Affordable Design: A Methodology to implement Process-Based Manufacturing Cost Models Into The Traditional Performance-Focused Multi-Disciplinary Design Optimization

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Multidisciplinary Optimization in Airframe Design

- LaRC HPCCP HSCT Application Goal:
  - Design Environment
    - MDO Technology
    - Information Technology
  - Results (Changes from 94 to 99)
    - Design variables: 5 to 271
    - Constraints: 6 to 31868
    - Major Codes: 5 in 1999
    - Analysis Processes: 10 to 70
    - Optimization Cycles: 100 to 10^5

Cost Consideration

- In the past cost was derived from structural Weight.
- Now there is possibility to include acquisition cost, ie Manufacturing and Assembly costs, of aircraft in conceptual design phase.
- Purpose of paper: to demonstrate the use of a PBMAC modeling tool with a performance analysis tool for cost-performance optimization

Review of Cost Models

1. Learning Curve:
   - Basic Tenet: There is a relatively constant percentage reduction in the cost, or manhour, for doubled quantities of production
   - Two types of curves: Unit, and Cumulative Average
   - Requirement of established method(s) of production

Review of Cost Models (Ctd)

2- 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:

$$mhr = f(y)^s \quad \text{vs} \quad t = a(x)^m$$

(LC) (PL)

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:

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

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...

Examples of Power Law Models (Continued 2)

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

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:

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

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

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

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

Multiple Regression

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

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3$$

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1 x_2$$

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1 x_2 + b_4 x_1^2 + b_5 x_2^2$$

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

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

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

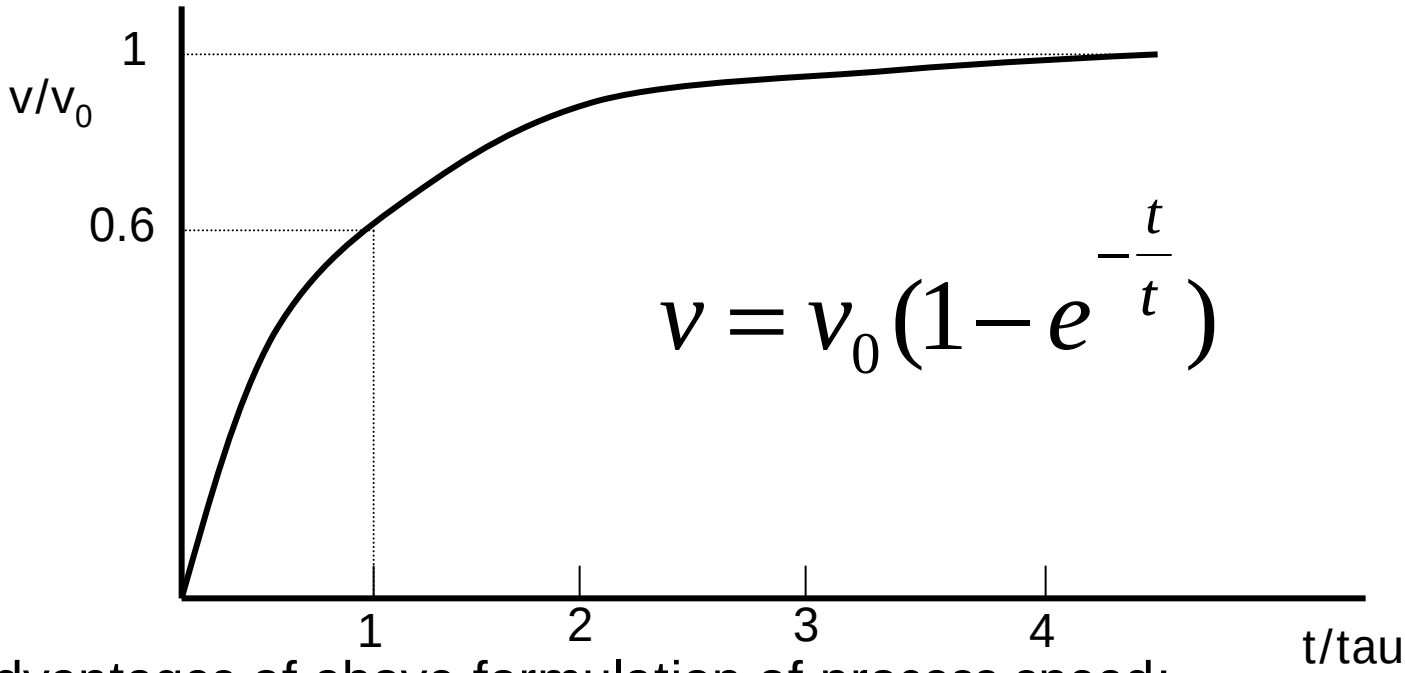
First Order Velocity Model

- 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

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.

First Order Velocity Response



$$v = v_0(1 - e^{-\frac{t}{t}})$$

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

First Order Model

- Math Derivation:

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

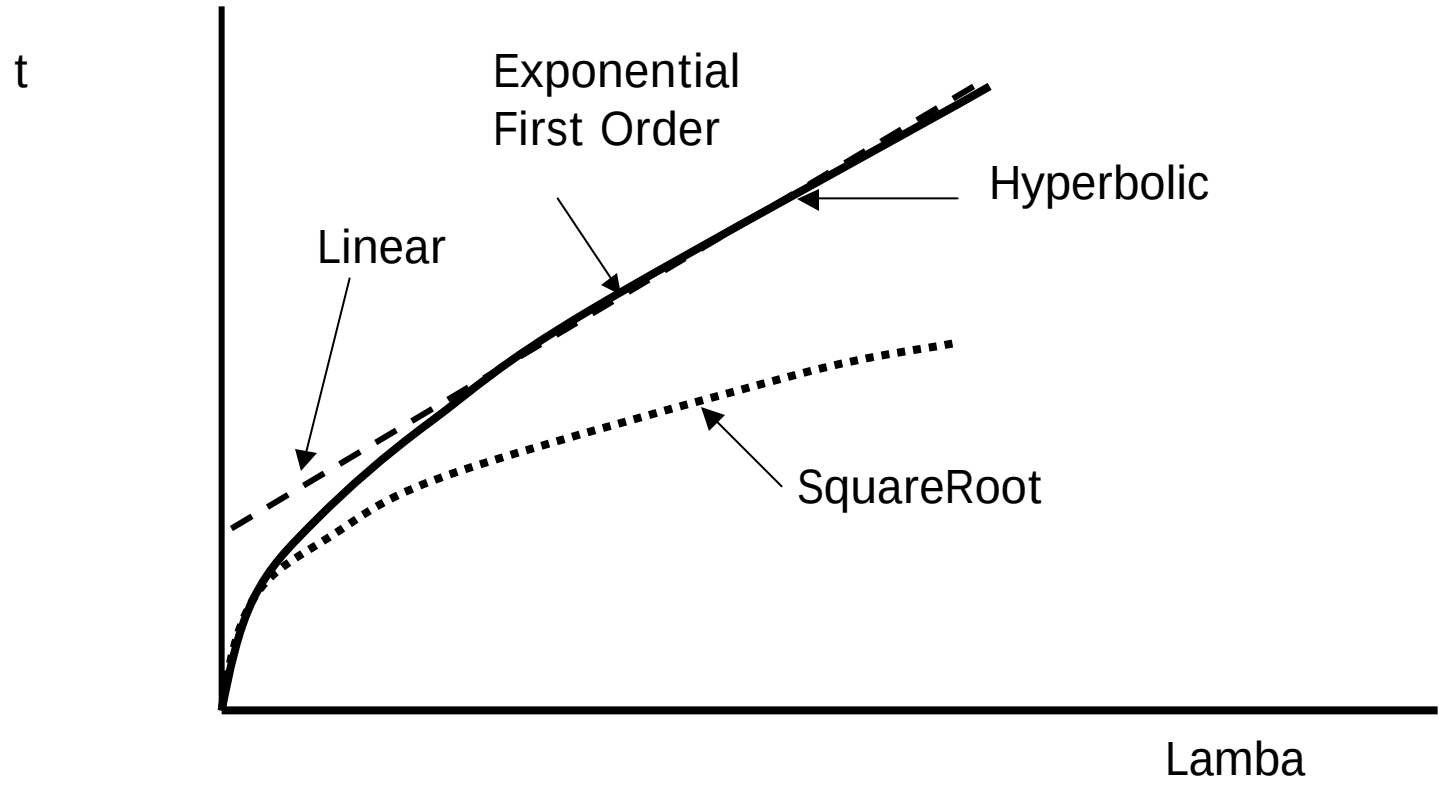
- 2 Approximations:
  - For $t << t \quad : \quad t \cong \sqrt{(2t\ \ l)/v_0}$ (SquareRoot)
  - For $t >> t \quad : \quad t \cong t + l/v_0$ (Linear)

- A Hyperbolic equation has been proposed (Mabson):

$$t = \sqrt{(l\ /v_0)^2 + (2t\ \ l\ /v_0)} \qquad \text{(eq.1)}$$

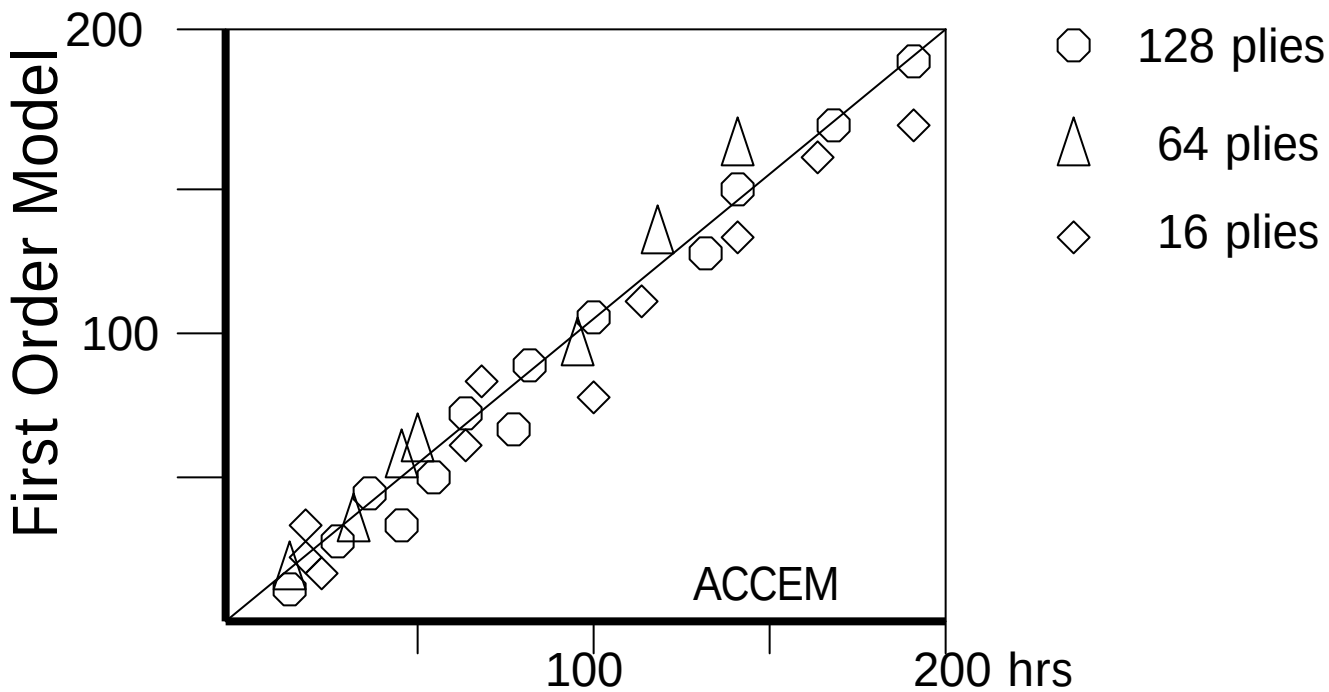
First Order Model (Continued 1)

- The three approximations to the Exponential First Order equation:



First Order Model (Continued 2)

- Validation of Model (Neoh 95):



Comparison between First Order and ACCEM for Hand Layup

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

First Order Model (Continued 3)

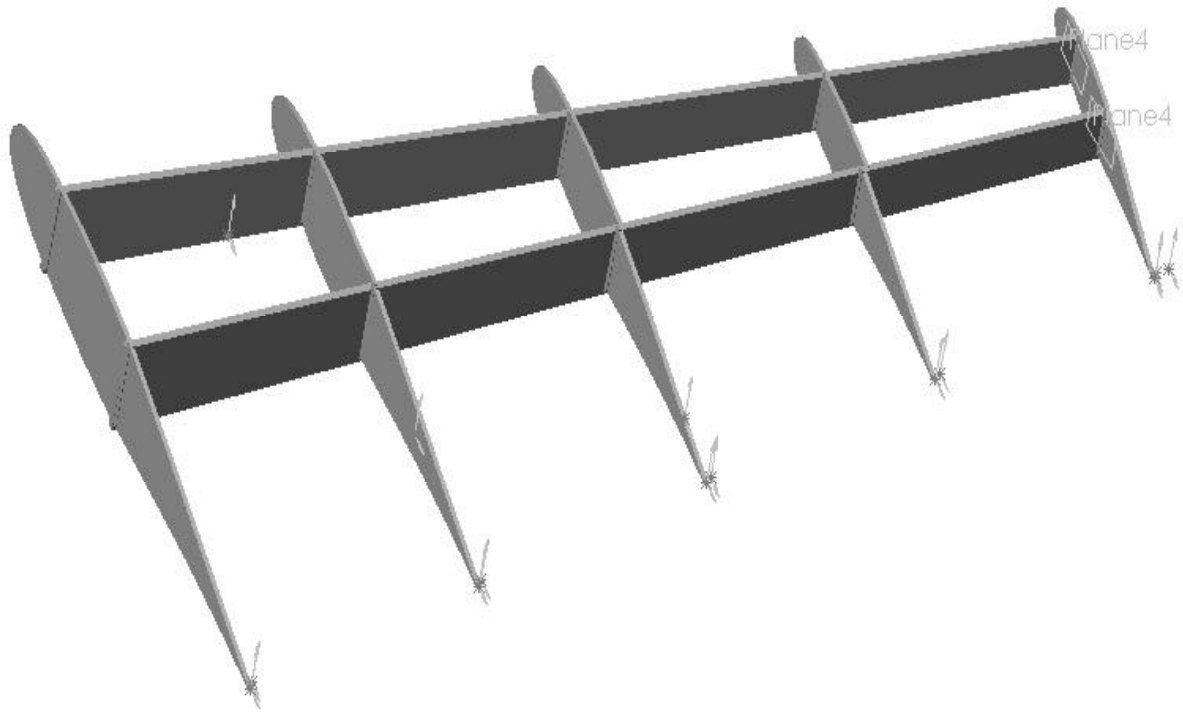
- Estimation of process time for commercial airframe structures:

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

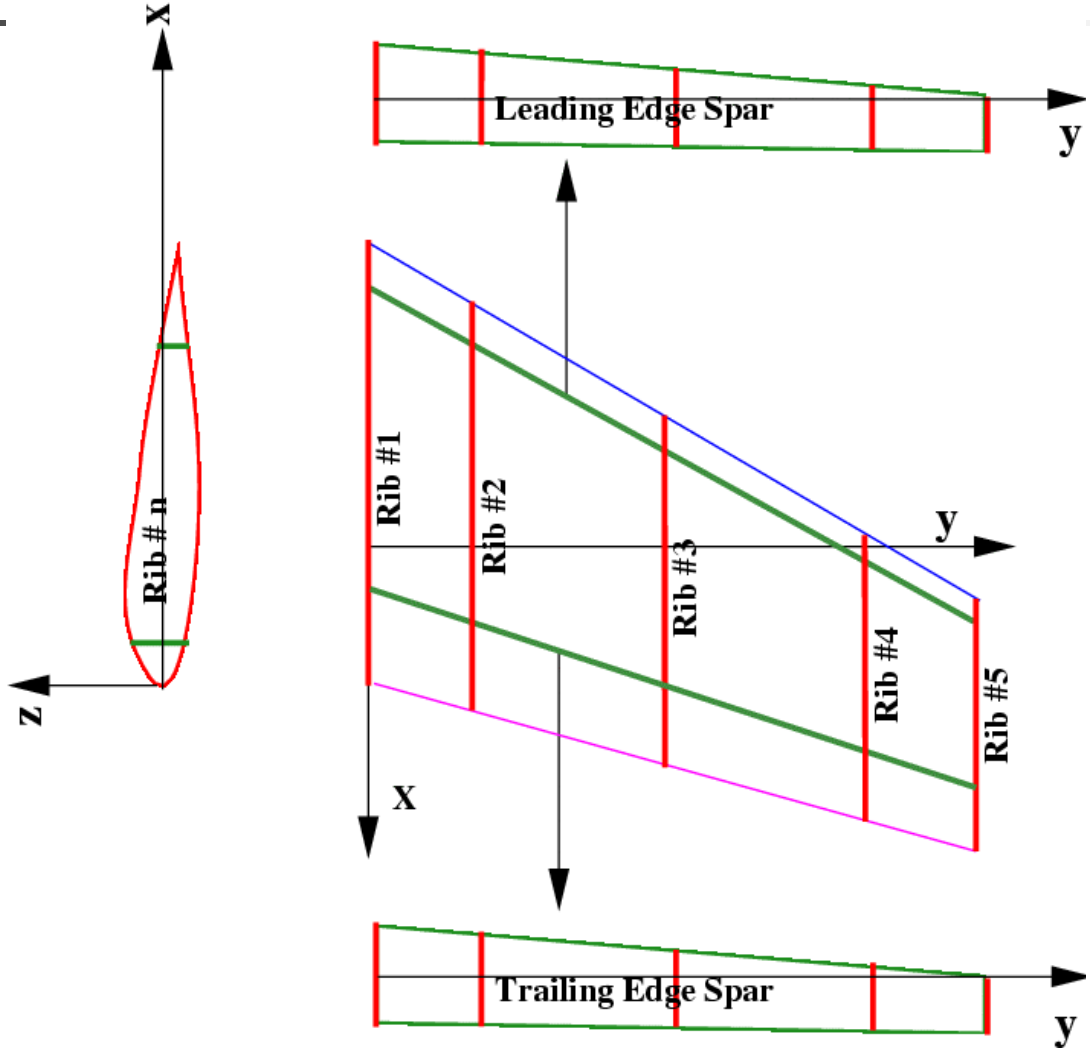
First Order Model (Continued 4)

- Cost Estimation of Generic wing
  - 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

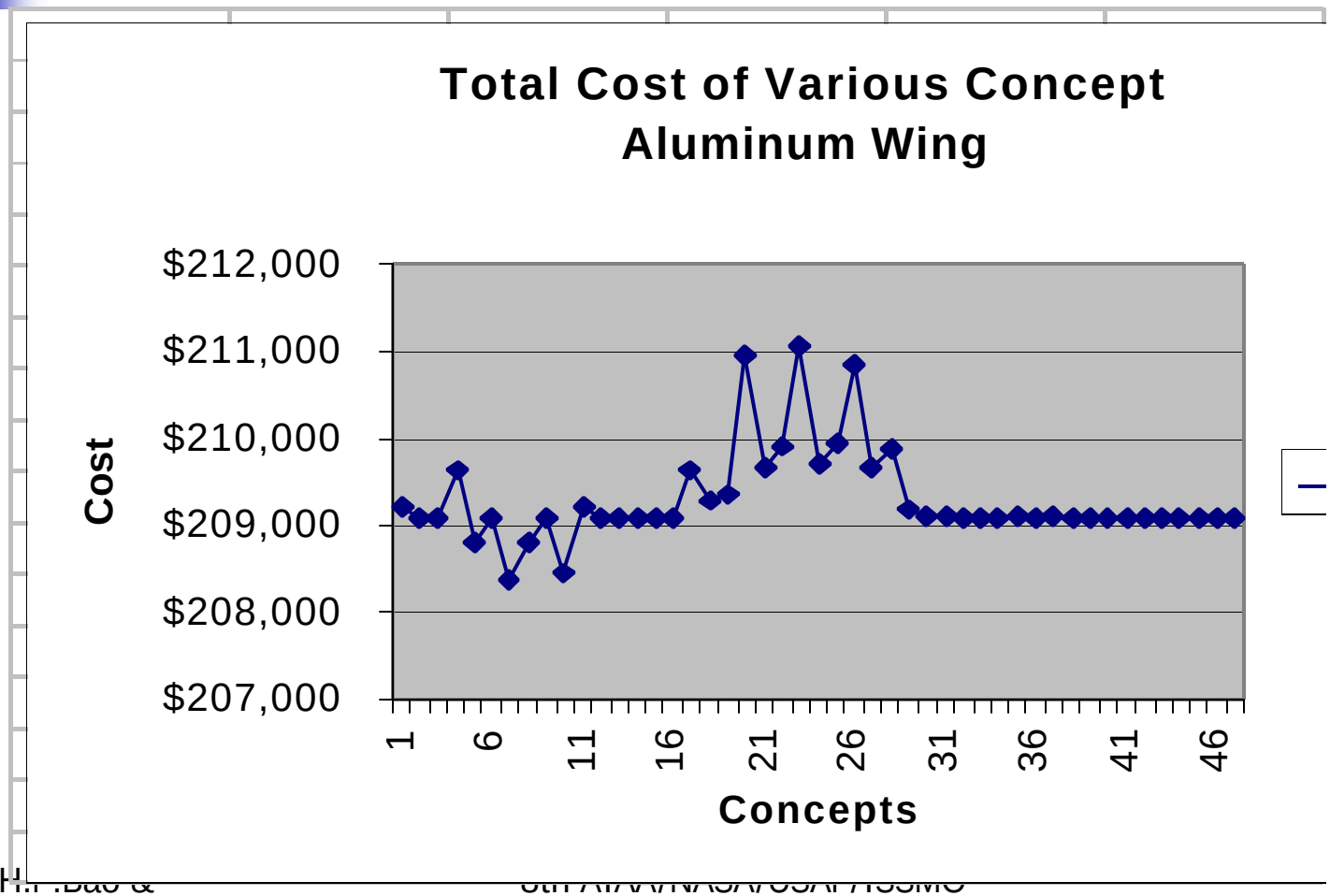
Cost Estimation of Generic Wing: Solid Model



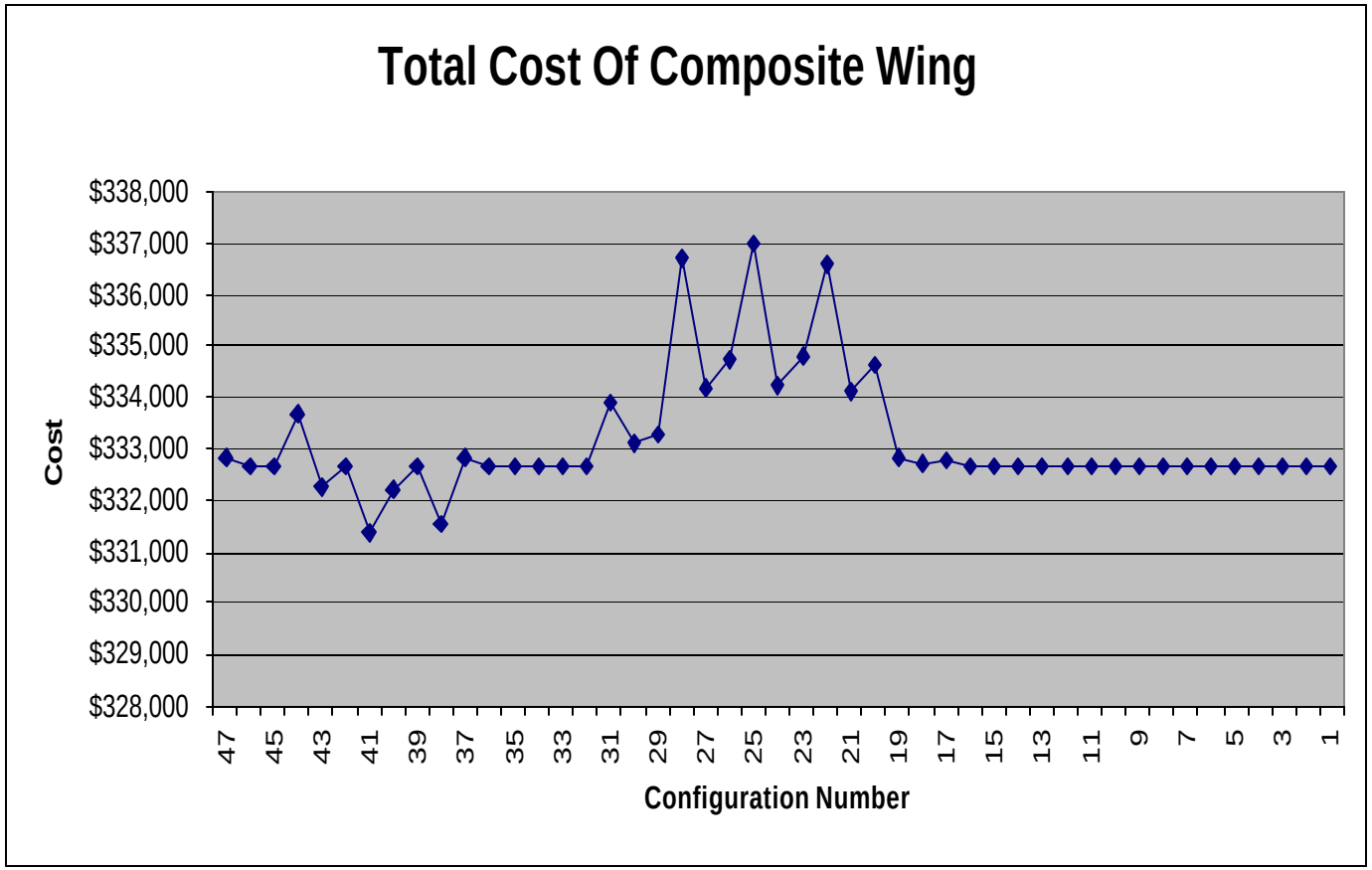
Cost Estimation of a Generic wing:Parametric Model



Cost Estimation of a Generic Wing: Aluminum

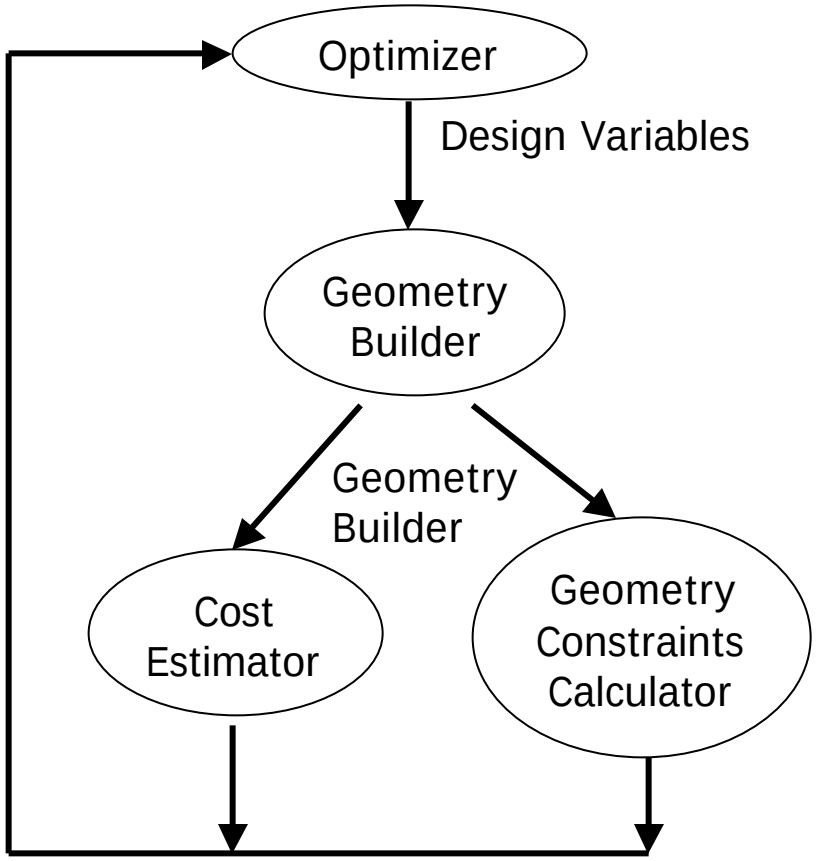


Cost estimation of a Generic Wing: Composite Material

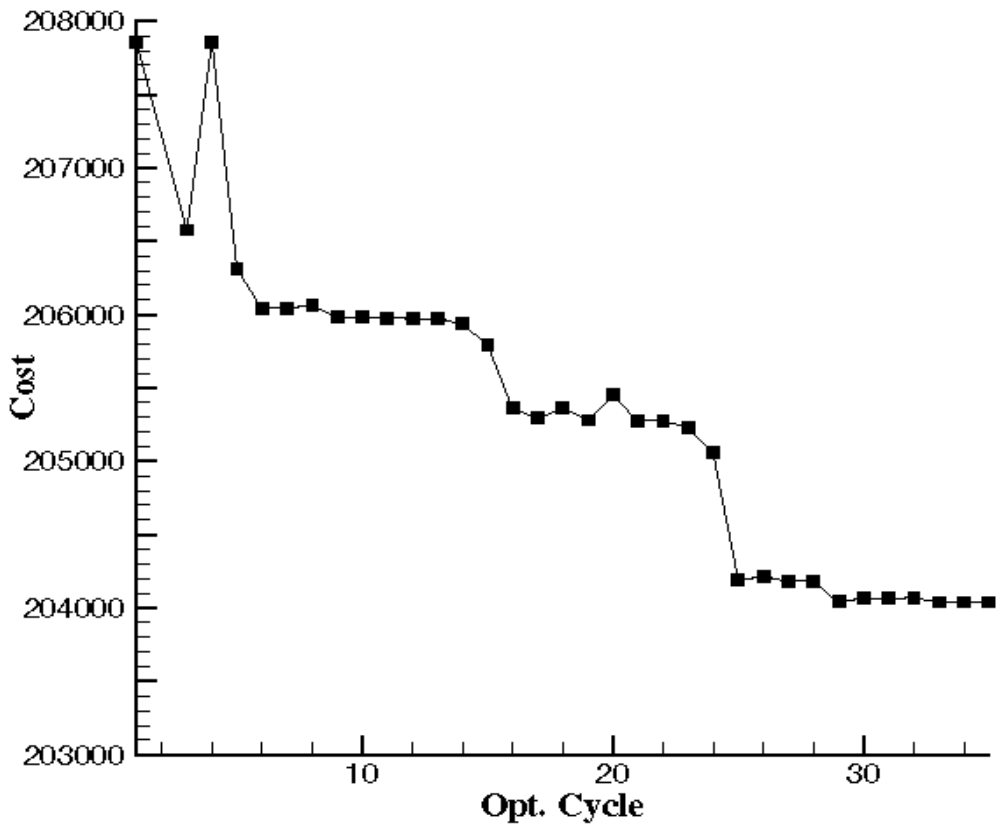


Cost Optimization Process

- Diagram



Cost Estimation of a Generic wing: Optimization for Aluminum Wing



Summary

- Review of a good number of cost/time estimation models
- First Order Velocity Model appears to be a good model for the following reasons:
  - Based on physical parameters
  - Has been validated in a 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, and has in fact been initiated.