Characterizing Aerospace Cost Estimate Dynamics: Distributional Metrics for Contextualizing Outcome Variability

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The Challenges of Cost Estimation

Cost estimates are fundamental to project planning, approval, and feasibility assessments.

The Reality

A cost estimate is a range of values that reflect the uncertainty and variability of a project.

- Scope, inflation rates, execution, etc.
- Represents a *distribution* of outcomes
- Well understood, but conveying the extent of these models is often overlooked [1]

The Problem

Traditional metrics fail to capture the complexity of potential outcomes

- Min, max, average
- What about rare, impactful (outlier) events? *E.g. COVID-19*
- Outliers are more common in long-duration programs/projects

Rephrased as a research question:

“*How can the dynamic nature of cost estimates be communicated to account for rare events and the diversity of potential outcomes?*”

Case Study: Space Shuttle Program (SSP)

- Large scale, long duration program with ample publicly available data
- Elements of the Space Shuttle Program continue to influence modern day programs
- Three core elements of the study
  1. Demonstrate the shortfalls of traditional metrics,
  2. Propose supplemental options,
  3. Compare two sets of metrics

"The primary objective of the Space Shuttle Program (SSP) is to provide a new space transportation capability that will
(a) reduce substantially the cost of space operations, and
(b) prove a future capability designed to support a wide range of scientific, defense, and commercial uses."
Space Shuttle Program Request for Proposal No. 9-BC421-67-2-40P

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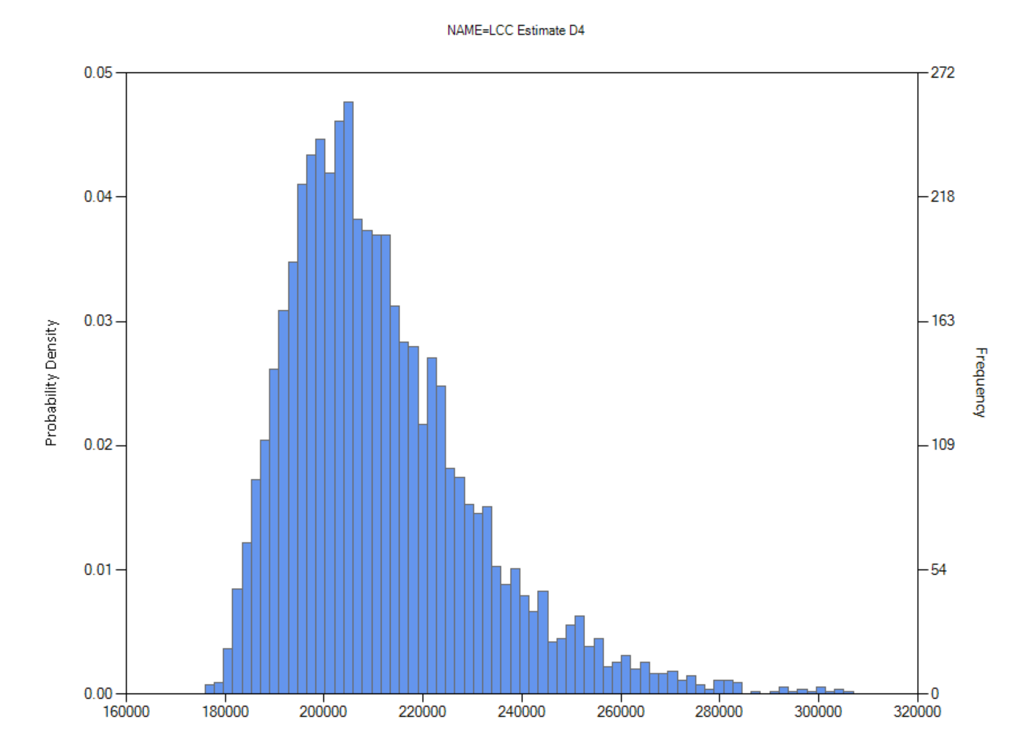
Traditional Metrics

Creating a cost estimate for the SSP is beyond the scope of this paper, data from [3]

This estimate reconstructs a Work Breakdown Structure for the SSP within NASA's parametric cost estimating tool *Project Cost Estimating Capability* (PCEC).

Metric	$B (2024 dollars)	Limitation
Mean	$211.591	Does not convey distribution shape.
Median	$208.098	Ignores tail risks and outliers.
Minimum	$176.900	Likely optimistic.
Maximum	$319.082	Doesn't define the probability of this extreme.



Distributional Metrics

Spread, Shape, Risk Measurement

Measuring Spread

Coefficient of Variation (CV)

A scale-invariant metric to compare variability across different projects.

- Higher CV indicates more spread relative to mean.
- Suggests higher sensitivity to inputs (e.g. learning rates) for cost estimate

$CV = \frac{\sigma}{\mu}$ → 0.08896

Index of Dispersion (Variance-to-Mean Ratio)

Project specific value, useful for identifying clusters

- Project specific due to units
- 1130 + 1230 lunch shows low CV but misses the two clusters
- Can be used to identify specific WBS elements or project phases with high variability

$D = \frac{\sigma^2}{\mu}$ → \$1,674.39 [M \$2024]

Semi-Deviation

Variation is often not consistent across a distribution, semi-deviation and semi-variance allows for subset analysis.

- See portfolio mgmt. for variability below a loss threshold [5][6]
- Relevant to space programs due to Congressional notification if >30% of Agency Baseline Commitment
- Median set as threshold for example

Semidev(50) → \$16,984 [M \$2024]

Measuring Shape

It is widely known that aerospace project costs tend to skew significantly upwards [7], these metrics enable a more precise description of the shaping.

Skew

Measures direction and magnitude of bias

- Positive means higher costs
- A strong positive skew may indicate numerous uncertainties and potential for significant cost overruns

$$\widetilde{\mu_3} = E[(\frac{X-\mu}{\sigma})^3] \longrightarrow 1.20102$$

Kurtosis

Describes the shape of a distribution's tails relative to its overall shape

- Higher kurtosis= higher probability of outliers
- Informs both outlier cost planning and a validity check for the model
- Std. normal distribution has $\widetilde{\mu_4} = 3$

$$\widetilde{\mu_4} = E[(\frac{X-\mu}{\sigma})^4] \longrightarrow 2.08901$$

Measuring Risk (Data Proportions)

Percentile Ranges

Captures the proportion of the distribution falling below a certain value or a confidence level

- 50th and 70th percentiles recommended by NASA NPR 7120.5F [1]
- Conservative recommendation is 85th
- Can also determine the percentile contained around a value, e.g. the mean

"The SSP will cost $230B or less, with 85% confidence."

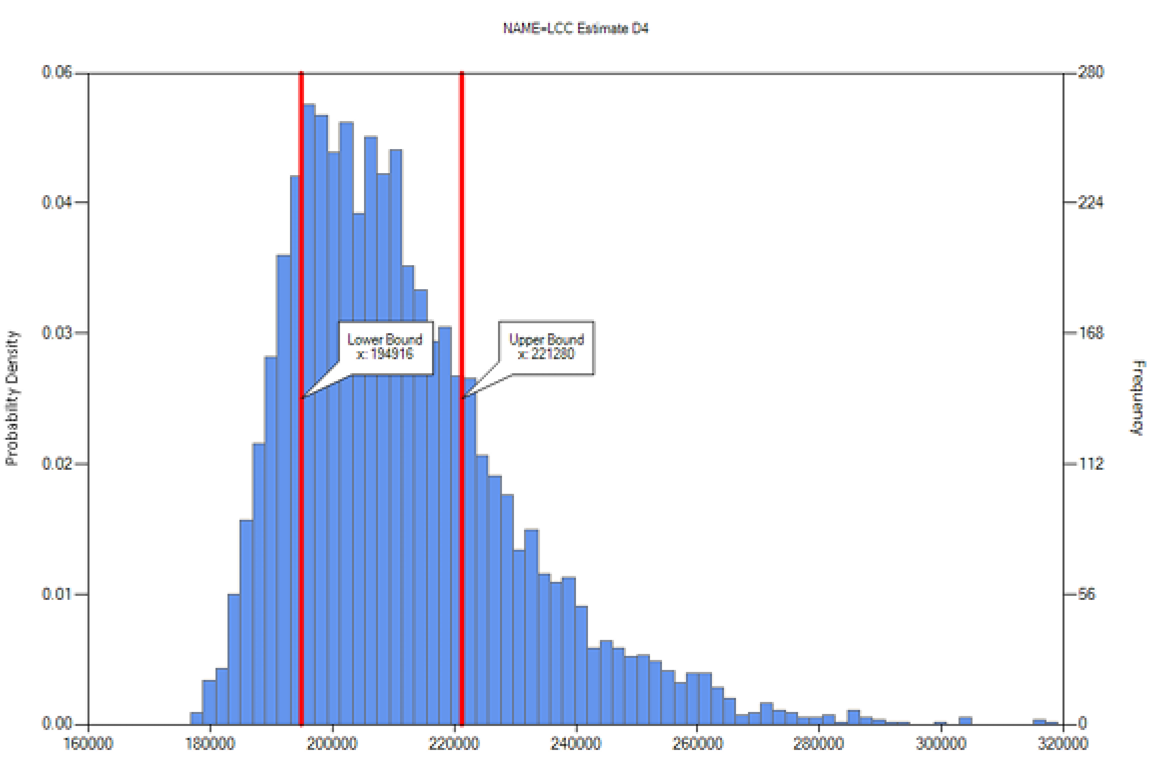


Fig. 2 VMPCR-50 around the mean, SSP Life Cycle Cost estimates [$M]

Measuring Risk (Outlier Presence)

Frequency of Exceedance

Quantifies the risk beyond a do not exceed level

- Set a threshold -> calculate the exceedances
- Alt. set the exceedances -> calculate threshold
- Examples for the SSP
    - Set threshold at most recent LCC est.
    - Set exceedances at 5%

$254.5 B @ 3.5% 5% @ $248.9 B

Z-Score

Converts a point to the number of standard deviations in relation to the mean

- 68-95-99.7 rule for characterizing extremeness [9-10] *in relation to z= [1, 2, 3]*
- Allows for placement of prior estimates within study
- Consider the worst case Shuttle LCC estimate from the NASA commissioned 1972 Mathematica study: *$323.3B -> z= 5.9391*
- Example uses most recent LCC estimate

$254.5 B -> z= 2.2808

Measuring Risk (Outlier Impacts)

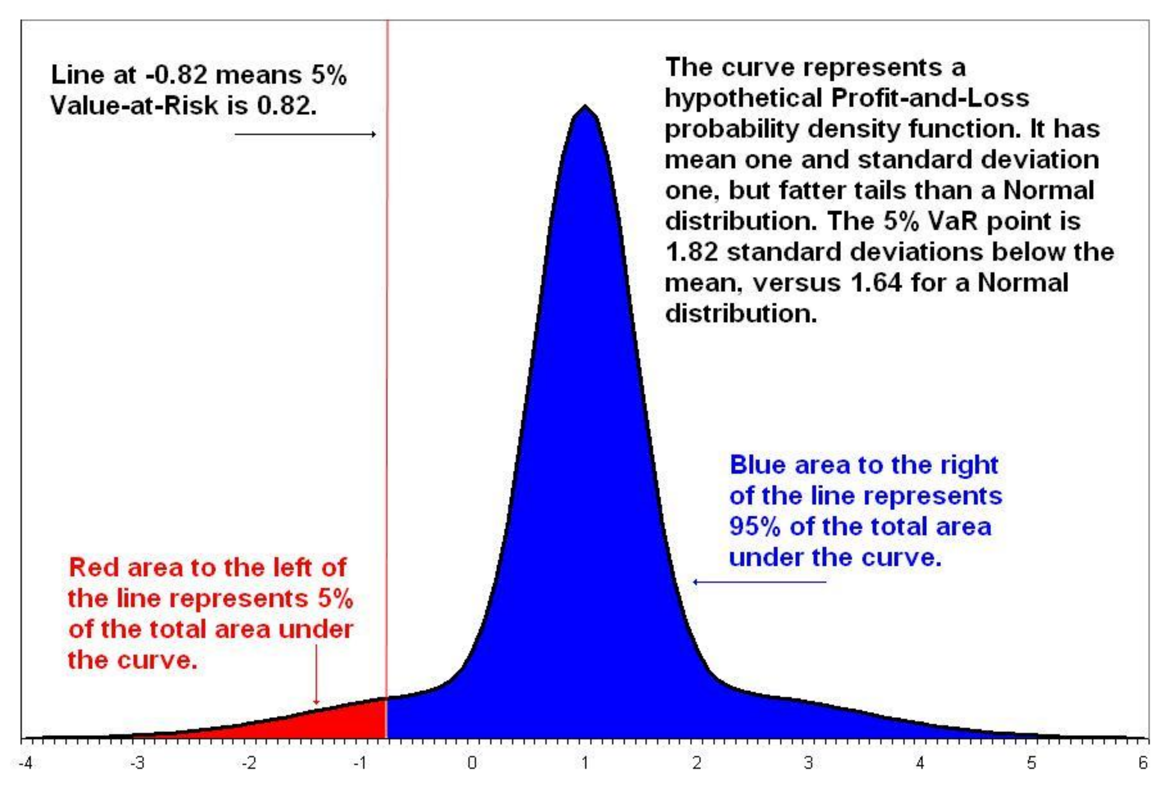
Conditional Value at Risk (CVAR)

Variant of Value at Risk, averages the extreme losses in the distribution beyond the VAR threshold

- VAR provides a threshold value α such that the probability of exceeding the threshold value is at most $(1-\alpha)$ [12]
- VAR estimates *maximum* potential loss
- CVAR provides the *average* potential loss [13-14]

$$ES_{\alpha}(X) = \frac{1}{\alpha}\int_{0}^{\alpha} VAR_{\gamma}(X)\, d\gamma$$

CVAR(5)= $262.6 B   CVAR(1)= $285.0 B



Traditional vs. Distributional

Distributional metrics offer a more nuanced view

Metric Category	Traditional Approach	Distributional Approach
Central Tendency	Mean: \$211.6 B	50^{th} Percentile: \$208.1 B 70^{th} Percentile: \$217.6 B 85^{th} Percentile: \$230.1 B
Spread	Min: \$176.9 B Max: \$319.1 B	CV: 0.089 Index of Dispersion (VMR): \$1.67 B Semi-deviation from mean: \$16.98 B
Shape	*Not Captured*	Skewness: 1.201 Kurtosis: 2.089
Risk Measures	"Cost is between \$176.9 B and \$319.1 B"	Z-score: A cost of \$254.4B is 2.28 std. dev from the mean Freq. of exceedance: 3.5% chance of exceeding a budget of \$254.4 B CVAR(5): Average cost in the worst 5% of cases is \$262.6 B

Summary of Findings

I. **Context is King:** Traditional metrics (mean/min/max) overlook the dynamic nature of cost inputs and subsequent estimates.

II. **Quantify the Tails:** Distributional metrics (CVAR, Kurtosis) reveal insights into potential outliers and "Black Swan" events.

III. **Robust Planning:** Understanding the shape and spread of the cost distribution enables better reserve allocation for long-term O&S phases.

IV. **Enhanced Decision Making:** Moving beyond single-point estimates allows for a comprehensive risk assessment framework.

The background for this work, its applications, and additional development are further explored in “Adapting the Past for Future Flight: Preliminary Design Framework for Long Duration O&S Aerospace Programs” [3]

Thank You