Using Historical Cost and Schedule Data to Predict Cost Risk for Future NASA X-planes

International Cost Estimation and Analysis Assication
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Introduction

• In today’s cost-constrained environment, NASA should consider using historical data to establish a baseline for aeronautical cost and schedule research.

• Aircraft have various design parameters including weight, size, and speed regimes. These parameters generate a significant complexity factor that makes it difficult to estimate cost.

• Both cost and schedule assessments are needed to predict the future costs of a successful X-plane program.
Definition of an X-plane

• X-planes are a series of experimental U.S. aircraft used to test and evaluate new technologies and aerodynamic concepts.

• X-planes are not prototypes, they are complex flight research vehicles / engineering tools that are not intended to go into full-scale production.

• X-planes are usually produced in groups of 2 or 3 vehicles to ensure the completion of program objectives.
Definition of an X-plane

• The "X" or “experimental” designation is assigned to a U.S. research vehicle to indicate the higher risk associated with the dedicated research mission objectives.

• Not all U.S. experimental aircraft have been designated X-planes; some have been known only by the manufacturer’s designation, non-'X'-series designations, or classified code names.
Our Research Starts with X-1E Bell

The X-1 broke the sound barrier on October 14, 1947. The X-1E is the most photographed aircraft at NASA Armstrong, yet no one seemed to know how much it cost to design, build, nor how long it took to fly all of the test cards.
Armstrong’s X-Plane Database
During the 1940s, -50s, -60s and -70s, projects were basically jointly funded through NACA, NASA, and various DoD programs.

NASA Dryden (now Armstrong) was under various NASA Centers until January 1994.

Full-cost accounting went into effect in 2002.

Some Project Managers still have physical cost data stored:
- Organized in three-ring binders
- Organized by burning technical, scope, schedule, and cost data onto CDs
Data Requirements

• NASA has a Cost Analysis Data (CAD) Requirement (CADRe) for Space and Launch Vehicle like projects subject to NPR 7120.5E.

• Generally, CAD and NASA Aeronautic Centers cover CADRe for NPR 7120.8 Research and Technology Programs and Projects (X-planes).
Research Introduction

• AFRC in Edwards, California, is NASA's primary center for atmospheric flight research and operations.

• NASA is moving forward with the construction of new research planes.

• These planes will help NASA make major breakthroughs in flight technology.
This project looks to provide historical cost and schedule setback data that may be of use to future X-plane project managers.

This project also will use historical X-plane data to calculate a risk-infused, expected cost for a notional flight research project (NFRP).
One major goal for this project was to develop a database using historical X-plane cost and schedule data.

This database outlined many types of schedule delays in completed X-plane programs.

Schedule events were recorded if they caused a setback in a program’s intended timeline.
Why is this important?

• Each setback occurrence costs NASA valuable time and money.

• Some schedule slips cause direct costs, like the material costs resulting from repairs.

• Other slips cause indirect costs, like additional labor costs due to delays in equipment delivery.
• The X-Planes: X-1 to X-45 by Jay Miller read cover-to-cover

• Documented the following details for each X-plane program:
  – Schedule slip details
  – Schedule slip duration
  – Schedule slip class
  – Schedule slip project phase

• Compiled setback information for X-1 through X-47
## Setback Database

Sample of Setback Database developed for X-plane program schedule slips:

<table>
<thead>
<tr>
<th>X-Plane Program</th>
<th>Setback Length (Months)</th>
<th>Setback Type</th>
<th>Setback Details</th>
<th>Setback Class</th>
<th>Project Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-1 (second model)</td>
<td>1.5</td>
<td>Repairs</td>
<td>engine thrust chamber, rudder</td>
<td>R</td>
<td>D</td>
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<tr>
<td></td>
<td>5</td>
<td>Installation</td>
<td>recording instrumentation</td>
<td>I</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Repairs</td>
<td>nose gear collapse, significant damage</td>
<td>R</td>
<td>D</td>
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<tr>
<td></td>
<td>6</td>
<td>Repairs, Installation</td>
<td>fuel tank rust fix, new test instrumentation</td>
<td>R, I</td>
<td>C</td>
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<tr>
<td></td>
<td>1</td>
<td>Staging</td>
<td>Couldn’t use area until powerplant was built</td>
<td>De</td>
<td>B</td>
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<tr>
<td>X-1 (third model)</td>
<td>36</td>
<td>Development, Funding</td>
<td>develop turbopump longer than planned, problems with funding, lack of AF interest</td>
<td>D, F</td>
<td>A</td>
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<tr>
<td>X-1D</td>
<td>0.75</td>
<td>Repairs</td>
<td>nose gear fail, ungraceful landing</td>
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<td>D</td>
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<td>X-1A</td>
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<td>Modifications</td>
<td>modifications, replacement of pressurization system</td>
<td>M</td>
<td>C</td>
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<td>X-1B</td>
<td>8</td>
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<td>NACA test instrumentation</td>
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<td>36</td>
<td>Development, Delivery</td>
<td>rocket engine development and delivery longer than expected</td>
<td>D, De</td>
<td>A</td>
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<td></td>
<td>6</td>
<td>Development</td>
<td>landing instability</td>
<td>D</td>
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Schedule Findings

The 39 programs with complete data encountered a total of 74 schedule setbacks, accumulating to just over 40 years of program delays.
Lessons Learned

• Several of the setbacks in X-plane programs tended to be repeated, avoidable issues.

• There are two major lessons that come from these issues:
  – Avoid overoptimism or arrogance when developing budget and schedule plans.
  – Clearly document all key decisions, costs, and changes to the program.
Setback findings were generalized into 8 classes of setback causes:

1.) Repairs
2.) Installations
3.) Developments
4.) Modifications
5.) Delivery
6.) Funding
7.) Political
8.) Weather.
Setback Classifications

All setback occurrences in each class were then summed and averaged to find mean setback duration in months.

<table>
<thead>
<tr>
<th>Repairs</th>
<th>Average Length</th>
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<tbody>
<tr>
<td>19</td>
<td>4.43</td>
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<table>
<thead>
<tr>
<th>Installations</th>
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<td>8</td>
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<th>Modifications</th>
<th>Average Length</th>
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<td>8</td>
<td>5.13</td>
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<table>
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<th>Political</th>
<th>Average Length</th>
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<tr>
<td>4</td>
<td>5.50</td>
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<th>Weather</th>
<th>Average Length</th>
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<tr>
<td>2</td>
<td>1.25</td>
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</table>
The number of recorded setback occurrences for each setback class:

- Weather: 2
- Political: 4
- Funding: 6
- Delivery: 8
- Installation: 8
- Modification: 13
- Development: 14
- Repair: 19
The average duration of each setback class (in units of months):

- Weather: 1.25 months
- Repair: 4.43 months
- Installation: 4.44 months
- Delivery: 5.13 months
- Political: 5.5 months
- Modification: 5.96 months
- Funding: 9.5 months
- Development: 11.96 months
Further analysis of schedule setback data produced both an occurrence frequency percentage and an occurrence probability percentage for each setback class.

<table>
<thead>
<tr>
<th>Setback Class</th>
<th>Frequency of Occurrence</th>
<th>Percentage of Programs in Which Setback Occurred</th>
<th>Probability of Setback Occurrence</th>
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<tbody>
<tr>
<td>Repairs</td>
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<td>48.72%</td>
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<td>35.90%</td>
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<td>Funding</td>
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<td>Funding</td>
<td>15.38%</td>
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<td>Political</td>
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<td>Political</td>
<td>10.26%</td>
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<tr>
<td>Delivery</td>
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<td>Delivery</td>
<td>20.51%</td>
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<td>Weather</td>
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<td>Weather</td>
<td>5.13%</td>
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<tr>
<td>Modifications</td>
<td>13</td>
<td>Modifications</td>
<td>33.33%</td>
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</tbody>
</table>

Average Frequency of Occurrence: 9.25
Standard Deviation: ± 5.68

Average Percentage of Occurrence: 23.72%
Standard Deviation: ± 14.55%

Average Probability of Occurrence: 12.50%
Standard Deviation: ± 7.67%
Setback Analysis

Probability of occurrence for each setback class based on number of recorded schedule slips:

Setback Probability by Class

Repair: 25.7%
Development: 18.9%
Weather: 2.7%
Political: 5.4%
Funding: 8.1%
Installation: 10.8%
Delivery: 10.8%
Modification: 17.6%
Phase Analysis

• Another form of analysis was to identify the project phase in which each of the 74 identified setbacks occurred.

• Official NASA phasing begins at Pre-Phase A and continues to Phases F.

• For this project, the start date of project development was mined from Phase-A activity due to information shortages.
Phase Analysis

Total number of setbacks in each project phase:

Setback Distribution by Project Phase
and the corresponding percentage by Project Phase

Number of Setbacks

<table>
<thead>
<tr>
<th>Project Phase</th>
<th>Number of Setbacks</th>
<th>Percentage</th>
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<tr>
<td>Phase A</td>
<td>9</td>
<td>12.16%</td>
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<td>Phase B</td>
<td>16</td>
<td>21.62%</td>
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<td>Phase C</td>
<td>15</td>
<td>20.27%</td>
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<td>Phase D</td>
<td>34</td>
<td>45.95%</td>
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<tr>
<td>Phase E</td>
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<td>0.00%</td>
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<tr>
<td>Phase F</td>
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<td>0.00%</td>
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## Phase Analysis

Breakdown of individual setback classes by phase:

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<thead>
<tr>
<th>Repairs</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Phase D</th>
<th>Phase E</th>
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</tbody>
</table>
The next task was to utilize the schedule slip analysis with program budgets.

This research project aimed to determine the delta between a program’s baseline budget and the total program cost.

The delta between these two points is called the residual.
Cost Data

- Despite many interviews with past project managers and CFO accountants, only a few full-picture cost documents were obtained.

- Both baseline and actual budgets were only found for three aircraft: X-43, X-47B, and SOFIA.

- The costs were found through a combination of print and online research and personal interviews.
The proportional budgeted and actual cost for the programs in consideration for cost analysis:

![Budgeted vs. Actual Cost Diagram]

- **X-47B**
  - Budgeted Cost
  - Actual Cost

- **SOFIA**
  - Budgeted Cost
  - Actual Cost

- **X-43**
  - Budgeted Cost
  - Actual Cost
Cost Analysis

• Every program experiences different difficulties and is unique in terms of objectives, schedules, and costs.

• Therefore, rather than simply considering the dollar value that a program overran, each of the residual values for X-43, X-47B, and SOFIA were converted to a percentage of overrun instead.

• As this project only had cost data for a few programs, there was an aim to eliminate the greatest possible amount of bias or skewed data.
Calculate total-program burn rate

Total burn rate = \( \frac{\text{Total Actual cost}}{\text{Total program length}} \)

**Estimated residual impact of each setback class**

Estimated residual impact of a setback class = Avg length of setback class * project burn rate

Setback Class Residuals denoted of \( x \) from \( x_1 \) to \( x_8 \)

\[
\text{Total estimated residual impact} = \sum_{i=1}^{8} X_i = x^1 + x^2 + \cdots + x^8
\]

Setback class residuals denoted as values of \( x \) from \( x^1 \) to \( x^8 \)

Percentage breakdown of the estimated residual for each class

Setback class percent breakdown = \( \frac{\text{Setback class residual impact}}{\text{Total residual impact}} \times 100 \)
The process for converting project residuals to percentage overruns included the following steps:

1. A burn rate was calculated for each aircraft program by dividing the total program cost by the program length.

2. The estimated residual impact of each setback class was determined by multiplying the burn rate by the average duration of a setback class.

3. The total estimated residual impact for all schedule setback classes was determined by summing the classes’ individual estimated residual impacts.

4. The percentage breakdown for each setback class was calculated by dividing the estimated residual impact value of each setback class by the total estimated residual impact of all setback classes.
The process for converting estimated residual impacts to allocated residual values included the following steps:

1. The allocated residual values for each setback class were then found by multiplying the actual total residual of each aircraft by the residual percentage for each setback class.

2. The allocated residual amounts were then transformed to detail cost overrun as a percentage of the baseline by dividing the allocated residual of each setback class by the recorded baseline budget of a project.

3. Summing these percentages for all setback classes determines the total additional buffer percentage value that should have ideally been in place for the historical program.
• Averaging all of these additional buffer percentages from each project creates a general, historically-focused buffer percentage that could be added onto buffer reserves plans for future NASA programs.

• Based on these averages, each historic program analyzed should on average have had 15.54% more management reserve in its budget.
• In order to determine the suggested dollar increase to the NFRP management reserves, the suggested buffer addition percentage was multiplied by the NFRP baseline budget.

• When the estimated buffer addition was applied to the NFRP, calculations showed that project managers could consider adding at least $19,769,156 in reserves to the program.
The dollar increase was then broken down further to show the distribution of funds by setback class.

<table>
<thead>
<tr>
<th>Setback</th>
<th>% of residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repairs</td>
<td>9.20%</td>
</tr>
<tr>
<td>Installations</td>
<td>9.22%</td>
</tr>
<tr>
<td>Development</td>
<td>24.83%</td>
</tr>
<tr>
<td>Funding</td>
<td>19.72%</td>
</tr>
<tr>
<td>Political</td>
<td>11.42%</td>
</tr>
<tr>
<td>Delivery</td>
<td>10.65%</td>
</tr>
<tr>
<td>Weather</td>
<td>2.59%</td>
</tr>
<tr>
<td>Modifications</td>
<td>12.37%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Setback Type</th>
<th>Residual Cost Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repairs</td>
<td>$1,818,089</td>
</tr>
<tr>
<td>Installations</td>
<td>$1,822,193</td>
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<tr>
<td>Development</td>
<td>$4,908,431</td>
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<tr>
<td>Funding</td>
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<tr>
<td>Political</td>
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<tr>
<td>Delivery</td>
<td>$2,105,372</td>
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<tr>
<td>Weather</td>
<td>$513,005</td>
</tr>
<tr>
<td>Modifications</td>
<td>$2,446,007</td>
</tr>
</tbody>
</table>

Total Residual: $19,769,156
Summary

• Because NASA programs often involve work that has never been attempted before, cost and schedule setbacks are common and should be appropriately planned for in projects.

• Every NASA program is different, and that should be taken into account when considering budget and schedule plans for new programs.

• NASA has extremely limited cost and schedule data available, which makes it difficult to analyze data trends or to learn from historical occurrences.
Questions

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Data Sources

- Armstrong’s Technical Reference Library
- *The X-Planes: X-1 to X-45* by Jay Miller
- Interviews with subject matter experts
  - Current NASA Project Managers
  - Former NASA Project Managers
  - NASA Accountants
- Government Accountability Office (GAO)
- Wikipedia and other online sources
Interviews

- Joel Sitz – X-43 data
- Dave Voracek – X-53 data
- Cheng Moua – X-56 data
- John Kelly – Dream Chaser data
- Patricia Daws – SOFIA data
- Darren Elliott – Risk calculations
- Josh Martin – Budget calculations
- Kerri Tannert – Cost data
- Karen Green – Cost data