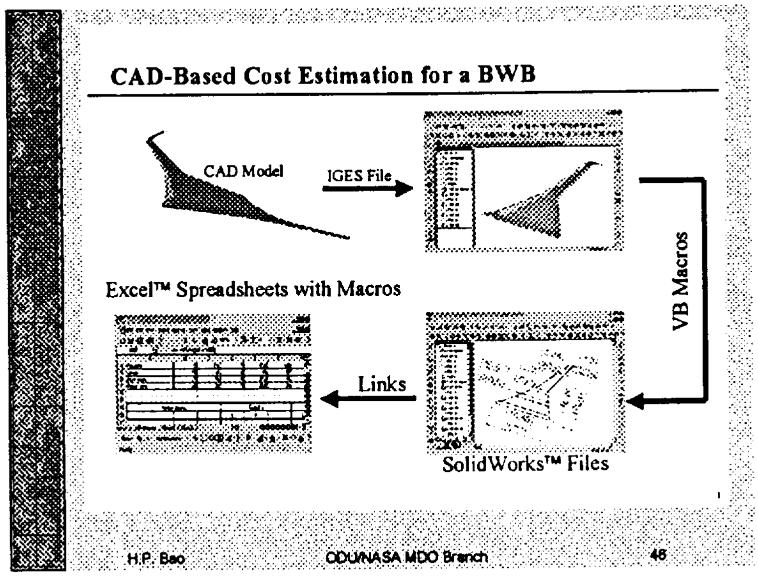

Figure 6.3 Calculation process applied to cost estimation of BWB

The cost estimation work for the Blended Wing Body (BWB) has only begun at the very end of the time allocated for this project. This work will be continued on another project to be arranged between the author and the MDO Branch at NASA Langley Research Center.

.7.0 Summary and Future work

The cost method identified in this report attempts to address the issue of cost determination based on realistic industry findings. In summary, two new concepts have been put forward: Process velocity and cost modulus.

The process velocity model initiated by work at MIT through a NASA contract (NASA 89) advocates the use of simple first-order dynamic models for the most influential process steps in the sequence of production. The MDO Branch at NASA LaRC has adopted this model as a basis for cost modeling of advanced vehicles. Current work involves the expansion of this basic model to production activities beyond machining.

The second concept is the concept of cost modulus. Essentially it is an index of the cost of a design compared to some reference design for which production and cost data are known. The reader might think that cost modulus is simply a substitute for the manufacturing complexity index, the so-called MCPLXS index in the PRICE H system often quoted in papers related to process costing. Ultimately, both cost modulus and MCPLXS serve the same purpose, which is to provide a means of capturing the manufacturing complexity of a design. But the big difference comes from the way each of these indices were derived. In the case of MCPLXS, the index was based on very general notions of precision of fabrication, machinability of material, difficulty of assembly, number of parts and specification profile. On the other hand, cost modulus is much more specific and directly related to the design features such as size, shape, precision, material and equipment needs. Another important aspect of cost modulus is the fact that it can be used for all phases of the design from conceptual to development to production. The more details one has, the more accurate the cost modulus index can be. From an MDO standpoint, the development of a process-based cost model plus the availability of the cost modulus formulation means that there is now a capability to carry out sensitivity analyses using cost as an objective function. Much more work remains to be done as we have barely scratched the surface with this type of approach.

Appendix 1:
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AIAA-2000-4839

AFFORDABLE DESIGN: A METHODOLOGY TO IMPLEMENT PROCESS-BASED MANUFACTURING COST MODELS INTO THE TRADITIONAL PERFORMANCE-FOCUSED MULTIDISCIPLINARY DESIGN OPTIMIZATION

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Abstract

The primary objective of this paper is to demonstrate the use of process-based manufacturing and assembly cost models in a traditional performance-focused multidisciplinary design and optimization process. The use of automated cost-performance analysis is an enabling technology that could bring realistic process-based manufacturing and assembly cost into multidisciplinary design and optimization. In this paper, we present a new methodology for incorporating process costing into a standard multidisciplinary design optimization process. Material, manufacturing processes, and assembly processes costs then could be used as the objective function for the optimization method. A case study involving forty-six different configurations of a simple wing is presented, indicating that a design based on performance criteria alone may not necessarily be the most affordable as far as manufacturing and assembly cost is concerned.

Introduction

The Multidisciplinary Design Optimization (MDO) methodology exploits the synergism of mutually interacting phenomena. The readers are referred to recent review articles on MDO. [1,2] Traditional MDO tends to ignore cost and focuses primarily on vehicle performance criteria such as lift, drag, and range. If cost is included at all, then it is typically based solely on the weight of the vehicle. But this is inadequate and could even be misleading. High manufacturing cost could easily overwhelm any incentive to improve the design to the point of forcing the cancellation of the entire project. Determining the cost of manufacturing and assembly processes has been elusive in the past because of the difficulty of correctly modeling the cost of these processes.

Typically the MDO processes focus on either optimizing the vehicle aerodynamic performance[3] or minimizing its structural weight.[4-5] The weight is indirectly related to the manufacturing cost, and the aerodynamic performance is related to operational cost. Both weight and performance play an important role in life-cycle cost. But they are not accurate for estimating the process-based manufacturing and assembly cost (PBMAC), which is directly related to the acquisition cost. Unfortunately it has been difficult to model the PBMAC in term of typical parameters and design variables used in a traditional MDO process. The purpose of this paper is to demonstrate the use of a PBMAC modeling tool with a performance analysis tool for cost-performance optimization.

For our study, we have chosen to use the COSTRAN™ϴ code,[6] which is a commercial PBMAC. This code is an offshoot of a decade-long NASA effort[7] in developing PBMAC tools that is

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traditionally used for aircraft trade study. The COSTRAN™ model is function of individual component parts such as spars, ribs, and skin, and it is a useful tool during the conceptual design phase of an aircraft. The goal of this paper is to demonstrate the use of commercial PBMAC in a traditional performance-focused MDO. The focus of this work is to determine the "what" (interface variables) and the "how" (interface methods) of integrating PBMAC tool with high-fidelity disciplinary models such as FEM structural models and CFD aerodynamics models. In the rest of this paper, the PBMAC model is first introduced. This will be followed by illustrative results obtained for the design of a generic wing.

Process-Based Manufacturing and Assembly Cost Model (PBMAC)

The published literature abounds with articles and textbooks that advocate various PBMAC models.[8-11] A majority of these models rely on empirical data. In general, when manufacturing and/or assembly time is plotted against some design parameter on a log-log paper, a power law relationship between the variables can be determined. This procedure is the basis for a large number of cost estimating relationships (CER) widely used in the industry. Another popular cost estimating procedure is the response surface methodology (RSM) that relies primarily on multiple regression analysis.[12] Finally the genetic algorithm (GA) is another cost estimating procedure tackling the problem from the standpoint of a biological phenomenon that enhances the successful processes while progressively eliminating the unsuccessful ones.

All of the cost estimating methods mentioned above suffer from the following drawbacks: 1- Complete dependency on existing data, 2- Application is limited to the range of available data, and 3- Unnecessary complication for early design optimization. Readers are referred to the literature for explanation of the drawbacks mentioned above.[13-14]

The work presented in this paper is supported by a commercial PBMAC.[6,7] The fundamental tenet of this PBMAC is a first order cost model first proposed in 1994.[15] This model was born out of an observation that many manual as well as automated processes can be represented as dynamic systems with first-order velocity response to a step input as mathematically represented by the following equation:

$$V = V_0(1 - e^{-t/\tau}) \qquad (1)$$

where V_0 is the steady-state process velocity, τ the dynamic time constant, and t the process time.

In general, t is governed by a major geometric property of the part, which could be its length, surface area, or volume. Using the terminology of reference 15, this property is designated as λ, the extensive variable for the process.

The process velocity V can be equated to the first time derivative of λ, i.e. $V=d\lambda/dt$. λ can therefore be obtained by integration of V over time, resulting in

$$\lambda = V_0[t - \tau(1 - e^{-t/\tau})] \qquad (2)$$

Equation 2 cannot be inverted explicitly for t. However two approximations can be made depending on the value of t relative to τ such that:

a- For $t \ll \tau$: $t \cong \sqrt{(2\tau\lambda)/V_0}$

b- For $t \gg \tau$: $t \cong \tau + \lambda/V_0$

As suggested by Mabson (reported in reference 16), the above approximations can be combined into a single hyperbolic relation as followed:

$$t = \sqrt{(\lambda / V_0)^2 + (2\tau\lambda / V_0)} \qquad (3)$$

The validity of equation 3 can be seen in figure 1 shown below. Other proofs are available in references 14 - 16.

As indicated in reference 16, a total of 18 base time equations have been identified to directly relate the process time to the extensive variable under various conditions of operation. Bao provided a few case studies to illustrate the use of these equations.[17]

To illustrate the use of equation 3, consider the fabrication of a front spar for wing construction. Experience indicates that the V_0 and τ values for a typical spar are respectively 2.4624 and 3.6934E+04. The extensive variable, λ, was determined to be the wetted area, i.e. area receiving machining, of the spar. Therefore, if the spar's wetted area is 100 in^2, then the fabrication time will be approximately 1732 minutes. Note that this fabrication time constitutes an overall time estimate without knowing all the details of part preparation, fabrication, and quality control/inspection requirements. During conceptual design phase, this time estimate is probably all that the designer needs to know for fabrication cost.

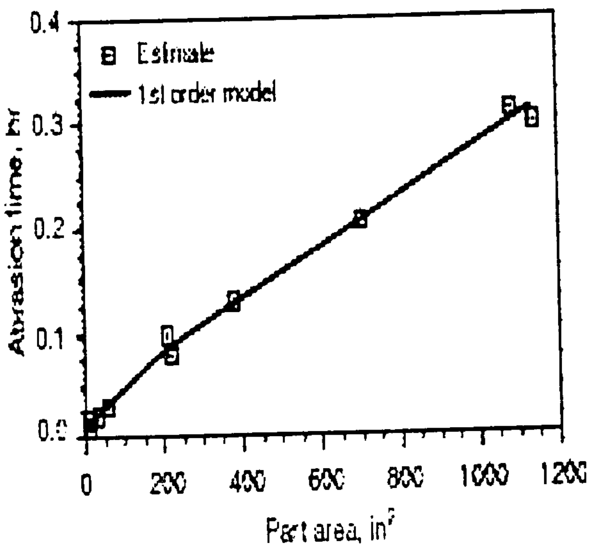

Figure 1- First-Order fit through industry estimates for abrasion operations (Reproduced from reference 15).

Preliminary Results

For the purpose of demonstration, we have selected to use a generic wing, which is made of two spars, five ribs, and skin. Figure 2 shows the CAD representation of the generic model. The results are presented for two test cases: 1) cost comparisons for forty-six different concepts, and 2) cost optimization of generic wing concept.

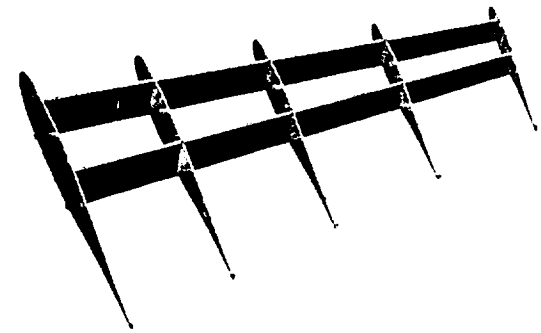

Figure 2 CAD representation of a generic wing.

This model was parameterized using Multidisciplinary Aero/Structural Shape Optimization Using Deformation (MASSOUD[18]) code. The MASSOUD code is based on a novel parameterization approach for complex shapes suitable for a multidisciplinary design optimization application. The approach consists of three basic concepts: 1) parameterizing the shape perturbations rather than the geometry itself, 2) utilizing SOA computer graphics algorithms, and 3) relating the deformation to aerodynamics shape design variables such as thickness, camber, twist, shear, and planform.

The MASSOUD formulation is independent of grid topology, and that makes it suitable for a variety of analysis codes such as CFD and CSM. The analytical sensitivity derivatives are available for use in a gradient-based optimization. This algorithm is suitable for low-fidelity (e.g., linear aerodynamics and equivalent laminated plate structures) and high-fidelity analysis tools (e.g., nonlinear CFD and detailed FE modeling).

Figure 3 shows the parameterized model of a generic wing shown in Figure 2. This model has forty-five design variables, which consist of planform, twist, shear, camber, and thickness.

Each set of forty-five design variables constitutes a design concept. All together, forty-six different design concepts were investigated. The basis for cost estimation per design concept is indicated in tables 1 and 2.

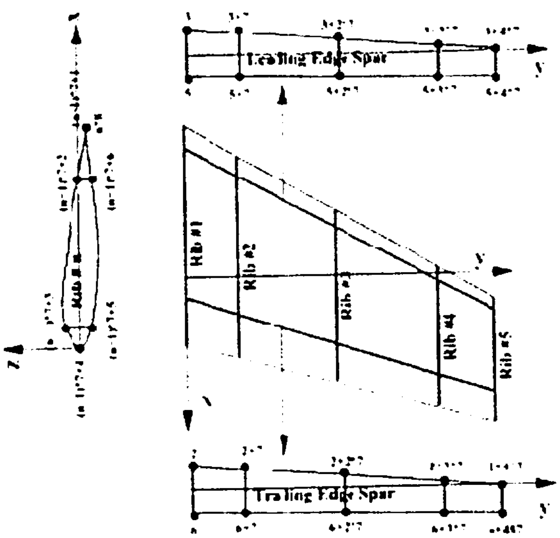

Figure 3 Parameterized model of the generic wing.

Table 1: Basis for Cost Estimation of Generic Wing, V_0 and τ

Material: Aluminum	V_0	τ	Extensive Variable‡
Skin Fabrication	1.228	0.843	A
Rib Fabrication	0.836	1.122	A
Spar Fabrication	1	1	A
Wing Assembly	1	1	B
Material: Composite	**V_0**	**τ**	**Extensive Variable**
Skin Fabrication	0.871	1.188	A
Rib Fabrication	0.334	0.280	A
Spar Fabrication	0.588	1.700	A
Wing Assembly	0.714	1.399	B

‡ Where, A is wetted area in inch^2 and B is perimeter in inch.

Table 2: Basis for Cost Estimation of Generic Wing, Common Parameters

Labor	\$60/Hour
Material Cost:	
- Skin	\$20/Lb
- Rib	\$12/Lb
- Spar	\$15/Lb
- Fasteners	\$.20/Unit
Set Up and Delay Time per operation	Not considered; Recurrence cost only

The interpretation of tables 1 and 2 should be as follows: the published values of V_0 and τ for an average spar were used as base values. The V_0 and τ for all other wing components such as rib and skin were expressed in relative term compared to those of the base spar. Similarly the V_0 and τ for the assembly of a typical wing were also used as base values. Values for the composite wing assembly were expressed in relative term compared to those of the aluminum wing assembly. It should be noted that wing assembly process should be separated from fabrication of skin, spar and rib because the former process depends critically on the perimeter while the latter process depends on the wetted area. Expressing all V_0 and τ relative to those of the spar would be erroneous. Data in table 2 are representative of each of the indicated elements in a given year.

For each design concept, the wetted areas for upper and lower skin, front and rear spar, and average rib were determined. Next, the perimeter for each of the above components was determined. Finally the data indicated in tables 1 and 2 were used to, first determine the fabrication cost of each component, second their assembly cost, and third and finally the total cost per design concept. Figure 4 shows the cost comparison for all forty-six different concepts, based on discrete choices of materials and shapes for a given structural topology, and given manufacturing and assembly processes.
Figure 5 shows the cost comparison of individual cost factors for a given concept.

For the first test case, i.e. aluminum wing, the parameterized model was embedded into an optimization process as shown in figure 6.

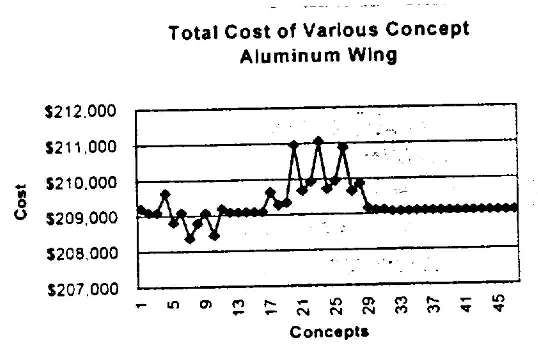

Figure 4 Cost comparisons for forty-six different concepts.

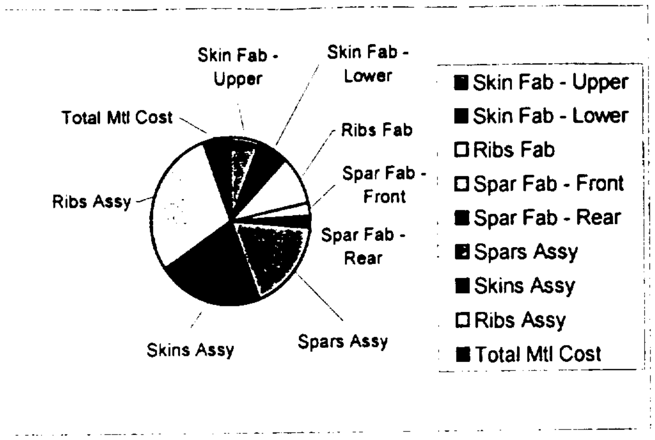

Figure 5. Cost comparisons of individual cost factors for a generic wing.

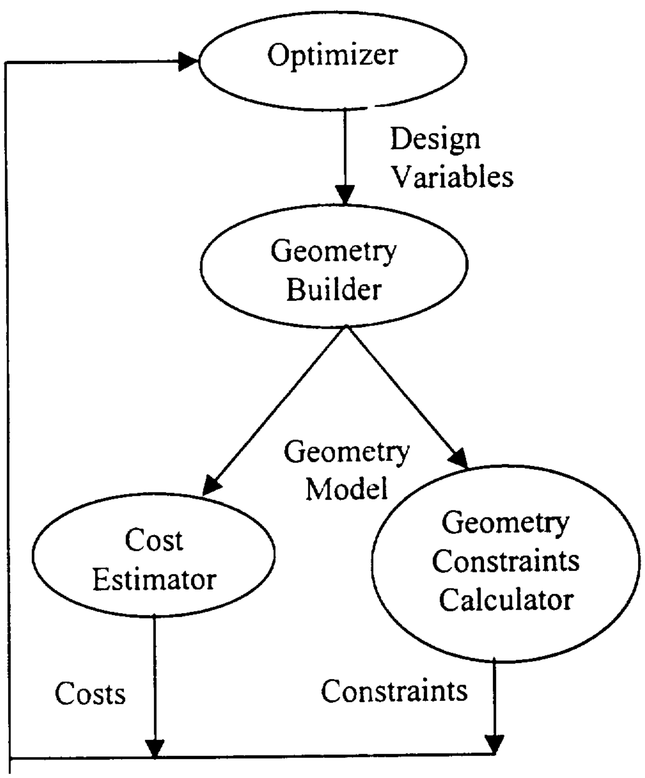

Figure 6. Optimization Process

The optimization process is made of four modules: optimizer, geometry builder, cost estimator, and geometry constraints calculator. The optimization code CONMIN[19] was used for the optimizer module. As mentioned before, the MASSOUD code was used to parameterize the geometry. The cost estimating concept described previously was used to estimate the cost of a generic wing. The total wetted skin, rib, and spar areas were constrained to stay below the baseline design.

Figure 7 shows preliminary optimization result for the generic wing shown in figure 2. The cost was reduced by more than 1.8%.

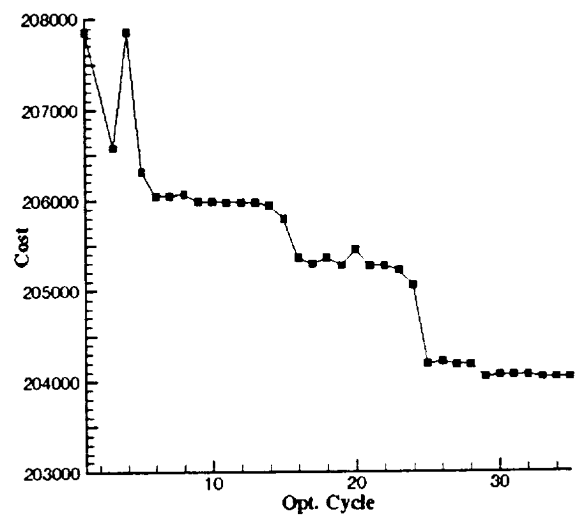

Figure 7. Cost optimization.

Discussion

Cost consideration is among the most important elements in any multi-disciplinary design optimization scheme. There are many kinds of cost involved in a typical airplane program. As described by Roskam,[20] there are costs associated with the planning and conceptual design, with preliminary design and system integration, with detail design and development, with manufacturing and acquisition, with operation and support, and with disposal. This paper deals strictly with the first type of costs, notably costs associated with the planning and conceptual design. As indicated earlier, the MDO community so far tends to treat cost as solely based on the weight of the vehicle. The case studies included in this paper the vehicle. The case studies included in this paper indicate that fabrication and assembly costs are much more significant than material costs – as expressed by weight- and should be part of the optimization scheme.

Even at the conceptual design phase. there is a need to incorporate the costs of fabrication and assembly of the major components such as spars, ribs, and skins. Using the first design configuration as a typical design, the following table reveals how dominating fabrication and assembly costs were over material costs.

	Mtl	Mfg	Assy	Total Wing
Front Spar	5.5%	21.3%	73.2%	12.3%
Rear Spar	4.3%	19.5%	76.2%	11.4%
5 Ribs	3.9%	23.4%	72.7%	39.9%
Upper Skin	7.5%	33.4%	59.1%	18.4%
Lower Skin	7.6%	33.9%	58.5%	18.0%
Total Wing	5.5%	26.4%	68.1%	100%

From the above percentage table, it can be said that, in general material cost was only about 5% of the cost of fabrication and assembly. Also, fabrication cost of either spar or rib was about 30% of corresponding assembly cost, while fabrication cost of skin was about 50% of assembly cost. The numbers quoted above are close to industry standards.

As to the cost comparison of the forty-six different design concepts, while the magnitude of the overall cost reduction was less than 2%, the point was that the proposed cost model was detailed enough to accommodate all design concepts. Furthermore it could be easily incorporated in any multi-disciplinary optimization methodology.

Conclusions

We have demonstrated the use of process-based manufacturing and assembly cost models in a traditional performance-focused multidisciplinary design and optimization process. Three major conclusions can be drawn from this paper. First the weight may not be directly related to cost, and minimizing the weight may increase the overall cost. Second the analytical cost models can be incorporated in a traditional MDO process. And third, the fabrication and assembly costs could drive the optimization process to minimize the actual cost of the part being considered.

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Seminar Presented to
Multidisciplinary Optimization Branch
NASA Langley Research Center

In-Depth Survey of Cost/Time Estimating Models

By
Han P. Bao, Ph.D., P.E.
Dept of Mechanical Engineering
Old Dominion University

July 21, 2000

Cost Control Is a Strategic Policy

- Langley Management System's Strategic and Quality Framework:
  - Three critical success factors for NASA LaRC:
    - Product User Value
    - Funder Value
    - Organization Value
- No Product is technically successful unless it's financially successful.
  (Dennis Pawley, Chrysler VP of Manufacturing)

7/19/00 Han P. Bao, Dept of Mech. Eng., ODU 2

MDOB's Interests in Cost Estimation Models

- Cost models based on process requirements more than just weight
- Quantitative models based on physical parameters
- Models that can be readily integrated with current automated optimization codes
- Do not depend on computer platform
- Suitable for preliminary design, i.e. higher flexibility of use, more accurate estimation, and less detail dependency

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Objectives of Seminar

- Review a majority of cost models for engineering applications
- Highlight advantages and disadvantages
- Highlight good areas of applications
- Discussion of preliminary results derived from First-Order Velocity Cost Model
- Recommendation of Cost Model(s) for MDO Branch

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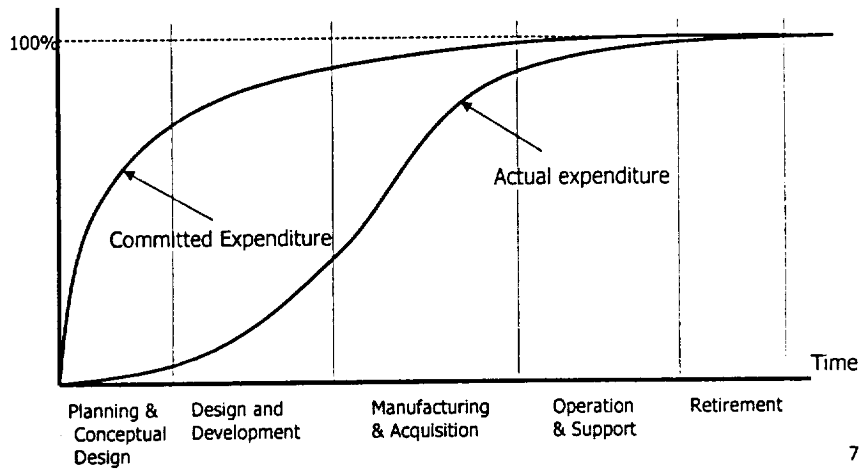
Outline

- General Framework for Discussion
- Part 1: Exact and Detailed Models
  - Time Study
  - Predetermined MTM
  - ACCEM
  - Work Sampling
- Part 2: Technological Forecasting models
  - Qualitative models
  - Growth curves
  - Comparative models
- Part 3: Correlation/Trend Analysis Models
  - Learning Curves
  - Regression
  - Power Laws
  - Response Surface
  - First-Order Velocity
- Discussion and Conclusion

General Framework for Discussion

- Life Cycle of a Product or System
- Life Cycle Costs
- Manufacturing Costs
- Effect of Inflation
- Cost Model Selection

Life Cycle of a Product or System



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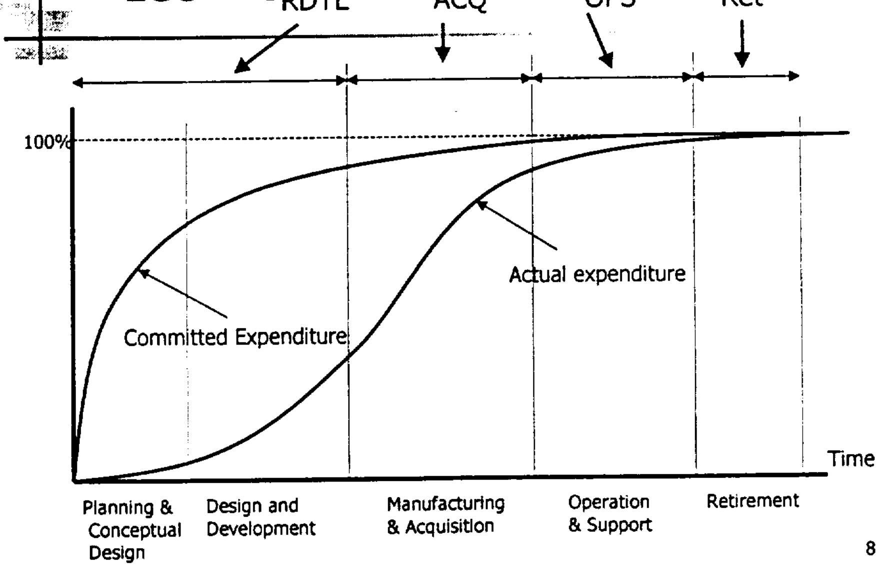
Life Cycle Costs

$$LCC = C_{RDTE} + C_{ACQ} + C_{OPS} + C_{Ret}$$



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Manufacturing Costs

- Manufacturing cost of any product and service consists of two main components:
  - Direct costs (also called variable costs)
  - Indirect costs (also called overheads)
- Manufacturing cost = Direct costs + Indirect costs

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Manufacturing Cost (Continued 1)

- Direct costs (depend on quantity of production):
  - Input materials
  - Purchased components
  - Payroll and Fringe benefits
  - Maintenance
  - Supplies
  - Utilities
  - Miscellaneous (e.g. royalties, packaging,etc... as long as incurred per unit of production)

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Manufacturing Cost (Continued 2)

- Indirect costs (independent of quantity of production):
  - Indirect materials and labor
  - Support payroll
  - Supervision and management payroll
  - Costs of outside operations
  - License fees
  - Insurance
  - Rental fees
  - Property taxes
  - Interest on working capital
  - Depreciation and obsolescence

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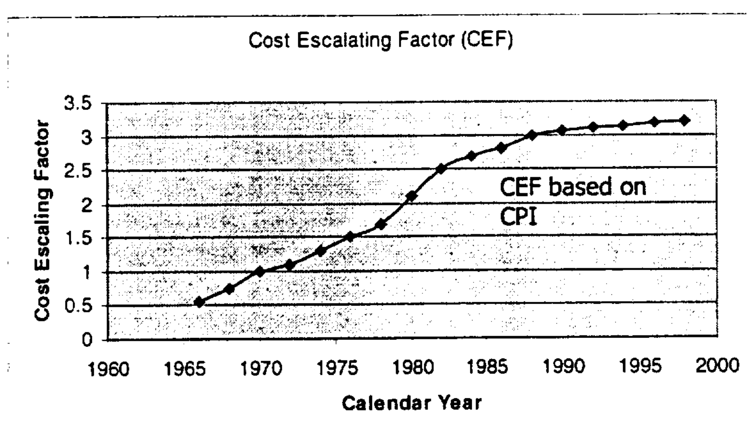
Effect of Inflation



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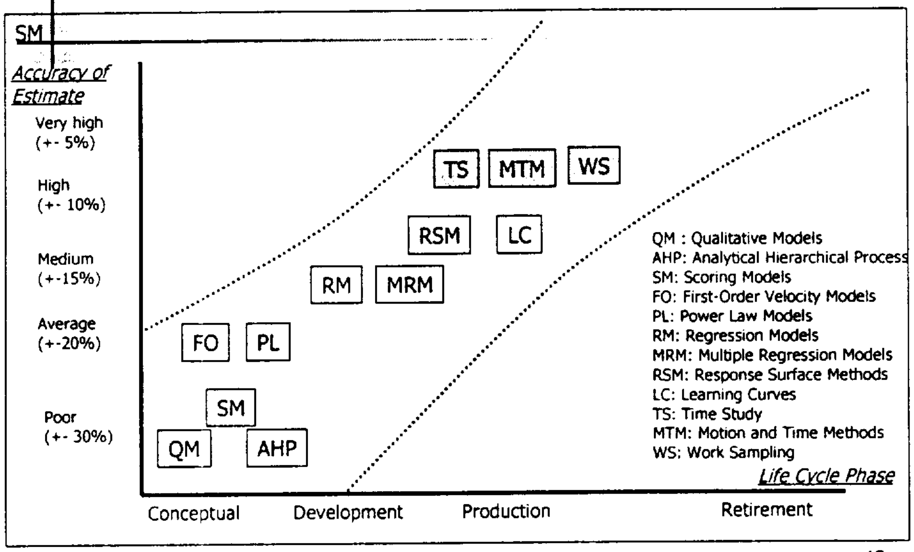
Cost/Time Models Selection



7/19/00 13

Part 1: Detailed Models

- Requirements:
  - Operations well established
  - Labor and equipment ready for production work
- Goal is to establish standardized costing for an average worker to do the job
- Four specific models for discussion:
  - Time Study
  - Pre-determined Motion and Time Measurement
  - ACCEM
  - Work Sampling

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Time Study

- Procedure:
  - Analyze and improve method of production
  - Record significant data
  - Separate operations into elements
  - Record the time consumed by each elements
  - Rate the pace or tempo
  - Determine allowances
  - Convert elements into normal time including allowances, and express time standard in common units of production

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Time Study (Continued 1)

- Each work element measured by stop watch
- Element rating factor: 1 is average; <1 is below average; >1 is above average
- Allowances: Personal 4 to 5%; Fatigue 4 to 5%; Delay 4 to 5%; Total: 15%
- Allowance multiplier (F_a) = $\frac{100\%}{100\% - PDF}$

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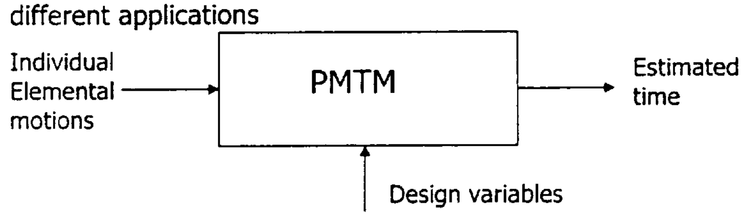
Time Study (Continued 2)

- Normal cycle time = Ave. cycle time * Cycle factor
- Job standard time = normal cycle time * F_a
- Example: Manual assembly of electrical receptacle
  - Normal cycle time = 0.515 min per unit
  - Allowance Multiplier (F_a) = 1.176
  - Job std time = 0.515 * 1.176 = 0.606 min per unit
  - Std hours per 100 = 1.010

Predetermined Motion and Time Measurement

- Based on very detailed analysis of motion
- Elemental motions, called Therbligs,include Reach, Move, Turn, Apply pressure, Grasp, Position, Release, Disengage, Eye travel and Eye Focus, and Body, Leg, and Foot Motions
- The time (in TMU, 1 TMU = 0.0006 min) for each elemental motion is given in the corresponding table for a number of different applications



Predetermined Motion and Time Measurement (Continued 1)

- Examples of design variables:
  - Reaching distance
  - Distance moved
  - Placement accuracy

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Predetermined Motion and Time Measurement (Continued 2)

- <u>Example</u>: Pick up a pencil jumbled with other objects from the floor and putting it on a table

Bend, stoop, or kneel	29.0 TMUs
Reach (Class D,10 in.) to pencil	12.9 TMUs
Pick up pencil (Class 1C2)	8.7 TMUs
Arise from kneel	76.6 TMUs
Move pencil (Class B,24 in.)	20.6 TMUs
Drop pencil (Class 2)	2.0 TMUs
Total	149.8 TMUs
or	0.089 min

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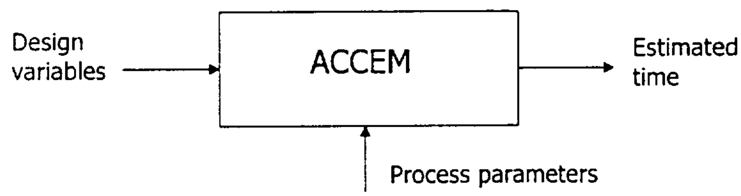
Advanced Composites Cost Estimating Manual (ACCEM)

- Developed by Northrop for the US Air Force



Design variables: part perimeter, area, volume etc...

Process parameters: For hand lay-up

apply release agent → $0.9.10^{-5}$ * area

apply adhesive → $0.55.10^{-4}$ * length

etc...

ACCEM (Continued)

- ACCEM requires detail description of all process steps
- ACCEM Manual is limited to a few well-known processes for composite materials
- ACCEM's Accuracy drops off dramatically once product's physical characteristics exceed design ranges

Work Sampling

- Used in analysis of undesignated or non-repetitive work activities
- Consists of a number of observations taken at random intervals
- Work Sampling is a statistical technique for time and cost estimation

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Work Sampling (Continued 1)

- Statistical analysis based on normal distribution
- Number of observations:

$$N = \frac{Z^2 p_i (1 - p_i)}{A^2}$$

N = Number of observations
Z = 1.645 for 90% confidence
1.960 for 95% confidence
P_i = Percentage of occurrence of event i
A = desired accuracy, typically 0.01 to 0.05, 0.05 being the most commonly used accuracy.

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Work Sampling (Continued 2)

- Example: use of carpenter crews in dam construction
- Preliminary study:
  - Form lay-up walls 62%
  - Set up for form work 16%
  - Wait for crane 12%
  - Miscellaneous 6%
  - Wait for materials 4%

Total: 100%

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Work Sampling (Continued 3)

- Determine number of observations:

Element	Prob. P	Accuracy	N_i
1	0.62	0.02	1594
2	0.16	0.015	1616
3	0.12	0.01	2858
4	0.06	0.01	1727
5	0.04	0.01	1042

We need a total of 2858 observations

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Work Sampling (Continued 4)

- Spread observations equally among the days, then randomly within each working day. Take observations for final determination of labor cost.
- Labor cost(per unit): $H_s = \dfrac{(N_i/N)HR(1+PFD)}{N_p}$

H_s = std hrs for each job element
N_i = number of observations
N = total number of observations
H = total manhours in entire study
R = rating factor
PF&D = allowances
N_p = work units achieved in entire study

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Work Sampling (Continued 5)

- Example:

H_s = std hrs for first job element, i.e. form layup walls
N_i = number of observations =1772
N = total number of observations = 2858
H = total man-hours in entire study (14 men for 3 weeks@ 40 hrs/week) =1680
R = rating factor = 0.96
PF&D = allowances = .20
N_p = work units achieved in entire study = 17 frames

Then $H_s = \dfrac{(1772/2858)*1680*0.96*1.2}{17} = 70.6 \quad man-hours$

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Summary for models in Part 1

- The four models discussed so far include Time study, Predetermined MTM, ACCEM, and Work sampling
- Models applied in phase 4 (Operations and Support) of life cycle
- Final cost estimates are fairly accurate
- Main requirements: existence of database for process details
- Probably unsuitable for use in early conceptual/design phase (Phase 1 of LC)

Part 2: Technological Forecasting Models

- These models are used more for assessing trends in technologies than for assessing costs. Nevertheless a good prediction of where technologies are heading can yield insight to costing aspects, at least on a qualitative basis
- Three categories of models for consideration:
  - A- Qualitative models
    - Based on opinions of panel of experts
    - Definite lack of quantitative data
    - Serve as broad predictor of trends and patterns
  - B- Growth curves
    - Focus on upper limits of technology development
  - C- Comparison models
    - Also serve as broad predictor of trends and patterns
    - Availability of quantitative data

Qualitative Models

- The models to be discussed:
  - Delphi
  - Nominal Group Process
  - Case studies
- Delphi Approach:
  - Requires a panel of experts
  - Goal is to forecast likelihood and timing of future events
  - Process: sequence of individual interrogations followed by opinion feedback from analysis of initial response data
  - A single forecast is typically agreed upon after several rounds of this process

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Qualitative Models (Continued 1)

- 2- Nominal Group Process
  - Requires panel of experts, like the Delphi process
  - Each expert writes his/her opinions, which will be shared among all panel members
  - Unlike the Delphi process, GNP involves intensive discussion among members
  - Goal of GNP is to come to a panel consensus

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Qualitative Methods (Continued 2)

- 3- Case Study Method
  - Entails study of technological developments that have already occurred
  - Predictions of future technologies are then made based upon analysis of past developments

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Growth Curves

- Used primarily to predict the upper limit of the level of technology growth
- Three growth curves for consideration:
  - Pearl
  - Gompertz
  - Fisher-Pry

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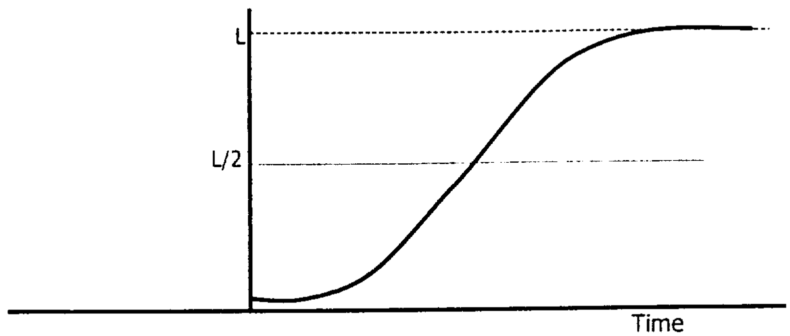
Graphical Representation of Pearl Growth Curve



Growth Curves (Continued 1)

- Pearl curve:
  - Patterned after growth of a living organism
  - Best known form: Base 10 Pearl curve

$$y = \frac{L}{1+10^{a-bt}}$$

y= value of technological parameter
L = natural limit
a,b = coefficient relevant to technology in question

  - 1/b is known as T-time (or ten-fold time): Ratio (L-y)/y decreases by a factor of 10 for every increase of (1/b) in time.

Example of Use of Pearl Curve

- Suppose current technology (year 2000) is 10% of its limit L. Also suppose technology follows Base 10 Pearl curve with T-time = 5. In what year do you expect technology to be 90% of its limit?
- Answer:
  - b=1/T =1/5 = 0.2
  - t=2000 log[(L-0.1L)/0.1L]=a-0.2(2000)
    Hence a=400.954
  - t=x? log[(L-0.9L)/0.9L]=400.954-0.2(x)
    x=2009

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Growth Curve (Continued 2)

2- Gompertz Curve:

$$y = \frac{L}{e^{be^{-kt}}}$$

Note: Which curve to use?

- Pearl curve is ideal for a technology for which future growth appears to be dependent on past growth
- Gompertz curve is for situation where commodity seems to be unaffected by progress made in the past

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Growth Curve (Continued 3)

- Fisher-Pry Curve:
  - Curve used to assess the rate at which one technology will displace another technology
  - Formulation:

$$f = \frac{1}{1+10^{a-bt}}$$

f is market penetration
t is time, ie year
a and b are curve parameters usually obtained from regression analysis

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Example of Fisher-Pry Curve

- We are interested in adoption of cable TV as encroachment over network TV
- Using regression data, we have:

  Log[f/(1-f)] = -129.299+0.065t

  So, in year 2005, f would be about 91%

  (f is market penetration)

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Comparative Models

- These models attempt to evaluate the relationships among the major factors affecting the process, then set up pair-wise comparison to assess these relationships
- Models to be discussed:
  - Analytical Hierarchical Process (AHP)
  - Scoring Models

Analytical Hierarchical Process (AHP)

- AHP exploits the breakdown structure of most processes and provides pair-wise assessment of all the factors contributing to the complexity of the process.
- The application of AHP results in a figure of complexity for each process, which can then be correlated to the cost of fabrication.
- One crucial advantage of AHP is its tolerance for accepting a mixture of actual and judgmental data.

Analytical Hierarchical Process (Continued 1)

- Weighting of attributes and sub-attributes

If x is .... As (than) y	Then preference number to assign is
Equally important	1
Weakly more important	3
Strongly more important	5
Very strongly more important	7
Absolutely more important	9
Use even numbers to represent compromises	2,4,6,8

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Analytical Hierarchical Process (Continued 2)

- Example of attribute weighting:

With respect to mfg cost	Material	Handling	Versatility	Fabrication	Weight
Material	1	0.25	3	0.167	0.12
Handling	4	1	5	1	0.38
Versatility	0.333	0.2	1	0.2	0.07
Fabrication	6	1	5	1	0.43

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Analytical Hierarchical Process (Continued 3)

- Example: 2 designs are to be compared
  - Design A: known design, known process, known cost
  - Design B: unknown process, unknown cost
- Assume process is characterized by 4 main factors (Material cost, Handling, Versatility, and Fabrication), and Fabrication alone can be broken down into 3 subfactors (labor, equipment, and tooling)

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Analytical Hierarchical Process (Continued 4)

- A panel of experts have agreed to the following assessment of importance, or weight:
- Main factors:

Main factors:		Sub factors of Fab:	
Material cost	0.12	Labor	0.4
Handling	0.38	Equipment	0.3
Versality	0.07	Tooling	0.3
Fabrication	0.43		

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Analytical Hierarchical Process (Continued 5)

- Rating of the 2 designs (on scale of 1 to 5, 1 being best or least complex):

	Design A	Design B
Material cost	1K	3K
Handling	2	2
Versatility	4	1
Fabrication		
labor	1	2
Equipment	4	2
Tooling	3	3

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Analytical Hierarchical Process (Continued 6)

- Complexity of Design A:

  0.12(1/4) +0.38(2/4)+0.07(4/5) + 0.53[0.4(1/3)+0.3(4/6)+0.3(3/6)] = 0.4838

- Complexity of Design B:

  0.12(3/4) +0.38(2/4)+0.07(1/5) + 0.53[0.4(2/3)+0.3(2/6)+0.3(3/6)] = 0.5162

- Design B is about 7% more complex than design A

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Scoring Model

- This model is used to rank or compare several designs or products where several parameters or characteristics are important, and there is no analytical procedure for combining them into a composite measure
- The scoring procedure consists of three steps:
  - Identify all the important factors
  - Weight the factors
  - Construct the model then obtain the individual scores

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Scoring Model (Continued 1)

$$Score = \frac{A^a B^b (cC + dD + eE)^z (1 + hH)^x}{(iI + jJ)^w (1 + kK)^v}$$

Numerators: desirable factors

Denominators: undesirable factors

Capital letters: factors

Small cap letters: coefficients of factors

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Scoring Model (Continued 2)

$$Score = \frac{A^a B^b (cC + dD + eE)^z (1 + hH)^x}{(iI + jJ)^w (1 + kK)^v}$$

- A and B: overriding factors
- C,D,E can be traded for each other
- H and K cannot be traded , but they are not as overriding as A and B
- I,J, and K are detrimental factors, e.g. cost factors
- c+d+e=1 ; i+j =1 ; a+b+z+x = 1 ; w+v = 1 ;
- 0<h<1 ; 0<k<1

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Scoring Model (Continued 3)

- <u>Example</u>: Scoring of US fighter aircraft from 1945 to 1985 (Martino 1993)
  - No overriding factors, ie no A's and B's
  - Maneuverability=0.3(inst. turn rate) +0.3(sust. Turn rate) +0.4(sea climbing rate)
  - Availability=0.5(flying time)+0.5(maint. hrs)
  - Range/payload= 0.5(range)+0.5(payload)
  - Speed=0.5(max speed)+0.5(cruise speed)
  - Avionics=0.5(radar range)+0.5(number of targets)
  - Weapons=0.2(missiles)+0.2(BVR missiles)+0.2(range of missiles)+0.2(range of BVR)+0.2(number of guns)

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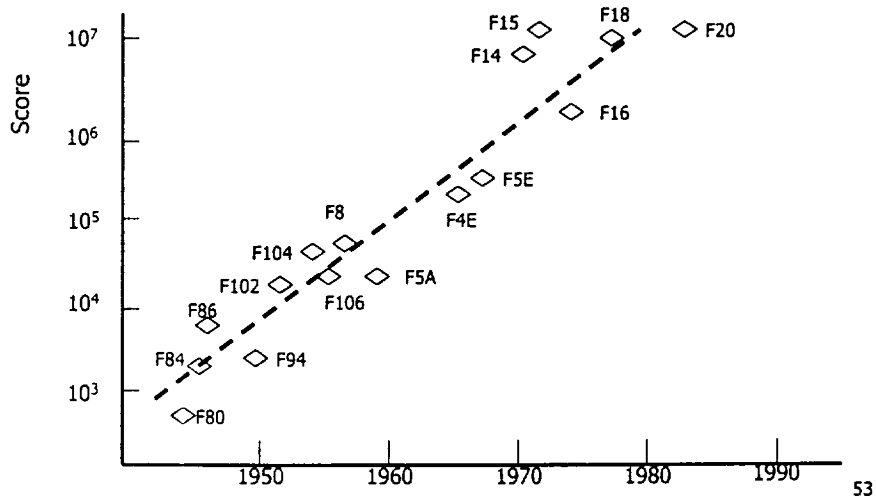
Scoring Models (Continued 4)

$$Score = \frac{(maneuv)^{1/8}(avail)^{1/8}(range\ payload)^{1/8}(speed)^{1/8}(avionics)^{2/8}(weapons)^{2/8}}{(1+takoff)}$$



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Summary for Models in Part 2

- Models in this second category do not reveal man-hours, but they provide qualitative means of assessing each design.
- In the case of AHP and scoring models,correlation analysis could be used to correlate estimated costs with the technology value of each design

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Part 3:
Correlation/Trend Analysis Models

- These models are most appropriate for cost estimation during conceptual/design phase of product
- The models for discussion include:
  - Learning curve
  - Power law
  - Regression
  - Response Surface Methods
  - First-Order velocity

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Learning Curve (LC)

- The learning curve is a mathematical representation of how resources are reduced as the production of a product or service is repeated without critical material and process change.
- The basic assumption underlying all learning curves is that there is a relatively constant percentage reduction in the cost, or man-hour, for doubled quantities of production
- First described by T.P. Wright in 1936, the LC theory has been used extensively by industry and government agencies to estimate the required man-hours for repeated jobs.

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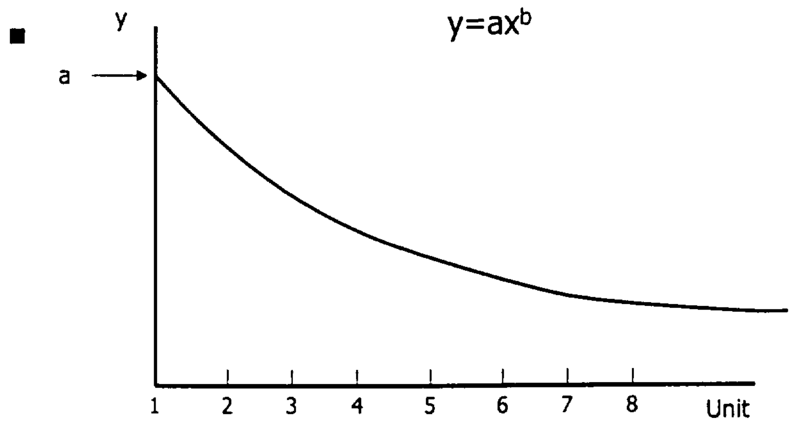
LC Graphical Representation



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Learning Curve (Continued 1)

- Two types of LC's:
  - Unit Curve
  - Cumulative Average Curve
- The Unit Curve plots the cost of the individual unit versus the unit
- The Cumulative Average Curve plots the average unit cost up to the unit of interest versus that particular unit
  - Which LC should be used depends entirely on the nature of the data being handled. Typically the Unit Curve is used for well established processes, while the Cumulative Average Curve is used for less well established or unreliable processes.

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The Unit Cost Curve

- Formulation: $$y = ax^b$$

  Y = Man-hours for unit x
  a = Man-hours for first unit, unit F
  b = Slope of LC curve on log-log paper
- Learning Percentage (p):
  P = $100(2^b)$
  Ex: 85% LC means $2^b = .85 \longrightarrow b = -0.234$

The Unit Cost Curve (Continued 1)

- The five basic formulae:
  - Cost of unit x $y = ax^b$
  - Cum. Total Cost of N units $T = a\left[\sum_{x=1}^{N} x^b\right]$
  - Cum. Average Cost of N units $Av = \frac{T}{N}$
  - Cost of Lot of F to L units $T_{F\,to\,L} = a\left[\sum_{x=1}^{L} x^b - \sum_{x=1}^{F-1} x^b\right]$
  - Lot Average Unit Cost $L\_Av = \frac{T_{F\,to\,L}}{Lot\ size}$

The Unit Cost Curve (Continued 2)

- Example:

Unit	Manhours	Log(Unit)	Log(manhours)
1	**100**	**0**	**2**
2	**80**	**0.301**	**1.903**
3	**70.2**	**0.477**	**1.846**
4	**64**	**0.602**	**1.806**
5	**59**	**0.698**	**1.770**
6	**56**	**0.778**	**1.748**
7	**53**	**0.845**	**1.724**
8	**51**	**0.903**	**1.707**

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The Unit Cost Curve (Continued 3)

- Using regression analysis to obtain value of coefficients:

$$y = 100x^{-0.325}$$

- Learning Curve Percentage is:

$100(2^b)$ or approximately 80% LC

- Estimated time for 10th unit?

$Y=100(10)^{-0.325} \longrightarrow$ y=47.3 manhours

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The Unit Cost Curve (Continued 5)

- Complications:
  - Fitting a curve with lot data
  - Production breaks
- Limitations of LC's:
  - They can be used only to estimate the recurring costs in a well established production environment
  - LC analysis is a model of a general trend; actual labor data may not necessarily decrease with each unit produced

Power Law Models

- These models are widely used in many current cost models, e.g. ACCEM, Price-H, AM's Cost Estimating, etc...
- Note similarity between LC formulation and PL formulation:

$$t = a(\lambda)^m$$

Lambda is a critical design feature that drives the cost
t is process time
a and m are coefficients relevant to process

Examples of Power Law Models

- From ACCEM applied to hand lay-up:
  - Position template and tape down:

    $$0.000107\ area^{0.77006}$$

  - 12 in. manual ply deposition:

    $$0.05 + plies\ (0.001454\ length^{0.8245})$$

  - Transfer layup to curing tool:

    $$0.000145 * (area)^{0.6711}$$

  - Stretch flange:

    $$plies * (length * 0.064 * radius^{-0.5379} * flange^{0.7456})$$

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Examples of Power Law Models (Continued 1)

- From Price-H:
  - Computerized method for deriving cost estimates for electronic and mechanical hardware assemblies and systems.
  - A parametric model of the traditional methods of production.
  - Adaptation to new situations requires calibration:
    - MCPLXS for mechanical/structure
    - MCPLXE for electronics
    - ECMPLX for development
    - Etc...

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Examples of Power Law Models (Continued 2)

- From Price-H:
  - Cost estimation of a system is based on 7 modules to be assessed concurrently:
    - General A (for qty, No. of prototypes, etc...)
    - General B (for No. of assemblies, integration factors, etc...)
    - Mechanical/structural design
    - Electronics design
    - Development (start date, milestones, etc...)
    - Production (start date, delivery dates, etc...)
    - Actual cost data (for building historical data bases)

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Examples of Power Law Models (Continued 3)

- Example of Mech/Structural module:
  - Design parameters:
    - Structural weight
    - New structure factor
    - Design repeat factor
    - Mechanical reliability factor
  - Manufacturing Complexity:

$$MCPLXS = \frac{A}{B} * [1 + ((N - MATUR) * 0.6)]$$

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Examples of Power Law Models (Continued 4)

- Manufacturing Complexity:

$$MCPLXS = \frac{A}{B} * [1 + ((N - MATUR) * 0.6)]$$

$A = 4.3(PLTFM^{.32}).(NP^{.04}))$
$B = 1.35(PREC^{.081}).(MI^{.024})$
N=3 if PLTFM < 2; or 4 if PLTFM > 2

PRECI: Precision of fabrication
MI: Machinability of material
MATUR: Difficulty of assembly
NP: Number of parts
PLYFM: Specification profile

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Examples of Power Law Models (Continued 5)

- From Rand Corporation:

$$Mhr = 0.0396\ (W_{ampr})^{0.791}\ (V_{max})^{1.526}\ (N)^{0.183}\ (F_{diff})\ (F_{cad})$$

Where:
Mhr= total number of manhours required to make N airframes
W_{ampr} =Aeronautical Manufacturers Planning Report Weight
V_{max} = Maximum design speed
N = number of program airframes
F_{diff} = Judgement factor of relative program difficulty
F_{cad} = Factor for use of CAD tools

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A Detailed Example of Airframe Engineering and Design Cost Estimation

- Source: "Airplane Design, Part 8", J. Roskam, The Univ. of Kansas, 1990

$$C_{aed} = Mhr_{sed} \cdot R_{er}$$

$$Mhr_{aed} = 0.0396\,(W_{ampr})^{0.791}\,(V_{max})^{1.526}(N_{rdte})^{0.183}\,(F_{diff})\,(F_{cad})$$

Mhr_{aed} = Total engineering manhours
R_{er} = Engineering rate
W_{ampr} = Aeroplane Manufacturers Planning Report Weight
V_{max} =Maximum speed
N_{rdte} = number of airplanes use in RDTE
F_{diff} = degree of difficulty
F_{cad} = factor for using CAD tools

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A Detailed Example of Airframe Engineering and Design Cost Estimation (Continued 1)

- For the Ourania jet:

R_{er} = Engineering rate = $63.64 per hour
W_{ampr} = Aeroplane Manufacturers Planning Report Weight = 39,437 lbs
V_{max} =Maximum speed = 295 knots
N_{rdte} = number of airplanes use in RDTE = 3 + 2
F_{diff} = degree of difficulty = 1.8
F_{cad} = factor for using CAD tools = 0.9

Hence, Airframe Engineering and design cost is
$C_{aed} = Mhr_{aed} \cdot R_{er}$ = (2,184,892).(63.64) = $139,046,557

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Regression Models

- To regress is to go back
- A regression model is one that goes back to the mean of all y values (dependent variables) for given x values (independent variables)
- Least-Square Best Fit (LSBF) Method:
  - Minimize sum of squared deviations of observed values of Y and calculated values of Y

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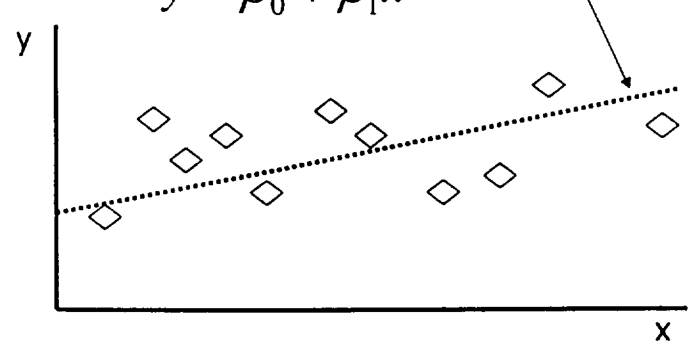
LSBF Method

- The LSBF equation is

$$\hat{y} = \beta_0 + \beta_1 x$$



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LSBF Method (Continued 1)

- Basic Formulations:

$$\beta_0 = \bar{y} - \beta_1 \bar{x} \qquad \text{and} \qquad \beta_1 = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sum (x-\bar{x})^2}$$

- Measures of accuracy:
  - Coefficient of determination:

$$r^2 = \frac{SS_{yy} - SSE}{SS_{xy}}$$

  - P value:

    Probability that t statistic is greater than $t_{critical}$

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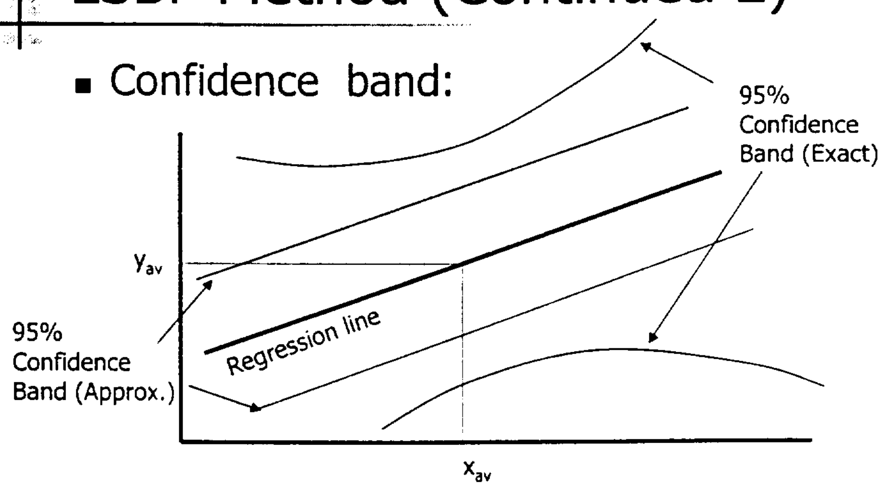
LSBF Method (Continued 2)

- Confidence band:



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Multiple Regression

- Involves multiple dependent variables, including dummy variables
- Examples:

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$$

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2$$

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 x_1^2 + \beta_5 x_2^2$$

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Multiple Regression (Continued 1)

- Example of use of dummy variables:
  $\hat{y}$ is estimate of sales of a commodity in 4 cities

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4$$

Where
$$\left.\begin{array}{l} x_1 = 1 \text{ if city 1, 0 if other} \\ x_2 = 1 \text{ if city 2, 0 if other} \\ x_3 = 1 \text{ if city 3, 0 if other} \end{array}\right\} \text{dummy variables}$$
x_4 = traffic flow

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Potential Problems with Multiple Regression

- Parameter estimability:
  - Problem is not having enough data points
  - General rule: sample size >=(p+1) where p is order of regression and level of x >= (p+1)
- Parameter interpretation
  - Be aware of existence or non-existence of causal relationship
- Multicollinearity from redundant information
- Prediction outside experimental range

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Response Surface Methods

- RSM is a competing method to Taguchi's method to significantly reduce the number of candidate designs
  - Taguchi: uses orthogonal arrays and ignores interactions
  - RSM: use Central composite designs to reduce 3^n designs (full factorial) to 2^n designs augmented by additional points to allow estimation of the coefficients of a second-order model
- Main effect of CCDs: reduce number of experimental point designs needed for fitting a second-order model

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Response Surface Methods (Continued)

- Example of RSM (Unal, Stanley,Joiner 1994):
  - Propulsion System Design for SSTO Launch System
  - 7 design parameters at 2 levels each
  - 16 2-parameter interactions at 5 levels each (low, -1, 0, +1, high)
  - Use multiple regression analysis to build second-order Response Surface Model
  - Objective of study was to determine weight of launch vehicle
  - Apply a gradient-based non-linear optimizer to determine optimum settings of design parameters

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Pitfalls to Avoid in the Use of a Parametric Estimate

- Using the parametric model outside its database range
- Using the parametric model without adjustment when new system requirements are not reflected in the parametric's database
- Using the parametric model without access to realistic estimated of the independent variables' values for product/effort being estimated
- Very little physical significance

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First Order Velocity Model

- Background:
  - NASA/Boeing Advanced Technology Composite Aircraft Structures (ATCAS) Initiative (Contract NAS1-18889)
  - MIT's Laboratory for Manufacturing and Productivity
  - Ph.D. Thesis :"Adaptive Framework for Estimating Fabrication Time", E.T. Neoh, MIT 1995

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Premises

- Vital Few and trivial Many:
  - Pareto's manifestation in many processes
  - Scaling relationship between the dominating step and the rest of the other steps could easily lead to the total time
- Manufacturing operations can be represented as dynamic systems with first order velocity response to a step input.

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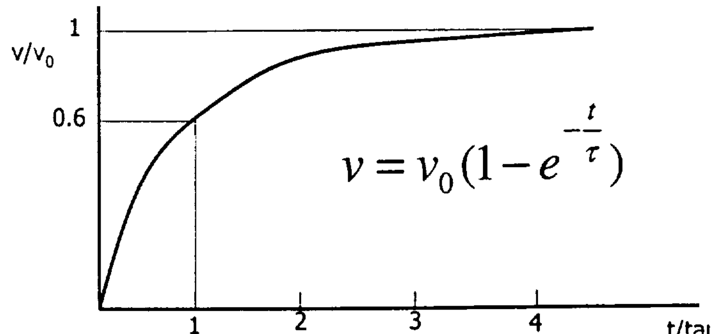
First Order Velocity Response



- Advantages of above formulation of process speed:
  - Amenable to physical modeling
  - V_0 and Tau have meaningful physical interpretation

First Order Model

- Math Derivation:

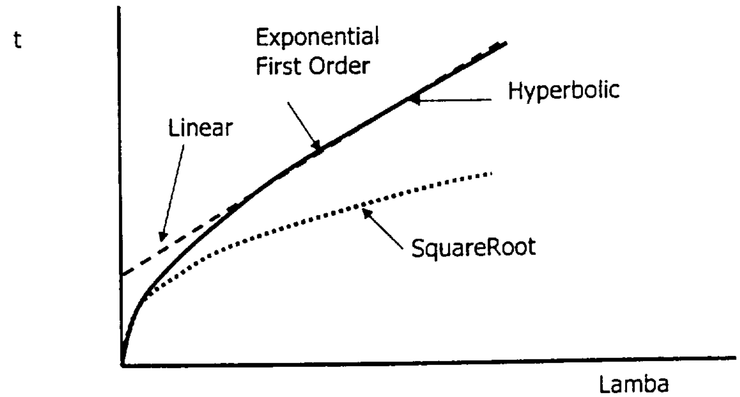
$$v = \frac{\partial \lambda}{\partial t} \longrightarrow \lambda = \int_{t=0}^{t} v\,dt = v_0[t - \tau\ (1 - e^{-t/\tau})]$$

- 2 Approximations:
  - For $t \ll \tau$: $t \cong \sqrt{(2\tau\,\lambda)/v_0}$ (SquareRoot)
  - For $t \gg \tau$: $t \cong \tau + \lambda/v_0$ (Linear)
- A Hyperbolic equation has been proposed (Mabson):

$$t = \sqrt{(\lambda / v_0)^2 + (2\tau\,\lambda / v_0)} \quad \text{(eq.1)}$$

First Order Model (Continued 1)

- The three approximations to the Exponential First Order equation:



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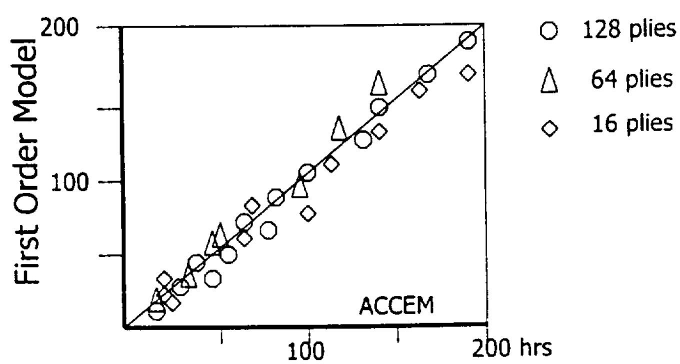
First Order Model (Continued 2)

- Validation of Model (Neoh 95):



Comparison between First Order and ACCEM for Hand Layup

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First Order Model (Continued 3)

- Sample Process time estimation:

Process	Tau	V_0	Design Feature
Hand lay-up 3 "tape	0.0191 hrs	10950 in/hr	Length
Hand lay-up 12" tape	0.0111 hrs	1896 in/hr	Length
Hand lay-up woven tape	0.0856 hrs	57500 in^2/hr	Area
Disposable bagging	0.0331 hrs	5137 in^2/hr	Area
Reusable bagging	0.0092 hrs	6219 in^2/hr	Area

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First Order Model (Continued 3)

- Estimation of process time for commercial airframe structures:

Material	Item	V_0	Tau, min	Design feature
Aluminum	Skin Fabrication	3.024	3.1123E+04	Wetted area, in^2
	Rib Fabrication	2.059	4.1423E+04	Wetted area, in^2
	Spar Fabrication	2.462	3.6934E+04	Wetted area, in^2
	Wing Assembly	0.0395	2.1341E+04	Perimeter, in
Composite	Skin Fabrication	2.1447	4.3883E+04	Wetted area, in^2
	Rib Fabrication	0.8236	1.0356E+05	Wetted area, in^2
	Spar Fabrication	1.4485	6.2788E+04	Wetted area, in^2
	Wing Assembly	0.02826	2.9877E+04	Perimeter, in

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First Order Model (Continued 4)

- Cost Estimation of Generic wing (Paper AIAA 2000-4839):
- Physical elements:
  - Front and Rear spars
  - Five ribs
  - Skins
- Process Costs Include:
  - Fabrication of Spars
  - Fabrication of Ribs
  - Fabrication of Skins
  - Assembly of Spars, Ribs, and Skins into Wing

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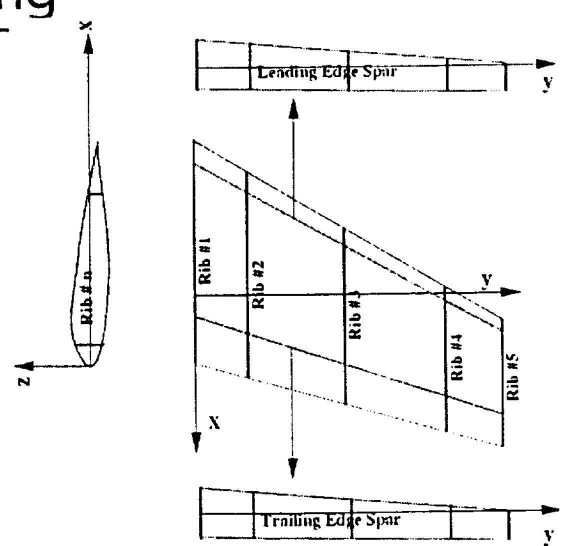
Cost Estimation of a Generic wing



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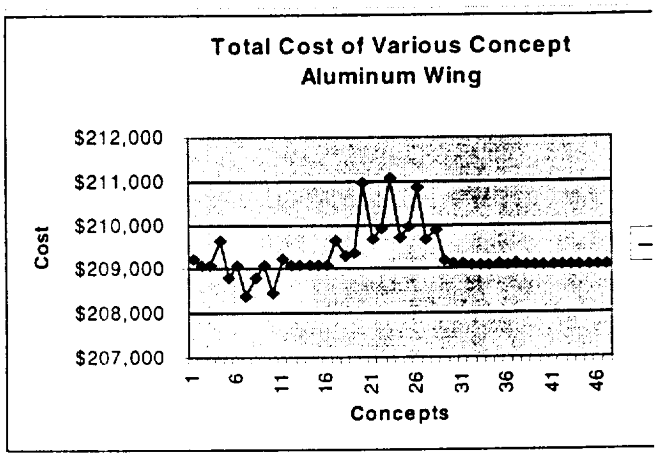
Cost Estimation of a Generic wing (Continued 1)



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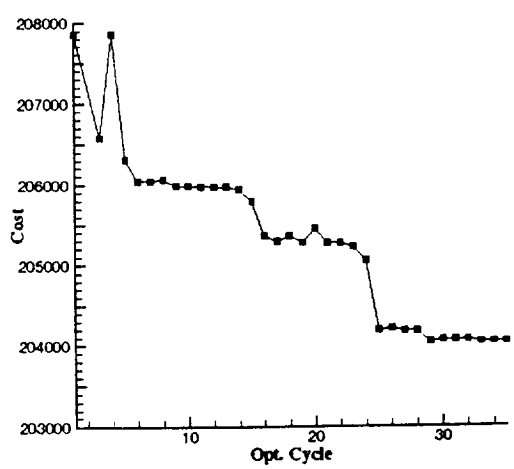
Cost Estimation of a Generic wing (Continued 2)



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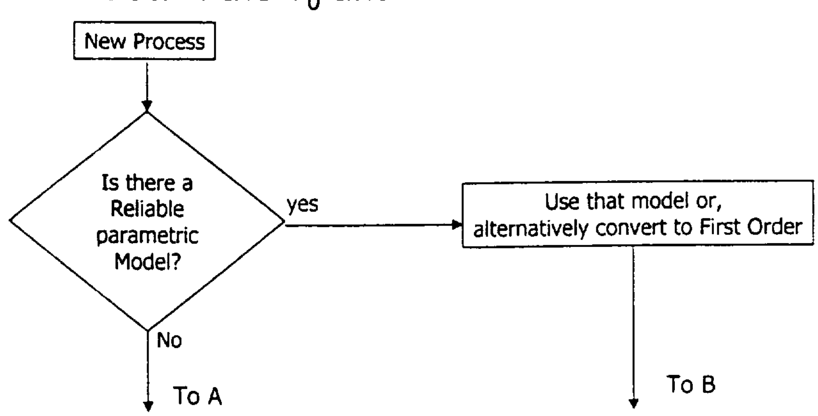
Estimating Time for New Processes

- Proposed strategy:
  - Apply "vital few and trivial many" concept to focus on the few dominating steps
  - For each of the dominating steps:
    - Identify the critical design features
    - Derive the V_0 and Tau values for the first order model (see diagram below)
    - Apply a scaling factor between the dominating step and the remaining steps

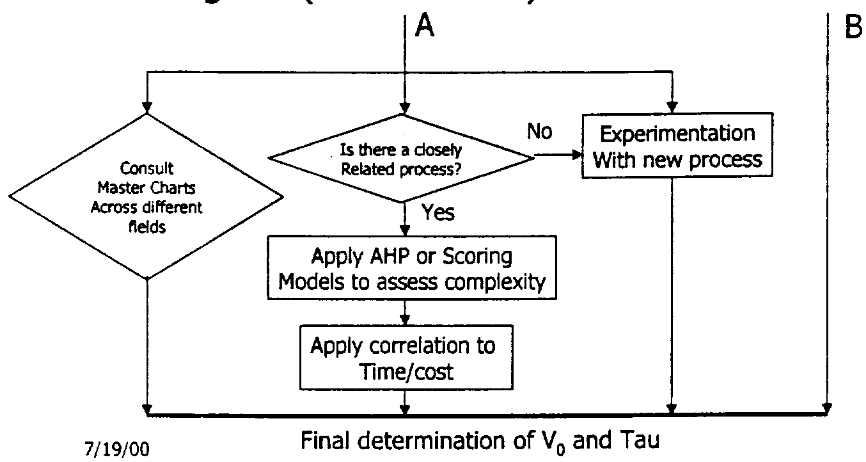
Estimating Time for New Processes (Continued 1)

- How to Obtain the V_0 and Tau values?



Estimating Time for New Processes (Continued 2)

- Diagram (Continuation):



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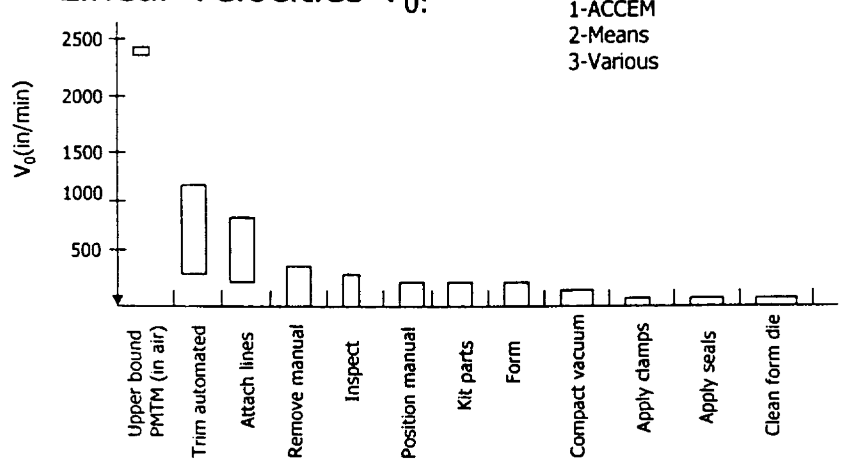
Master Chart for V_0 across Different Fields (Neoh 95)

- Linear Velocities V_0:

Sources:
1-ACCEM
2-Means
3-Various



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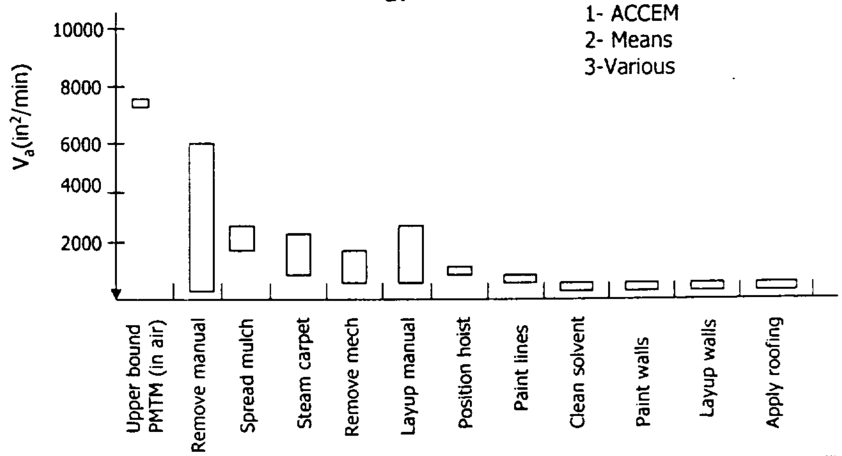
Master Chart for V_0 across Different Fields (Neoh 95)

- Areal Velocities V_a:



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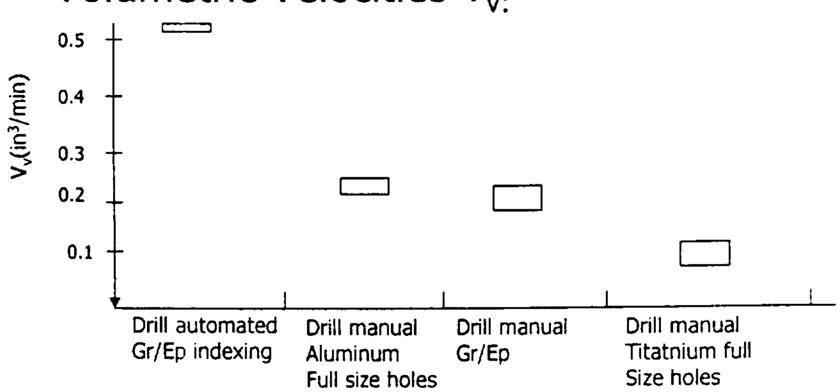
Master Chart for V_0 across Different Fields (Neoh 95)

- Volumetric Velocities V_v:



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Useful Facts about Airplane Price (Roskam 90)

- Ultralight Airplane (89 USD):
  - Pre-cut kits: AMP=5(W_{to}) to 10(W_{to})
  - Raw Material kits: AMP = 3(W_{to}) to 10(W_{to})
  - Range of W_{to} : 400 to 800 lbs
- Agricultural Airplane (89 USD):
  - AMP=invlog{-0.6681 +1.5799 log(W_{to})}

    For W_{to} between 3000 lbs and 15,000 lbs

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Useful Facts about Airplane Price (Roskam 90)

- Single Engine Piston (89 USD):
  - Normal or turboprop engine:
    - AMP = invlog{-1.2435+1.8459(log(W_{to})}
  - Turbocharged engine:
    - AMP = invlog{-1.1174+1.8459(log(W_{to})}
  - Range of W_{to}: 1500 to 10,000 lbs

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Useful Facts about Airplane Price (Roskam 90)

- Multiple-Engine Piston (89 USD):
  - AMP=invlog{-0.8526+1.7413(log(W_{to}))}
  - Range of W_{to} : 3000 to 8000 lbs
- Multi-Engine Turboprop (89 USD):
  - AMP=invlog{1.9153+1.1115(log(W_{to}))}
  - Range of W_{to} : 8000 to 50,000 lbs
- Business Jet:
  - AMP=invlog{0.6570+1.4133(log(W_{to}))}
  - Range of W_{to} : 10,000 to 60,000 lbs

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Useful Facts about Airplane Price (Roskam 90)

- Turboprop Commuter Airplane (89 USD)
  - AMP=invlog{1.1846+1.2625(log(W_{to}))}
  - Range of W_{to} : 6,000 to 50,000 lbs
- Commercial Jet (89 USD):
  - AMP=invlog{3.3191+0.8043(log(W_{to}))}
  - Range of W_{to} : 60,000 to 1,000,000 lbs
- Military jet (89 USD):
  - AMP=invlog{2.3341+1.0586(log(W_{to}))}
  - Range of W_{to} : 2500 to 1,000,000 lbs

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Useful Facts about Airplane Price (Roskam 90)

- Piston Engine (89 USD):
  - From 80 to 200 shp:
    - $Ep=invlog\{2.9923+0.4536(\log shp_{to})\}$
  - From 200 to 500 shp:
    - $Ep=invlog\{-0.777+2.0917(\log shp_{to})\}$
- Turboprop Engine (89 USD):
  - From 400 to 5000 shp:
    - $Ep=invlog\{2.5262+0.9465(\log shp_{to})\}$
  - For larger shp:
    - $Ep=(1.418)(2160000)\{0.533(SF)+0.467\}$
      $SF=SHP/20424$

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Useful Facts about Airplane Price (Roskam 90)

- Propeller Price (89 USD):
  - $PP=invlog\{0.6119+1.1432(\log shp_{to})\}$
  - Range: 100 to 20,000 shp
- Composite Propeller (89 USD):
  - $PP=invlog\{0.7746+1.1432(\log shp_{to})\}$
  - Range: 100 to 20,000 shp
- Jet Engine Price (89 USD):
  - $EP = invlog\{2.3044+0.8858(\log T_{to})\}$
  - Range: 1,000 to 50,000 lbs per engine

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Discussion

- Choice of Cost models
- What Model(s) is/are most appropriated for MDO Branch?

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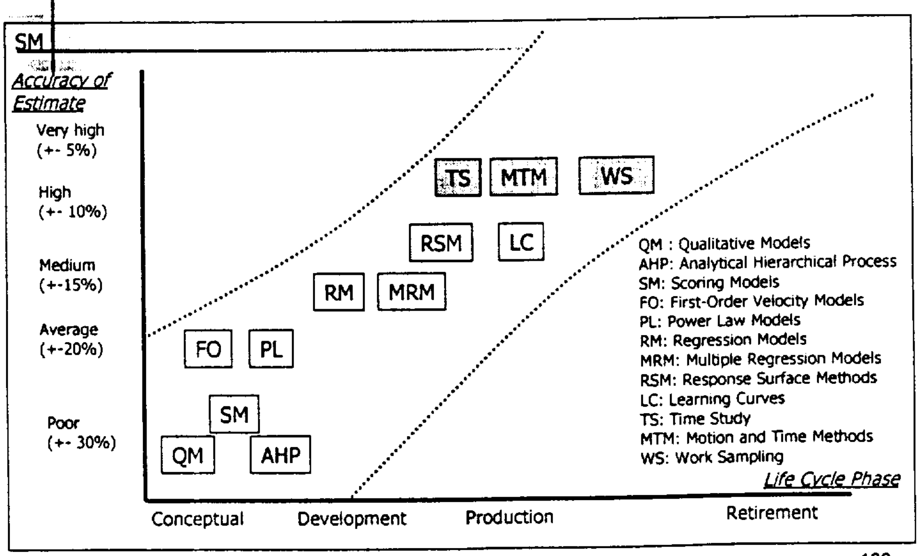
Choice of Models



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Which Model for MDOB?

- Criteria:
  - Cost models based on process requirements besides weight
  - Quantitative models based on physical parameters
  - Models that can be readily integrated with current automated optimization codes
  - Suitable for preliminary design, i.e. higher flexibility of use, more accurate estimation, and less detail dependency

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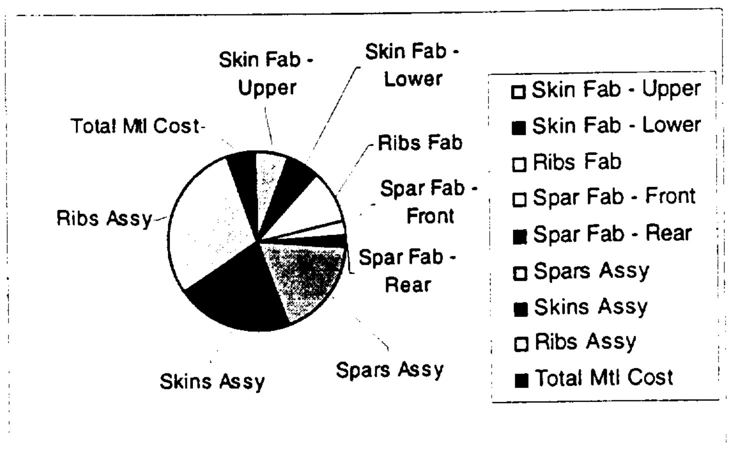
Criterion 1: Cost model based on Process requirements besides Weight



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Criterion 2: Quantitative Model based on Physical parameters

- Examples of Physical Parameters:
  - Length
  - Perimeter
  - Wetted Area
  - Volume
- Majority of Parametric Models, including First Order Velocity Model, can relate to physical parameters
- The principal variables of the First Order Velocity model, i.e. V_0 and Tau, are physical concepts that can be easily understood

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Criterion 3: Models that can be readily integrated with current automated optimization codes

- Discussion of such integration in paper AIAA-4839
- Much more work is needed:
  - Cost Models of Tails,Fuselages, Engines
  - Cross Platform integration
  - Corba or DCOM

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Criterion 4: Suitable for Planning and Conceptual Design

- Parametric Models, including First Order Velocity Model, are needed.
- Failures of conventional parametric cost models include:
  - Complexity
  - High dependency on historical data
  - Often not related to physical parameters

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Summary

- Review of good number of cost/time estimation models
- Discussion of model relevancy
- First Order Velocity Model appears to be a good model for the following reasons:
  - Based on physical parameters
  - Has been validated in a good number of studies
  - Can be readily integrated with current automated optimization codes
- Investigation of First Order Velocity model has only begun: much more work is needed

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