Introduction

• In today’s cost constrained environment NASA needs a X-Plane database and parametric cost model that can quickly provide a rough order of magnitude cost predictions for experimental aircraft.

• The model should be based on critical aircraft design parameters, such as weight, size, and speed, as well as some sort of complexity factor.

• It’s commonly known among cost engineering professionals, both government and industry that weight based CERs have the highest correlation.

• Last fall 2014 - the authority was given on a non-interference basis to develop an X-Plane Parametric Cost Model.

• Then early spring 2015 – I was given opportunity to hire a Summer Internship to assist in developing CERs using Regression Analysis.
Challenges in getting cost data

Throughout history every aircraft manufacturer, starting with the Wright brothers, has weighed their aircraft. The original Wright Flyer (Flyer I) weighed 604.1 pounds. A military version of the aircraft (Flyer III), capable of carrying one passenger, was procured by the Army Signal Branch for $30,000, thus establishing the first CER at $49.66 per pound.
The Story behind the X-1 Bell

I walked into work everyday for 10 years. One day I took the initiative to put my thoughts and my training into action with the question; what was the cost to design, build and fly the 1952 Bell X-1E?

I made a quick cost estimate using the Wright Flyer weight CER and adjusted for inflation. This gave me an estimate of $1.8 million in FY52 dollars, which is reasonably close to the actual cost.
Challenges in getting cost data

Timeline

- 1940’s 50’s, 60’s & 70’s. . . Were basically joint-funded Programs;
  - National Advisory Committee for Aeronautics (NACA)
  - National Aeronautics and Space Administration (NASA)
  - U.S. Army, and various U.S. Air Force
- Salary Dollars were paid under a different “Appropriation”.
- NASA Dryden/Armstrong was under Ames until January 1994.
- Full Cost Accounting did not go into affect until 2002.
- Some Project Managers (PM) have volumes of cost data stored away in their cabinets.
  - Organized in 3-ring binders
  - Organized by burning; technical, scope, schedule, and cost data onto CDs
- NASA has a Cost Analysis Data Requirement (CADRe) for projects subject to NPR 7120.5E.
- In general, CAD and NASA Aeronautic Centers will cover CADRe for 7120.8 Research and Technology Program and Projects i.e. X-Planes.
Source of the Data

- NASA Technical Libraries
  - Armstrong’s Technical Reference Library
  - Marshall Space Flight Center – Library “Redstone”
- Various publications “Books” specifically written on X-Planes
  - “The X-Planes”; written by Jay Miller
- Subject Matter Experts
  - Dr. Joseph Haymaker
  - 3rd Parties “Cost Research” Companies
- Government Accountability Office (GAO)
  - Various Cost Reports on X-Planes
- Industrial Partners or various Aeronautical Manufactures
  - Proprietary and “thin-slicing” the data
- Wikipedia and other “on-line” sources
  - Beware of the information and document the source, date, and URL
• Some of the X-planes had three or more sources of Cost Data
  – For Example: NASA Technical Data, GAO, Hamaker; for the same plane
  – How does the Cost Engineer know who’s data is correct?

• The entire set of X-Planes parameters are now catalog in an Excel data base with a word document linked in a separate folder serving as the source document.

• Source documents are in Word format
  – Name of the person collecting the data
  – Date the source was collected
  – URL name if the source was collected on-line
    • Copy of the entire online source document includes references.
    • Note: a data element appeared to be changed within a 1 year time span.

• Hierarchy currently being used for Source Data
  2.) People associated in collecting Cost for NASA or for the Government.
  3.) Thin-slicing, Wikipedia and other on-line forums.
Advance Composite Materials (ACM) have gone a long way since the creation of carbon fiber and epoxy.

Hand Lay-up versus Auto-Clave composite “Sandwich” Manufacturing

- **Hand-layup** - is the process where resins are impregnated by hand in the form of woven, knitted, stitched or bonded fabrics. Hand-lay up process usually accomplished by rollers or brushes and cooked in a warm “unpressured oven”, cured under standard atmospheric conditions.

- **Autoclave** - eliminates voids by placing the layup within a closed mold and applying vacuum, pressure, and heat.

ACM aircraft manufactures are replacing 30,000 or more rivets and other components that were used by earlier aircraft manufacturing processes.
Cost of using Advance Composite Materials for prototyping X-Planes

- Large and small aircraft manufactures are using Advance Composite Materials.
  - Reports are coming in with a 30% cost saving from aircraft companies using Composites rather than Aluminum and Rivets.
  - Yes, there were known problems with adhering process in the past – which now seems to be fixed.
- The current vision at NASA’s Aeronautical Research Centers are to Design, Build and Fly “One-of-a kind” research X-Planes every 2 to 3 years.
- Rapid Prototyping from Design to 1st Flight is expected.
- NASA needs to build-in “concurrent system engineering” into the process including; Preliminary Design Reviews (PDRs), Critical Design Reviews (CDRs), “Air-worthiness”, and Flight Readiness Reviews (FRRs)
- Eliminate the need for “Unidentified Future Expenses (UFE).
Future State

- Twin Glider Assisted Launch System (TGALs) has currently been priced using the earlier algorithms of Armstrong’s Parametric Cost Model.

- Show a 2 minute conceptual flight demo video
  
  https://www.youtube.com/watch?v=0hEnYyykaL8
Parametric Cost Modeling

- **Assumptions**
  - Cost can be predicted by a few design parameters.
  - Cost includes the initial design to first flight.

- **Parameters**
  - Technical and performance parameters for 22 experimental aircraft
    - Dry Weight, Takeoff Weight
    - Length, Wing Span, Wing Area
    - Mach, Thrust, Speed Regime
    - Maximum Altitude, Range
    - Material, Number of Engines, Crew size

- **Goal**
  - Identify the best parameters
  - Develop the “best fit” R2 value greater than .80
Linear Regression

- Supervised learning
- Conceptually simple
- \( Y_j = \beta_0 + \beta_1 X_{1j} + \beta_2 X_{2j} + \ldots + \beta_n X_{nj} + \epsilon_j \)
- Assumptions
  - Expected value of \( Y \) is a linear function of the \( X \)'s
  - Unexplained variations in \( Y \) are independent and normally distributed
  - All errors in \( Y \) measurements have the same variance
Summary of Variables

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<th>Statistic</th>
<th>Mean</th>
<th>St. Dev.</th>
<th>Min</th>
<th>Max</th>
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Categorical Predictors

Speed Regime
- Hypersonic
- Subsonic
- Supersonic

Crew Size
- 0
- 1
- 2

Engines
- 0
- 1
- 2
- 4
Continuous Predictors
Distribution: Original Data

- Normal Q-Q Plot
  - Dry Weight
  - Mach

- Normal Q-Q Plot
  - Length
  - Max Altitude

Sample Quantiles vs. Theoretical Quantiles
Distribution: Log-Transformed Data

- Normal Q-Q Plot
  - Dry Weight
  - Length
  - Mach
  - Max Altitude

Sample Quantiles vs. Theoretical Quantiles
Pairwise Scatter Plots

- Cost
- Mach
- Dry.Wt
- Max.Altitude
- Length
Cost vs Categorical Predictor

**Cost vs Speed Regime**
- Hypersonic
- Supersonic

**Cost vs Crew Size**
- 0
- 1
- 2
Cost vs Mach

![Graph showing the relationship between Cost and Mach with regression line and data points.]

Cost ~ Mach

<table>
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<tr>
<th>Residuals:</th>
<th>Min</th>
<th>1Q</th>
<th>Median</th>
<th>3Q</th>
<th>Max</th>
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<td>-1.2106</td>
<td>-0.5649</td>
<td>-0.3293</td>
<td>0.5581</td>
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| Coefficients: | Estimate | Std. Error | t value | Pr(>|t|) |
|---------------|----------|------------|---------|---------|
| (Intercept)   | 4.5592   | 0.2276     | 20.034  | 1.05e-14*** |
| Mach          | 0.8205   | 0.1659     | 4.946   | 7.79e-05*** |

Residual standard error: 1.007 on 20 degrees of freedom
Multiple R-squared: 0.5501, Adjusted R-squared: 0.5276
F-statistic: 24.46 on 1 and 20 DF, p-value: 7.79e-05
Cost vs Dry Weight

Cost ~ Dry.Wt

Residuals:
Min  1Q Median  3Q  Max
-2.3180 -0.7239  0.1129  0.8535  2.0023

Coefficients:
Estimate Std. Error t value Pr(>|t|)
(Intercept) -1.7177  2.0576  -0.835  0.41369
Dry.Wt  0.7516  0.2307  3.258  0.00393 **

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Residual standard error: 1.213 on 20 degrees of freedom
Multiple R-squared: 0.3468,  Adjusted R-squared: 0.3141
F-statistic: 10.62 on 1 and 20 DF,  p-value: 0.003934
Multiple Regression Model

Cost ~ Mach + Dry.Wt

Residuals:
Min 1Q Median 3Q Max
-1.2519 -0.5805 -0.1066 0.5989 1.7749

Coefficients:
Estimate Std. Error t value Pr(>|t|)
(Intercept) 0.8883 1.7024 0.522 0.607842
Mach 0.6630 0.1687 3.930 0.000899 ***
Dry.Wt 0.4229 0.1946 2.173 0.042652 *

Residual standard error: 0.9243 on 19 degrees of freedom
Multiple R-squared: 0.6397, Adjusted R-squared: 0.6017
F-statistic: 16.86 on 2 and 19 DF, p-value: 6.146e-05

<table>
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<tr>
<th></th>
<th>Cost</th>
<th>Mach</th>
<th>Dry.Wt</th>
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<th>Length</th>
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<td>Dry.Wt</td>
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<td>Max.Alt</td>
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<tr>
<td>Length</td>
<td>0.36</td>
<td>0.12</td>
<td>0.83</td>
<td>0.42</td>
<td>1.00</td>
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Model Assumptions

Residuals of Predicted Cost

Normal Q-Q Plot

Residuals

Sample Quantiles

Theoretical Quantiles
Final Model
Final Model
# Future X-Planes

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Point Estimate</th>
<th>Lower Estimate</th>
<th>Upper Estimate</th>
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<tr>
<td>LBFD</td>
<td>179.98</td>
<td>121.40</td>
<td>266.84</td>
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</table>
Future X-Planes and X-Wings
Summary

• Within a two-month effort the Armstrong Cost Engineering Team has gone through the full process in developing a parametric cost model.
• We have identified and collected key parameters, such as; dry weight, length, wing span, manned vs unmanned, altitude, Mach and thrust.
• We have summarized the Variables.
• We created a regression analysis on 22 CERs of the 65 X-Planes that are currently in the data base.
• We have gone through the initial stages in determining the “best fit” for R2 values.
• We have parametrically priced out several future X-Planes.
• More work needs to be done!
  – One recommendation is to stand-up a NASA Armstrong Cost Engineering Office on a non-interference basis.
Questions

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