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Cost and Schedule Risk Analysis

How to adjust your estimate for uncertainty and historical cost and schedule growth

"As we know, / There are known knowns. / There are things we know we know.
We also know / There are known unknowns. / That is to say
We know there are some things / We do not know.
But there are also unknown unknowns, / The ones we don't know / We don't know."
- "The Unknown" from *Pieces of Intelligence: The Existential Poetry of Donald Rumsfeld*, Hart Seely, 2003 [DoD news briefing, 02/12/2002]

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Acknowledgments

- ICEAA is indebted to TASC, Inc., for the development and maintenance of the Cost Estimating Body of Knowledge (CEBoK®)
  - ICEAA is also indebted to Technomics, Inc., for the independent review and maintenance of CEBoK®
- ICEAA is also indebted to the following individuals who have made significant contributions to the development, review, and maintenance of CostPROF and CEBoK ®
- Module 9 Cost and Schedule Risk Analysis
  - Lead authors: Richard L. Coleman, Jessica R. Summerville, Eric R. Druker, Richard C. Lee
  - Senior reviewers: Richard L. Coleman, Michael F. Jeffers, Kevin Cincotta, Fred K. Blackburn
  - Reviewer: Bethia L. Cullis
  - Managing editor: Peter J. Braxton

Unit Index

Risk Overview

- Key Ideas
  - Risk / bias (accuracy)
  - Uncertainty (precision)
  - Cost realism
  - Risk vs. Sensitivity
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- Practical Applications
  - Probabilistic Cost Estimates
    - S-Curves
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  - Risk Scoring and Mapping
- Analytical Constructs
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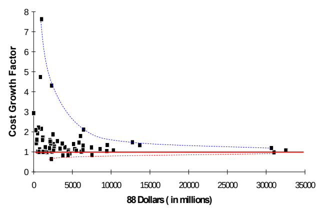
- Related Topics
  - Data Collection for Risk Analysis
  - Monte Carlo Simulation 10
  - Risk Management
  - Schedule Analysis

Risk Within The Cost Estimating Framework

Past

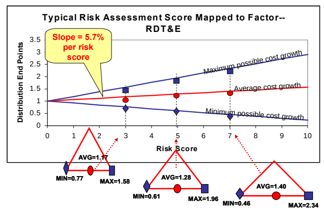
Understanding your historical data



Historical cost and schedule growth

Present

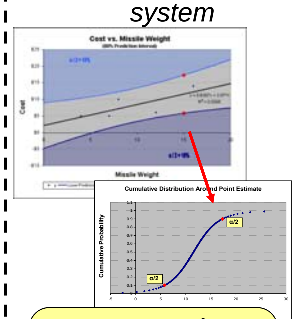
Developing estimating tools



Risk Mapping Equations

Future

Estimating the new system



CE and Sked/Tech Risk

Risk Outline

- Core Knowledge
  - Introduction to Risk
  - Cost Risk Models
    - Cost Risk Model Architecture Framework
    - Cost Risk Model Examples
- Summary
- Resources
- Related and Advanced Topics

Introduction to Risk

- Overview
- Historical Cost Growth
- Definitions
- Types of Risk
- Risk Process

Risk Overview

Why Learn (and Do) Risk?

- Risk analysis is a significant part of cost and schedule estimation
  - Captures ***uncertainty*** about the point estimate, expressed as Confidence and Prediction Intervals
  - Captures anticipated ***growth*** used to adjust estimates, budgets, and schedules
- Incorrect treatment of risk, while better than ignoring it, creates a false sense of security
- This module will define risk, discuss it in general, and describe several approaches to estimation
- It cannot possibly teach risk with enough depth to make you a seasoned risk analyst overnight, but hopefully it will both scare you and intrigue you
  - Ample citations are provided to encourage further study

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Risk Overview

- Traditionally, the aim of cost estimating has been the development of a single point estimate
  - This point estimate is, however, just one of many possible final costs the system could have
  - Also, it can be difficult to determine the meaning of this point estimate
    - Is it the mean, the mode, the median, or some other percentile?
- This is particularly true in estimates based on engineering judgment
  - One theory is that engineers provide the mode of the estimate
    - In fact, almost any time a triangular distribution is placed around these estimates, that is what is being asserted
  - In cases like this, if the risk around the estimate is skewed right, then the mean cost will be higher than the engineer's estimate
- Because of this and other reasons, it is important to determine:
  - The percentile of the point estimate
  - The distribution around the cost estimate
  - This is where Risk Analysis comes into play

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Are Our Costs Realistic?

- We claim our costs are realistic
- We claim we estimate costs at the 50th percentile
  - This should mean we have 50% low and 50% high outcomes
- But, we have an unchanging cost growth pattern showing only 12% of our estimates are high (underrun) and 88% are low (overrun)
  - As shown in the graphic on the next slide
- The conclusion is inescapable … our costs are not realistic
- This also means our costs are at the 12th percentile, not the 50th percentile

What Percentile Are We At Now (And Where Are We Going?), R. Coleman, E. Druker, P. Braxton, B. Cullis, C. Kanick, SCEA 2009, DoDCAS 2010.

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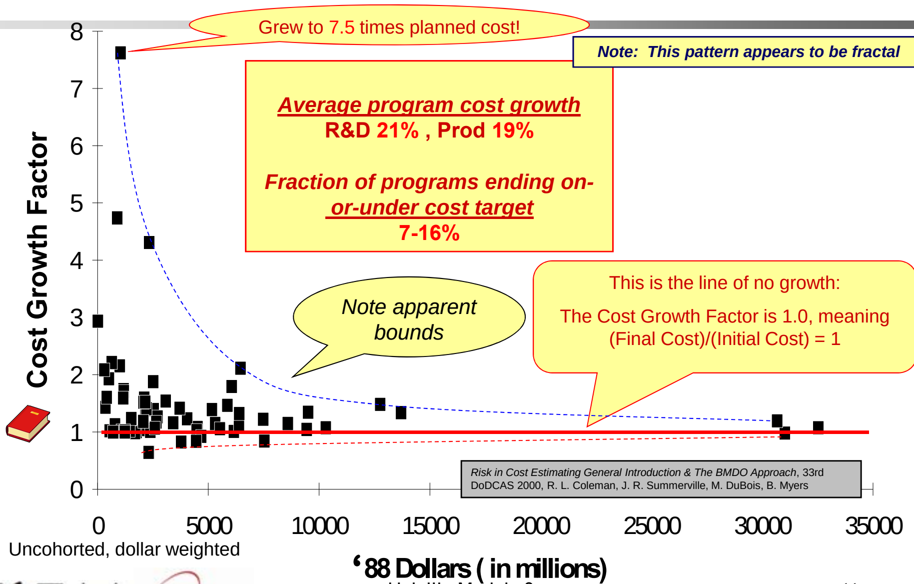
Historical Cost Growth



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Sources of Understatement of Costs

- Cost elements are often assigned incorrect initial percentiles; below are some guidelines to help determine the initial percentile of any cost element
  - If the basis is a linear CER, an average or an analogy then it should be a mean
  - If the basis is a non-linear CER, then the estimate is probably a median and correction must be made to arrive at the mean
  - If the basis is a build-up, using historical rates and engineering parameters, then the estimate is probably a mean (although allowance for understatement of driving parameters must be made)
  - If the basis is an engineering estimate (meaning judgment) then some risk analysts believe that the estimate may be a lower percentile, perhaps a mode
    - This is based on the assertion that the estimate is "a most likely estimate", and "most likely " is associated with the mode. Unfortunately, there is no research to show that judgment estimate s are prone to be done at the mode, and the association of "most likely" with the mode is not universally accepted.
- Elements cannot be added up to produce a total until correction is made, because only means add, other percentiles do not
- After the initial assignment of percentile, estimates must be reviewed for systematic errors; this is the role of risk analysis
  - Systematic errors in cost and risk are covered on the next slide

What Percentile Are We At Now (And Where Are We Going?), R. Coleman, E. Druker, P. Braxton, B. Cullis, C. Kanick, SCEA 2009, DoDCAS 2010.

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Sources of Understatement of Costs

- Systematic understatement of all percentiles is found in cost estimation and risk analysis
  - The sources are grouped below in rough descending order of impact
  - Some affect measures of central tendency (the mean) and so they will understate all percentiles and some affect measures of variability, understating upper percentiles
  - Both cost estimating errors and risk analysis errors affect the mean and the variance
- The distinction between "cost "and "risk" is somewhat arbitrary, but is customary

Area	Source	Mean & 50th	Standard Deviation	80th
Cost	Errors Which Seem "Always To Understate"	Understate	-	Understate
	Lack Of Basis In Historical Data	Understate	-	Understate
	Omissions of Elements	Understate	-	Understate
	Systematic Understatement In Non-linear CERs	Understate	-	Understate
Risk	Omission Of Risks And Elements Of Bias	Understate	Understate	Understate
	Omission Of Elements Of Variability	-	Understate	Understate
	Inadequate Determination Of Cost Relationships	-	Overstate	Overstate
	Failure To Include Functional Correlation	-	Understate	Understate
	Errors Which Seem "Always To Understate"	-	Understate	Understate
	Omission Of Correlation Of Any Type	-	Understate	Understate
	Insufficient Data Causing Unrecognized Wide(r) Prediction Intervals	-	Understate	Understate
	Systematic Understatement In Non-linear CERs	-	Understate	Understate

What Percentile Are We At Now (And Where Are We Going?), R. Coleman, E. Druker, P. Braxton, B. Cullis, C. Kanick, SCEA 2009, DoDCAS 2010.

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Independence and Risk

"Two 'Timely Short Topics': Independence and Cost Realism," R.L. Coleman, J.R. Towers (nee Summerville), S.S. Gupta, SCEA/ISPA 2005.

1

- Presumptions of independence can be tested
- Independence is positional, not absolute
  - Positional independence requires that there be no intervening common superior
  - What is independent in the eyes of lower levels of authority may not be independent in the eyes higher authority
- Presumptions of independence can be lost
  - Is there a connection or obligation? Is there factionalism?
- Independence can be accepted even where it can not be asserted
- Independence notwithstanding, a second opinion can and should be sought
  - Especially when factionalism or contention are afoot
- Independence notwithstanding, there is a clear pattern of higher cost estimates from higher offices
  - This implies greater disinterestedness or objectivity, leading to more cost realism
  - This suggests that higher offices incorporate more consideration of risk
- Last thought: Independence requires sufficient rigor and a mindset of objectivity
  - These are necessary *and* sufficient conditions for independence
  - Organization position is necessary but *not* sufficient
  - The sufficiency must be in the mind of the observer, not the asserter

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Definitions

- Cost Growth:
  - Increase in cost of a system from inception to completion
- Cost Risk:
  - Predicted Cost Growth
- Uncertainty and Risk
  - Range of possible estimates vs. calibration
- Risks and Opportunities
  - Bad vs. good outcomes for events which may happen

In other words:
Cost Growth = actuals
Cost Risk = projections

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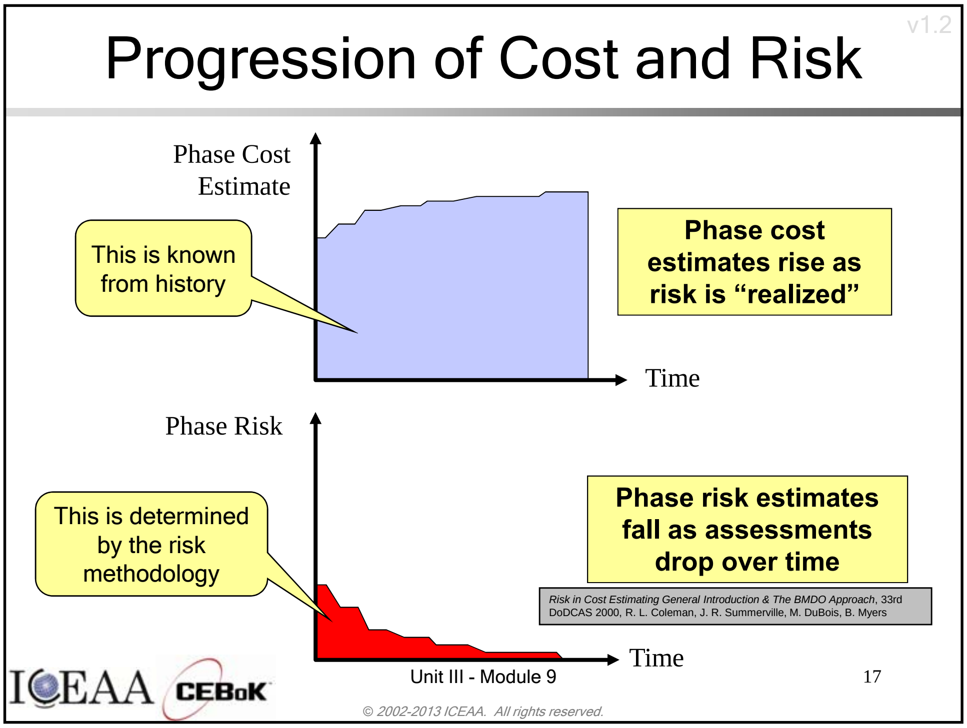
Types of Risk

- Cost Growth = Cost Estimating Growth + Sked/Tech Growth + Requirements Growth + Threat Growth
- Cost Risk = Cost Estimating Risk + Sked/Tech Risk + Requirements Risk + Threat Risk
  - **Cost Estimating Risk:** Risk due to cost estimating errors, and the statistical uncertainty in the estimate
  - **Schedule/Technical Risk:** Risk due to inability to conquer problems posed by the intended design in the current CARD or System Specifications
  - **Requirements Risk:** Risk resulting from an as-yet-unseen design shift from the current CARD or System Specifications arising due to shortfalls in the documents
    - Due to the inability of the intended design to perform the (unchanged) intended mission
    - We didn't understand the solution
  - **Threat Risk:** Risk due to an unrevealed threat; e.g. shift from the current STAR or threat assessment
    - The problem changed

Often implicit or omitted

1 2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Progression of Cost and Risk
Phase Cost Estimate
This is known from history
Phase cost estimates rise as risk is "realized"
Time
Phase Risk
This is determined by the risk methodology
Phase risk estimates fall as assessments drop over time
Risk in Cost Estimating General Introduction & The BMDO Approach, 33rd DoDCAS 2000, R. L. Coleman, J. R. Summerville, M. DuBois, B. Myers
Time
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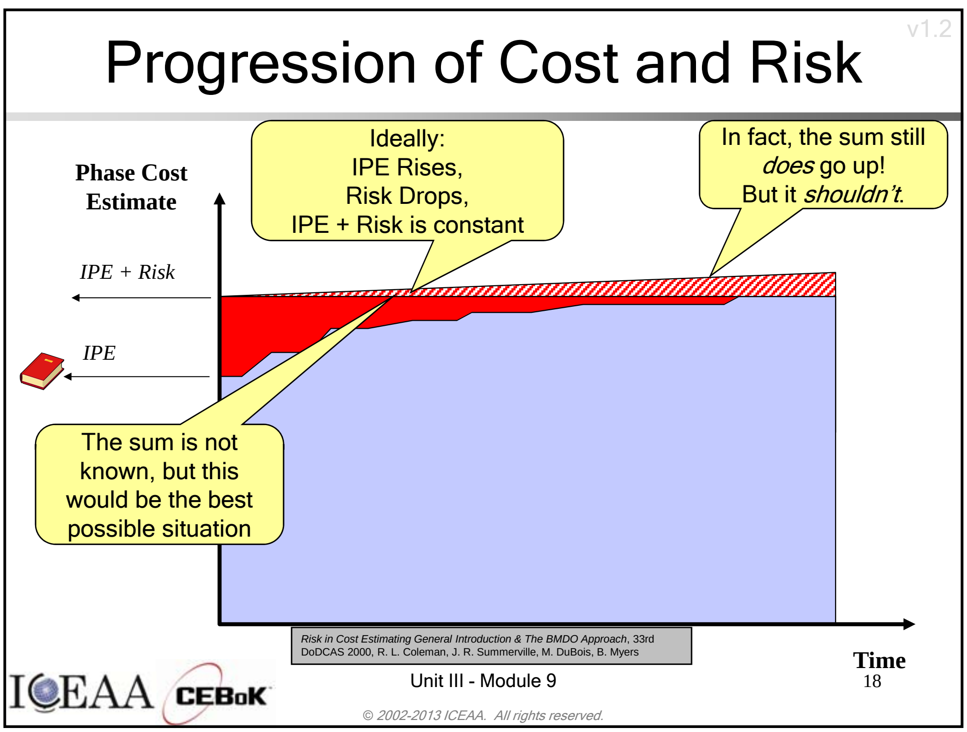
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Progression of Cost and Risk
Phase Cost Estimate
Ideally: IPE Rises, Risk Drops, IPE + Risk is constant
In fact, the sum still *does* go up! But it *shouldn't*.
IPE + Risk
IPE
The sum is not known, but this would be the best possible situation
Risk in Cost Estimating General Introduction & The BMDO Approach, 33rd DoDCAS 2000, R. L. Coleman, J. R. Summerville, M. DuBois, B. Myers
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Cost Risk

- Cost Risk Model Architecture Framework
- Cost Risk Model Examples

This section is principally from "The Manual for Intelligence Community CAIG Independent Cost Risk Estimates," R. L. Coleman, J. R. Summerville, S.S. Gupte, DoDCAS and SCEA, 2002.

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Basic Flow of the Risk Process

Inputs → **Structure & Execution** *Includes the organization, the mathematical assumptions, and how the model runs* → **Outputs**

From the cost analyst and technical experts
- The CARD
- Expert rating/scoring
- Point Estimate

To the decision maker and the cost analyst
- Means
- Standard Deviations
- Risk by CWBS

Inputs and outputs, although outside the purview of the risk analyst, are determined by the structure and execution of the risk model

Types of Cost Risk Models

- Historically- vs. Expert-Opinion-Based
- Historically-Based Risk Models
  - Apply actual cost growth from similar programs
  - Mean or distribution
- Expert-Opinion-Based Risk Models
  - Direct assessment of risk (e.g., Triangular)
  - Rely on Subject Matter Expert (SME) judgment
  - Scoring matrix on historical and new programs

CE V, SCEA 2003, R. L. Coleman, J. R. Summerville, TASC, Inc.

The Correct Use of Subject Matter Experts in Cost Risk Analysis, R.L. Coleman, Peter J. Braxton, Bethia L. Cullis, NPS ARS 2010, DOE 2010 CFO Conference/Cost Analysis & Training Symposium.

Warning: Experts tend to understate variance

Types of Cost Risk Models

Air Force Cost Risk and Uncertainty Handbook (2007), p. v.

- Input vs. Output
  - Input methods vary the input parameters or seek to define drivers, thus determining cost outputs
    - Uncertainty around CERs using the cost drivers
    - Vulnerable to under-response and correlation issues
  - Output methods consider the range of costs without determining the ranges of parameters or drivers
    - Schedule and technical risks added to the cost estimate
    - Can be perceived as unhelpful - nothing to "fix"
- Scenario-based methods
  - Experts are asked to imagine a variety of scenarios; they are explicitly modeled
  - Like sensitivity analysis, except that multiple inputs change simultaneously
  - Alternative to or cross-check for input/output methods

"Enhanced Scenario-Based Method for Cost Risk Analysis: Theory, Application, and Implementation, P.R. Garvey, B.J. Flynn, P.J. Braxton, R.C. Lee, *Journal of Cost Analysis and Parametrics*, 5:98-142, 2012.

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Types of Cost Risk Models

- Hybrids

CE V, SCEA 2003, R. L. Coleman, J. R. Summerville, TASC, Inc

  - It is possible to combine Historical and Expert-Opinion-Based
  - It is not safe to combine input and output methods
    - Specifically, the final costs and final parameters that are the basis of CERs already include schedule and technical risks that occurred on the programs in the dataset
    - Input risk adjusts initial parameters to final parameters, and to add output risk to the corresponding final costs would be double counting

	Expert	Historical	Input	Output	Scenario
Expert	--	X	X	X	X
Historical	X	--	X	X	X
Input	X	X	--		
Output	X	X		--	
Scenario	X	X			--

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Some Commonly Used Risk Assessment Techniques

- Add a Risk Factor/Percentage (Output-Based) (Minutes)
  - Low accuracy, no intervals
- Bottom Line Monte Carlo/Bottom Line Range/Method of Moments (Output-Based) (Hours)
  - Moderate accuracy, provides intervals
- 9 Historically-Based Detailed Monte Carlo (Output- or Input-Based) (Months of non-recurring work, but recurring in days)
  - Time consuming non-recurring work, but with recurring implementation being easier, accurate if done right; provides intervals.
- 9 Probability and Consequence (Pf*Cf) (Expert Opinion-Based) or Expert-Opinion-Based Detailed Monte Carlo (Months)
  - 9 Time consuming with no gains in recurring effort, but accurate if done right; provides intervals.
- Detailed Network (Resource-Loaded Schedule) and Risk Assessment (Months)
  - Time consuming with no gains in recurring effort, but accurate if done right; provides intervals.

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Probability Model - Distribution

- In risk, the assessment of the probability distribution for risks or WBS elements is fundamental to the purpose of:
  - *Correcting* understatement of means
  - *Determining* the various percentiles desired by decision makers
- There is ample evidence of error in the determination of distributions
  - Means are understated as evidenced in outcomes of programs
  - Standard deviations are understated as demonstrated in the literature of risk
- These errors are insidious and ubiquitous, occurring in every distributional type; great caution is required to avoid them

The Correct Use of Subject Matter Experts in Cost Risk Analysis, R.L. Coleman, Peter J. Braxton, Bethia L. Cullis, NPS ARS 2010, DOE 2010 CFO Conference/Cost Analysis & Training Symposium.

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Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	**Probability Model**
Computation	Cross-Checks

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Probability Model - Distribution

10

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- Normal
  - Best behavior, most iconic
  - Theoretically (although not practically) allows negative costs, which spook some users
  - Symmetric, needs mean shift to reflect propensity for positive growth

- Lognormal
  - A natural result in non-linear CERs
  - Indistinguishable from Normal at CVs below 25%
  - Skewed

10

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	**Probability Model**
Computation	Cross-Checks

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Probability Model - Distribution

- Triangular
  - Most common
  - Easy to use, easy to understand
  - Modes, medians do not add
  - Skewed

10

- Beta
  - Rare now, but formerly popular
  - Solves negative cost and duration issues
  - Many parameters - simplifications like PERT Beta are possible
  - Skewed

10

- Bernoulli
  - Probability is only assigned to two possible outcomes, success and failure (p and 1-p)
  - Simplest of all discrete distributions
  - Mean = p
  - Variance = p*(1-p)

10

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

Probability - Top-Level Distribution

- Normal
  - If there is a sufficiently large number of independently, identically distributed elements (or not too correlated and not too skewed) then the distribution of total cost is normal, due to the Central Limit Theorem
- Lognormal
  - For smaller data sets with large amounts of (positive) correlation and skewness, the lognormal distribution may be a better approximation of total cost
  - Many total cost distributions in smaller data sets test as both normal and lognormal
- Triangular
  - The sum of triangles is not a triangle, so this distribution should generally not be used to characterize total cost!
- Convolved
  - If total cost distribution is derived using simulation, then it may not particularly resemble anything. In this case, we simply have a convolved or simulated total cost distribution.

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

NEW!

Probability Model - Correlation

Correlation is a measure of the relation between two or more variables/WBS elements

- <u>Functional</u>: Arises between source and derivative variables as a result of functional dependency. The lines of the Monte Carlo are cell-referenced wherever relationships are known.
  - CERs are entered as equations
  - Cell references are left in the spreadsheet
  - When the Monte Carlo runs, input variables fluctuate, and outputs of CERs reflect this

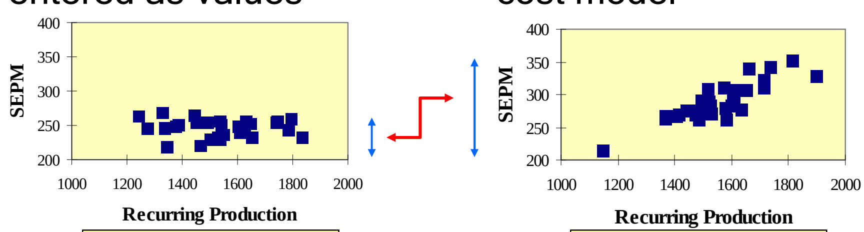
3

An Overview of Correlation and Functional Dependencies in Cost Risk and Uncertainty Analysis, R. L. Coleman and S. S. Gupta, DoDCAS, 1994

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	**Probability Model**
Computation	Cross-Checks

Functional Correlation

- **Old:** No Functional Correlation; Simulation run with WBS items entered as values
- **New:** Simulation run with functional dependencies entered as they are in cost model



Not Correlated

Correlated

Note shift of mean, and increased variability

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	**Probability Model**
Computation	Cross-Checks

Probability Model - Correlation

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- **Relational**: Introduces the geometry of correlation and provides a substantial improvement over injected correlations, and fills a gap in FC
  - Relational Correlation provides insight into
    - the tilt of the data, i.e., the regression line,
    - and the variance around the regression line

9

Relational Correlation: What to do when Functional Correlation is Impossible, R. L. Coleman, J. R. Summerville, M. E. Dameron, C. L. Pullen, S. S. Gupta, ISPA/SCEA Joint International Conference, 2001

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

Probability Model - Correlation

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- **Injected**: Imposed by setting the correlation directly between variables without having a functional relationship.
- **None**: No relationship exists among the variables. The lines of the Monte Carlo are self contained.

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

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Shortcomings of Injected Correlation

- Correlations are very hard to estimate
- No check of the functional implications of the correlations is done
  - This is troublesome because of the regression line that arises when we insert a correlation
  - Simply injecting arbitrary correlations of 0.2 - 0.3 to achieve dispersion is unsatisfactory as well
    - Unless the injected correlations are among elements that are actually correlated
- If correlations are actually known, no harm is done

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

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Execution - Computation

- Monte Carlo: A widely accepted method, used on a broad range of risk assessments for many years. It produces cost distributions. The cost distributions give decision makers insight into the range of possible costs and their associated probabilities.
- Method of Moments: The mean and standard deviation of lower-level WBS lines are known, and are rolled up assuming independence to provide higher-level distributions.
  - Only provides an analysis of distribution at a top level
  - Easy to calculate
  - Negated by the rapid advances in microcomputer technology
  - Only works for independent elements, unless covariances are allowed for
- S-Curve Specification: Direct specification of the cumulative distribution of total cost (c.d.f, or S-Curve) via a mean and standard deviation, CV, or assumed percentile
- Deterministic: Only point values are used. No shifts or other probabilistic effects are taken into account.

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Taking a Second Look: The Potential Pitfalls of Popular Risk Methodologies, E. R. Druker, R. L. Coleman, C. J. Leonetti, P. J. Braxton, ISPA/SCEA 2007, NASA PM Challenge 2008.

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

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Monte Carlo Simulation for Risk Analysis

- When risk analysis is performed, multiple risks are gathered
  - These risks may have various probability distributions
- Monte Carlo is the most commonly accepted way to produce an accurate characterization of the distribution of the combined effect of these many risks
  - Using this distribution, we can produce percentiles for cost impacts due to risk occurrences

10

Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

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Execution - Cross Checks

- **Means:** The mean cost growth factor for WBS items can be compared to history as a way to cross check results
- **CVs:** The CV of the cost growth factors for WBS items can be compared to history as a way to cross check results
- **Inputs:** Checks are performed on inputs or other parameters to see if historical values are in line with program assumptions
  - Example: Historical risk scores can be compared to program risk scores to see if risk assessors are being realistic, and to see if the underlying database is representative of the program.

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Native Data	Behavior of Data
Criteria	Dollar Basis
Organization	Probability Model
Computation	Cross-Checks

Summary – Cost and Schedule Risk Core Knowledge Conclusions

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- We've looked at various types of risk
  - Including several specific examples
- We've discussed some of the more common issues that arise
- We've considered some of the effects you need to be aware of
- Hopefully you are now
  - More aware of the scope of risk
  - Energized to delve into it some more
  - Able to be more discriminating when you see risk analysis

Risk Resources – Books

v1.2

- *Against the Gods: The Remarkable Story of Risk,* Peter L. Bernstein, August 31, 1998, John Wiley & Sons
- *Living Dangerously! Navigating the Risks of Everyday Life*, John F. Ross, 1999, Perseus Publishing
- *Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective*, Paul Garvey, 2000, Marcel Dekker
- *Introduction to Simulation and Risk Analysis,* James R. Evan, David Louis Olson, James R. Evans, 1998, Prentice Hall
- *Risk Analysis: A Quantitative Guide*, David Vose, 2000, John Wiley & Sons

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Risk Resources - Web

- Oracle Decisioneering
  - Crystal Ball for Monte Carlo simulation
  - http://www.crystalball.com
- Palisade
  - @Risk for Monte Carlo simulation
  - Best Fit for fitting probability distribution to (univariate) data
  - http://www.palisade.com

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Risk Resources - Papers

- *Approximating the Probability Distribution of Total System Cost*, Paul Garvey, DoDCAS 1999
- *Why Cost Analysts should use Pearson Correlation, rather than Rank Correlation*, Paul Garvey, DoDCAS 1999
- *Why Correlation Matters in Cost Estimating* , Stephen Book, DoDCAS 1999
- *General-Error Regression in Deriving Cost-Estimating Relationships*, Stephen A. Book and Mr. Philip H. Young, DoDCAS 1998
- *Specifying Probability Distributions From Partial Information on their Ranges of Values,* Paul R. Garvey, DoDCAS 1998
- *Don't Sum EVM WBS Element Estimates at Completion,* Stephen Book, ISPA/SCEA 2001
- *Only Numbers in the Interval -1.0000 to +0.9314… Can Be Values of the Correlation Between Oppositely-Skewed Right-Triangular Distributions*, Stephen Book , ISPA/SCEA 1999

Risk Resources – Papers

- *An Overview of Correlation and Functional Dependencies in Cost Risk and Uncertainty Analysis,* R. L. Coleman, S. S. Gupta, DoDCAS, 1994
- *Weapon System Cost Growth As a Function of Maturity,* K. J. Allison, R. L. Coleman, DoDCAS 1996
- *Cost Risk Estimates Incorporating Functional Correlation, Acquisition Phase Relationships, and Realized Risk,* R. L. Coleman, S. S. Gupta, J. R. Summerville, G. E. Hartigan, SCEA 1997
- *Cost Risk Analysis of the Ballistic Missile Defense (BMD) System, An Overview of New Initiatives Included in the BMDO Risk Methodology,* R. L. Coleman, J. R. Summerville, D. M. Snead, S. S. Gupta, G. E. Hartigan, N. L. St. Louis, DoDCAS, 1998 (Outstanding Contributed Paper) and ISPA/SCEA 1998
- *Risk Analysis of a Major Government Information Production System, Expert-Opinion-Based Software Cost Risk Analysis Methodology,* N. L. St. Louis, F. K. Blackburn, R. L. Coleman, DoDCAS, 1998 (Outstanding Contributed Paper), and ISPA/SCEA 1998 (Overall Best Paper Award)

Risk Resources – Papers

- *Analysis and Implementation of Cost Estimating Risk in the Ballistic Missile Defense Organization (BMDO) Risk Model, A Study of Distribution*, J. R. Summerville, H. F. Chelson, R. L. Coleman, D. M. Snead, ISPA/SCEA 1999
- *Risk in Cost Estimating - General Introduction & The BMDO Approach*, R. L. Coleman, J. R. Summerville, M. DuBois, B. Myers, DoDCAS, 2000
- *Cost Risk in Operations and Support Estimates*, J. R. Summerville, R. L. Coleman, M. E. Dameron, SCEA 2000
- *Cost Risk in a System of Systems,* R.L. Coleman, J.R. Summerville, V. Reisenleiter, D. M. Snead, M. E. Dameron, J. A. Mentecki, L. M. Naef, SCEA 2000
- *NAVAIR Cost Growth Study: A Cohorted Study of the Effects of Era, Size, Acquisition Phase, Phase Correlation and Cost Drivers,* R. L. Coleman, J. R. Summerville, M. E. Dameron, C. L. Pullen, D. M. Snead, ISPA/SCEA 2001

Risk Resources - Papers

v1.2

- *Probability Distributions of Work Breakdown Structures,* R. L. Coleman, J. R. Summerville, M. E. Dameron, N. L. St. Louis, ISPA/SCEA 2001
- *Relational Correlation: What to do when Functional Correlation is Impossible,* R. L. Coleman, J. R. Summerville, M. E. Dameron, C. L. Pullen, S. S. Gupta, ISPA/SCEA 2001
- *The Relationship Between Cost Growth and Schedule Growth,* R. L. Coleman, J. R. Summerville, DoDCAS, SCEA 2002
- *The Manual for Intelligence Community CAIG Independent Cost Risk Estimates,* R. L. Coleman, J. R. Summerville, S. S. Gupta, DoDCAS, SCEA 2002
- *Modeling the Effect of Program Size on Cost Growth*, M.E. Dameron, R.L. Coleman, J.R. Summerville, C.L. Pullen, D.M. Snead, SCEA 2002

Risk Resources - Papers

v1.2

- *Distributions for Total Cost - Normals, Lognormals, Triangles and Mistaken Identity, J. R. Summerville, R. L. Coleman, M. E. Dameron, SCEA 2003,*
- *Normality of Work Breakdown Structures, ISPA/SCEA 2001, M. E. Dameron, J. R. Summerville, R. L. Coleman, N.L. St. Louis*

v1.2

Related and Advanced Topics

- Historical Cost Growth Analysis
- Assessing Uncertainty Around OLS CER-Based Estimates
- Schedule Risk
- Risk and EVM
- Program Size
- Self-Fulfilling Prophecy
- Geometry of the Bivariate Normal

v1.2

Historical Cost Growth

- Methods and Data Sources
- By Phase
- By Commodity

v1.2

Intro to SARs - Sample

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Selected Acquisition Report
Section 13 -- Cost Variance Analysis

UNCLASSIFIED

Sample Program: XXX, December 31, 19XX

13. (U) ~~Cost Variance Analysis:~~

(U) Summary (FY 1982 Constant (Base-Year) Dollars in Millions)

	RDT&E	PROC	MILCON	TOTAL
Development Estimate	39.9	2,891.9	-	2,931.8
Previous Changes:				
Quantity	-	3,395.2	-	3,395.2
Schedule	3.4	80.7	-	84.1
Engineering	-	9.0	-	9.0
Estimating	-0.5	-381.0	-	-381.5
Other	-	-	-	-
Support	-	2.80	-	-
Subtotal	2.9	3,106.7	-	3,106.8
Current Changes:				
Quantity	-	-	-	-
Schedule	-	-	-	-
Engineering	-	-	-	-
Estimating	-0.5	2.5	-	2.0
Other	-	-	-	-
Support	-	-	-	-
Subtotal	-0.5	2.5	-	2.0
Total Changes	2.4	3,109.2	-	3,111.6
Current Estimate	42.3	6,001.1	-	6,043.4

UNCLASSIFIED

A SAR report is submitted for each year of a program's Acquisition cycle. The most recent SAR is used to determine cost growth

To calculate the CGF, adjust the current estimate for quantity changes, then divide by the baseline estimate

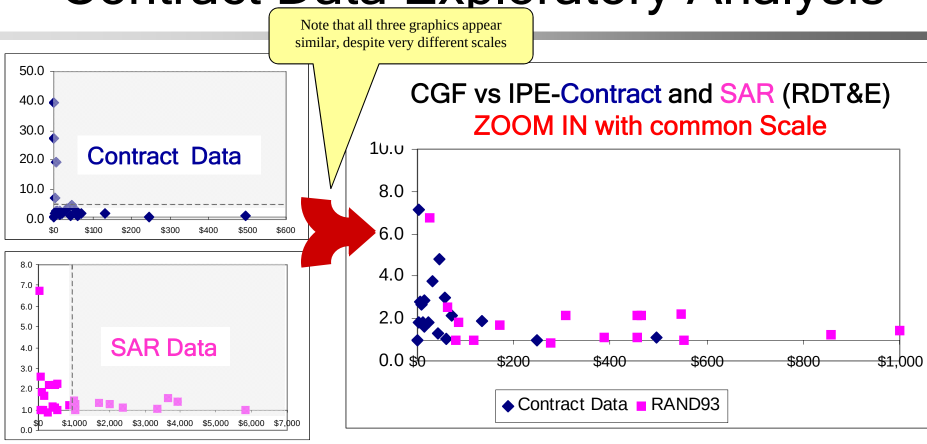
v1.2

Contract Data

- Hard to use – problems with changing baselines, lack of reasons for variances, and access to data
- Preliminary comparative analysis suggests Contract Data mimics patterns in SAR data
  - Shape of distribution
  - Trends in tolerance for cost growth
- K-S tests find no statistically significant difference between Contract data and SAR data for programs <$1B in RDT&E
  - Failed to reject the null hypothesis of identical distributions
- Descriptive statistics indicate amount of Contract Data growth and dispersion is more extreme than previously found in SAR studies
- SAR data remains the best choice for analysis and predictive modeling

NAVAIR Cost Growth Study: A Cohorted Study of The Effects of Era, Size, Acquisition Phase, Phase Correlation and Cost Drivers, R. L. Coleman, J. R. Summerville, M. E. Dameron, C. L. Pullen, D. M. Snead, DoDCAS and ISPA/SCEA, 2001.

Contract Data Exploratory Analysis



Contract Data blends well: Continues trend that tolerance for growth increases as program size decreases

Common Problems

- Most historically-based methods rely on SARs
  - Adjusting for quantity - important to remove quantity changes from cost growth
  - Beginning points - the richest data source is found by beginning with EMD
  - Cohorting must be introduced to avoid distortions
- 15 EVM data is also potentially useable, but re-baselined programs are a severe complication
- “Applicability” and “currency” are the most common criticisms

Applicability and Currency

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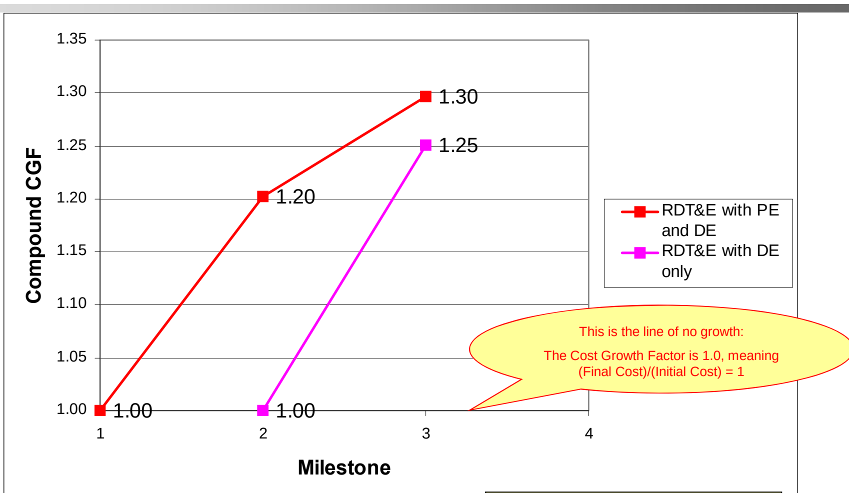
- Applicability: “Why did you include *that* in your database?”
  - Virtually all studies of risk have failed to find a difference among platforms (some exceptions)
  - If there is no discoverable platform effect, more data is better
- Currency: “But your data is so *old*!”
  - Previous studies have found that post-1986 data is preferable
  - Data accumulation is expensive

DoD RDT&E Cost Growth

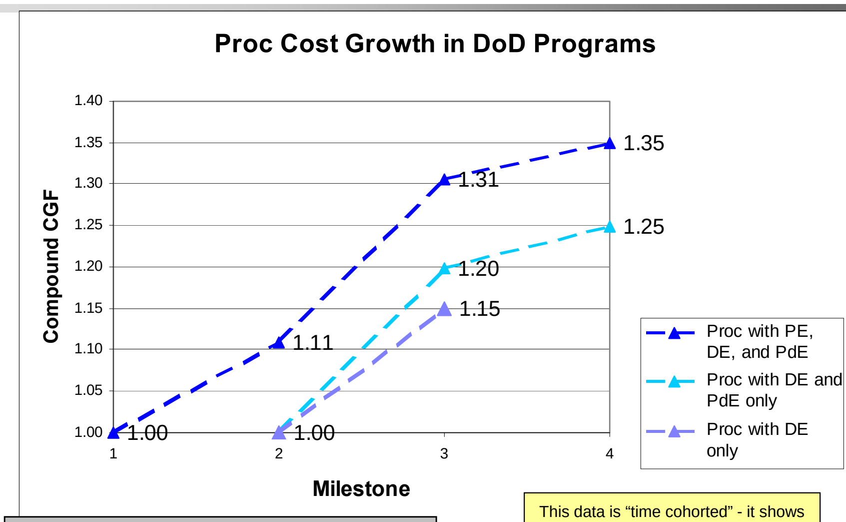


NAVAIR Cost Growth Study, ISPA/SCEA 2001, 34th DoDCAS and ISPA/SCEA 2001, R. L. Coleman, M.E. Dameron, C.L. Pullen, J.R. Summerville, D.M. Snead

This data is “time cohorted” - it shows the same programs as they progress

v1.2

DoD Procurement Cost Growth



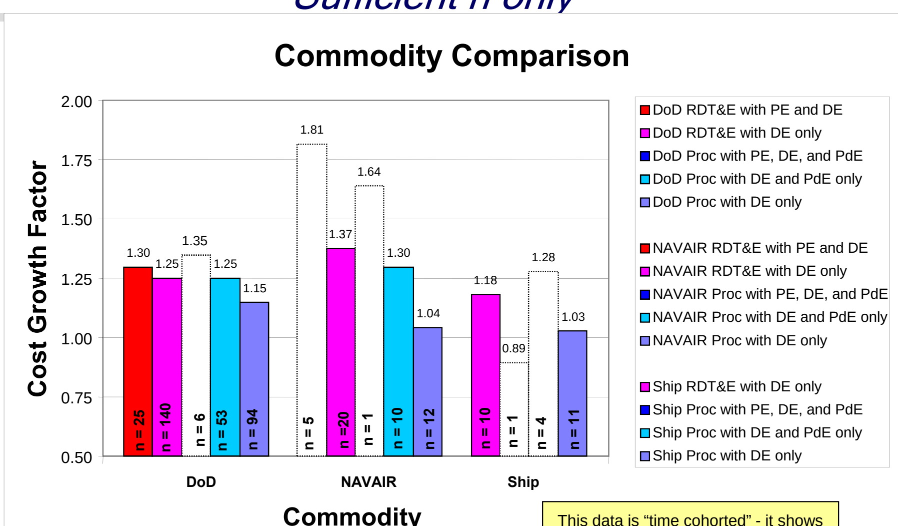
NAVAIR Cost Growth Study, ISPA/SCEA 2001, 34th DoDCAS and ISPA/SCEA 2001, R. L. Coleman, M.E. Dameron, C.L. Pullen, J.R. Summerville, D.M. Snead

This data is "time cohorted" - it shows the same programs as they progress

v1.2

RAND Commodity Comparison

Sufficient n only

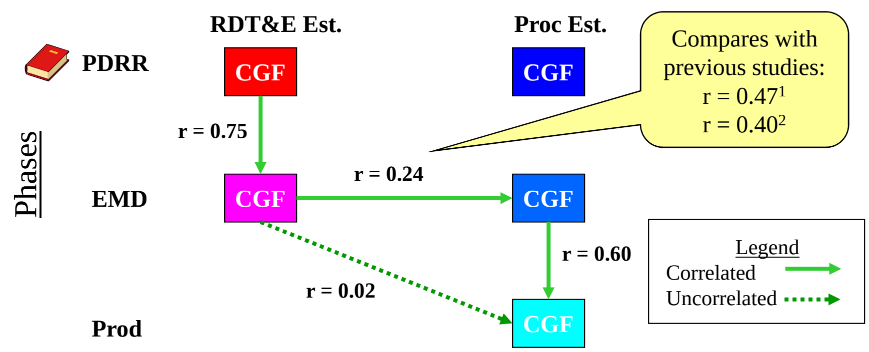


NAVAIR Cost Growth Study, ISPA/SCEA 2001, 34th DoDCAS and ISPA/SCEA 2001, R. L. Coleman, M.E. Dameron, C.L. Pullen, J.R. Summerville, D.M. Snead

This data is "time cohorted" - it shows the same programs as they progress

Correlation

Appropriations



Note: There were many areas where there were too few data points to feel sure, only those with sufficient data to conclude the presence of correlation are indicated

1. *Weapon System Cost Growth As a Function of Maturity*, DoDCAS 1996, K. J. Allison, R. L. Coleman
2. *Cost Risk Estimates Incorporating Functional Correlation, Acquisition Phase Relationships, and Realized Risk*, SCEA National Conference 1997, R. L. Coleman, S. S. Gupta, J. R. Summerville, G. E. Hartigan

This data is "time cohorted" - it shows the same programs as they progress

Historical Cost Growth

	Raw Average			$ Wtd Average				During Prod
Source	Tot	R&D	Prod	Tot	R&D	Prod	N	Prod
RAND 93:	1.30			1.20	1.25	1.18	100+	1.02
CAIG 91:	1.33	1.40	1.25	1.21	1.24	1.19	27	
TASC 94:		1.49	1.54				20+	
TASC 96:		1.43	1.55		1.21	1.35	14	0.99
Christensen 99:				1.09	1.14			1.06 *MSIII*

This chart presents data from different eras and different database subsets
The message it conveys is a general similarity, not precise equality

1. **All data are from DoD SARs, under <u>generally</u> the same rules and procedures, except for Christensen**
2. **Christensen data is EVM Data, which includes re-baselining, and is contract only, vice program**
3. **This cost growth data includes growth due to "Cost Estimating Errors"**
4. **RAND Data and CAIG Data are from MS I, TASC data is from MSII**

Sources of Cost Risk

- ☆ State-of-the-Art-Advance (Technology Readiness)
- ☆ Technical Risk Sources
  - Physical properties
  - Material Properties
  - Radiation Properties (emission and reception)
- Material Availability Risks
- ☆ Testing / Modeling Risks
- Integration / Interface Risks
- ☆ Program Personnel
- Safety Risks
- ☆ Software Design Risks
- Security Risks
- Critical failure modes
- Energy / Environmental Risks
- Schedule problems and delays
- ☆ Inadequate cost estimates
  - Process (need to assess contractor's assumptions)
  - Models
- ☆ "New Ways of Doing Business"
- ☆ Inflation
- ☆ Systems Engineering
- Cost Improvement Curve Assumptions

Amount of cost risk depends on the Basis of the Estimate

☆ Historical cost data available

Point Estimates of Cost

- **Funding organizations need best estimate of cost for**
  - **Cost/performance tradeoff studies**
  - **Cost/benefit analyses**
  - **Budget planning**
- **But program cost is nebulous, heavily impacted by**
  - **Technological (im)maturity**
  - **Programmatic considerations**
  - **Schedule slips**
  - **Unforeseen events**
- **Point cost estimates cannot be "correct" because**
  - **Every cost element contains uncertainty**
  - **Total system cost is sum of these WBS elements**
- **Actual program cost falls within a range surrounding the best estimate (with some degree of confidence)**
  - **The best we can hope to do is to understand the uncertainty**
  - **Understanding the uncertainty will help us make provision for it**

Correlation

- Correlation exists between work breakdown structure (WBS) cost element costs and between cost and schedule
- Correlation is a necessary consideration in cost risk analysis
- Correlation is a number that can vary between -1 and +1 and represents the strength of the relationship between the two variables
  - If both variable have a tendency to move in the same direction, correlation is positive
  - If when one variable increases, the other tends to decrease, and vice-versa, the correlation between the two variables is negative

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Correlation And Causation

- Note that correlation is not causation, however, causation implies correlation
  - For example, shark attacks and ice cream sales at the beach
- For example, for a launch vehicle structure, increasing the diameter will not only result in an increase in the structures cost, but will also result in higher costs for thermal coating (paint, etc.)
- Also simply because two subsystems do not appear to be related does not mean they are not correlated!
  - For example, structures and computer equipment seemingly have little relation to one another; however an external factor such as a funding cut, or a strike, will impact all subsystems, leading to delays and increasing cost across the board
  - Thus everything in a WBS has some correlation

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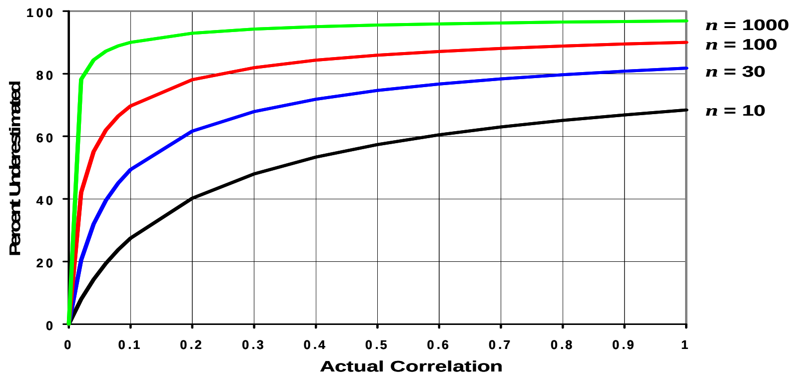
The Importance of Correlation

- Percent that total cost standard deviation is underestimated when correlation assumed to be 0 instead of ρ given *n* WBS elements



Reference: 32nd Annual DOD Cost Analysis Symposium Advanced Training Session, "Why Correlation Matters in Cost Estimating," Stephen A. Book

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The Importance of Correlation (2)

- For example if correlation is assumed to be 0 for all elements in a 30 element WBS, and the actual correlation is 20%, then the total cost standard deviation is underestimated by 60%
- For example assume the total cost is modeled as a normal distribution with mean = 100
- If correlation is assumed to be zero, with total cost standard deviation = 12, when correlation is actually 20%, then the true underlying standard deviation is actually 30
- 70th percentile with zero correlation assumption is 106
- 70th percentile with 20% correlation is 116

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Methods for Aggregating Risk

- Since percentiles do not add, we have to find other ways to aggregate risk
- One method is to use Monte Carlo simulation
- Unless cost risk is represented by normal distributions for all WBS elements, summing the means and variances does not result in a completely accurate depiction of overall system cost risk
- The normal distribution is not a realistic distribution for representing risk in many, or even most situations, since regarding project risk, more can go wrong, than can go right, which means the risk is NOT symmetric, unlike the Gaussian bell curve

Monte Carlo Simulation

- Simulation is a means for solving problems that are analytically intractable
  - Involves repeated random sampling
- It was developed during the Manhattan Project as a way to model the interactions inside an atom during nuclear fission
  - Allowed for more sophisticated mathematical modeling of atomic phenomena
- Most computer packages use pseudo-random number generators, that produce seemingly random results from an initial seed
  - Example is the linear congruential generator

$$X_{n+1} = (aX_n + b) \bmod m$$

Using Random Numbers to Simulate Distributions

- WBS cost risk is typically measured by a probability distribution
- The most common method for simulating a probability distribution is the inverse method
- This involve obtaining a simulated random value from a uniform distribution and then inverting this through the cumulative distribution function (CDF) to obtain the simulated value
- As an example, for a uniform distribution on the interval [0,100]

$$f(x)=\frac{1}{100} \qquad F(x)=\frac{x}{100} \qquad F^{-1}(x)=100x$$

- In this case, the CDF random value of 0.5 translates to 100*0.5 = 50

Simulating a Triangular Distribution

- For a triangular distribution with low = 0, most likely = 50, and high = 150, the CDF is given by

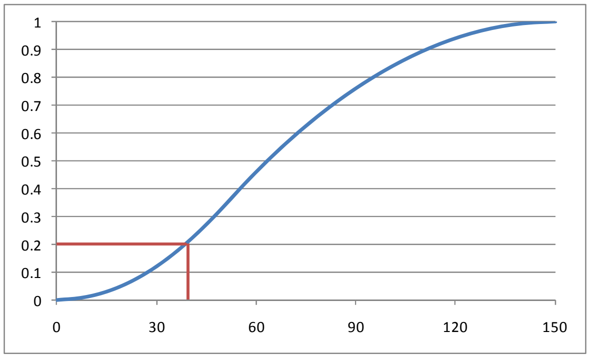
$$F(x)=\begin{cases}\frac{2}{15000}x^2 & 0\le x\le 50\\ \frac{x}{50}-\frac{x^2}{15000}-\frac{1}{2} & 50<x\le 150\end{cases}$$

- The inverse function is given by

$$F^{-1}(x)=\begin{cases}\sqrt{7500x} & 0\le x\le \frac{1}{3}\\ 150-7500\sqrt{\frac{1}{2500}-\frac{1}{3750}\left(x+\frac{1}{2}\right)} & \frac{1}{3}<x\le 1\end{cases}$$

Simulating a Triangular Distribution (2)

- **If the simulated uniform value is equal to 0.2, the corresponding inverse value from the CDF inverse is approximately 38.7**



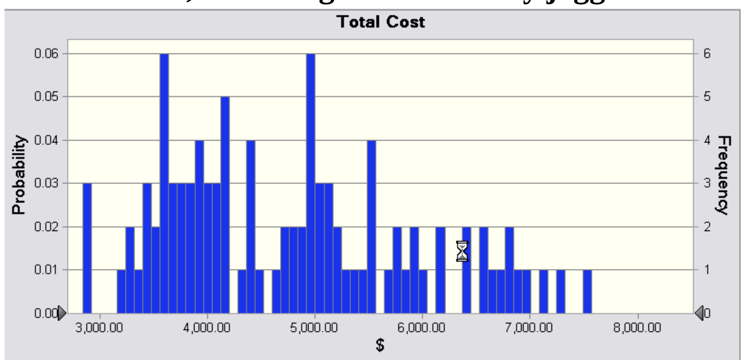
Monte Carlo and the WBS

- **Simulation involves repeated trials**

WBS			Draw					
			#1	#2	#3	#4	#5	
System			2912	3566	4390	2954	4655	Sum
	Structure		80	105	55	80	57	Sum
		Vehicle Structure	50	70	30	40	20	
		Tank Structure	30	35	25	40	37	
	Thermal Control		32	36	35	29	33	Sum
		Active Thermal Control	10	15	12	7	10	
		Induced Thermal Control	12	14	13	14	14	
		Tank Thermal Control	10	7	10	8	9	
	Main Propulsion System		100	150	125	140	100	
	Liquid Rocket Engine		1000	1100	1800	900	2200	
	Electric Power and Distribution		100	125	150	75	90	
	Command, Control, and Data Handling		200	250	225	230	275	
	System Integration		1400	1800	2000	1500	1900	

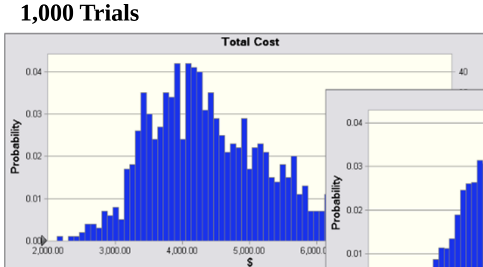
Number of Trials

- Monte Carlo involves a repeated number of trials
- The greater the number of trials, the more accurate the simulation will approximate the overall cost risk behavior of the system
- After 100 trials, the histogram looks very jagged

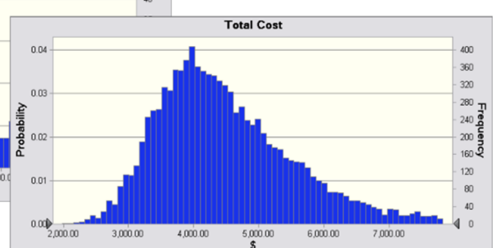


Number of Trials (2)

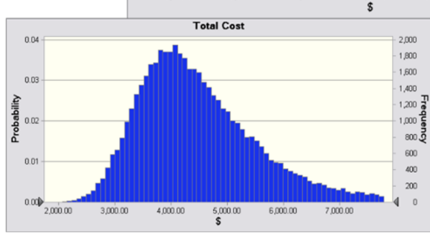
1,000 Trials



10,000 Trials



50,000 Trials



Additional trials give a more accurate depiction of the final result

Number of Trials (3)

- **If we want to simulate the underlying mean within 1%, with 95% confidence, for example, then we require**

$$\mathbf{0.95} = \Pr\left(0.99\mu \le \overline{X}_n \le 1.01\mu\right)$$

$$= \Pr\left(\frac{-0.01\mu}{\sigma/\sqrt{n}} \le \frac{\overline{X}_n - \mu}{\sigma/\sqrt{n}} \le \frac{0.01\mu}{\sigma/\sqrt{n}}\right)$$

$$= \Pr\left(\frac{-0.01\mu}{\sigma/\sqrt{n}} \le Z \le \frac{0.01\mu}{\sigma/\sqrt{n}}\right)$$

where Z is a standard normal distribution, by the Central Limit Theorem

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Number of Trials (4)

- **This means that the number of trials required is determined by**

$$\frac{.01\mu}{\sigma/\sqrt{n}} = 1.96$$

- **Solving for n, we find that at least**

$$38{,}416\frac{\sigma}{\mu}$$

trials are needed

- **Note that this term involves the coefficient of variation of the distribution, which means that distributions with less dispersion require fewer trials to accurate simulate**

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Number of Trials (5)

- **Simulating percentiles requires more trials than for simulating means**
- **Let P_n represent the number of trials in the sample at or below the 70th percentile of the underlying distribution (suppose this is known)**
- **By the Central Limit Theorem, P_n/n follows a normal distribution with mean equal to the 70th percentile, and variance equal to**
- **By a similar process for the mean, we find that the number of trials needed to simulate the 70th percentile within 1% with 95% confidence is**

Number of Trials (6)

- **If $P_n \cong 0.70$ for all n, then n is approximately**

$$38{,}416\frac{\boldsymbol{n}-\boldsymbol{P_n}}{\boldsymbol{P_n}} = 3(8{,}416)\left(\frac{\boldsymbol{n}-0.7\boldsymbol{n}}{0.7\boldsymbol{n}}\right) = 38{,}416\left(\frac{0.3}{0.7}\right) = 16{,}464$$

- **For the sake of comparison, suppose CV = 0.3 (reasonable approximation for hardware development), then the number of trials needed to simulate the mean with the same accuracy is then “only” 11,525**
- **More trials are needed to accurately simulate percentiles than means**

Methods of Simulation

- Monte Carlo simulation is a standard term for simulation
- However, there is an improvement on Monte Carlo that improves the accuracy of the results of a simulation for a given number of trials
- This method is call the Latin Hypercube approach to simulation
  - Similar to Monte Carlo, but an equal number of draws are taken from a set of subintervals, for example, dividing the interval (0,1) into [0.0,0.01), [0.1,0.2),…, [0.9,1.0]
  - Instead of 10 trials from [0,1], we have one trial from each subinterval
  - Rough rule of thumb is Latin Hypercube takes 30% fewer trials to achieve similar accuracy to Monte Carlo

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Method of Moments

- Note that normal distributions add, and that you can sum these normal distributions by summing the means and variances

Mean of Total Cost = $E\left(\sum_{k=1}^{n} X_k\right) = \sum_{k=1}^{n} E(X_k) = \sum_{k=1}^{n} \mu_k$

Variance of Total Cost =

$$Var\left(\sum_{k=1}^{n} X_k\right) = \sum_{k=1}^{n} \sigma_k^2 + 2\sum_{j=2}^{n} \sum_{i=1}^{j-1} \rho_{ij}\sigma_i\sigma_j$$

- Note that the only distributions whose sum is the same distribution as the individual summands are the normal, the Cauchy, and the class of Levy-stable distributions used in finance to model fat-tailed phenomena

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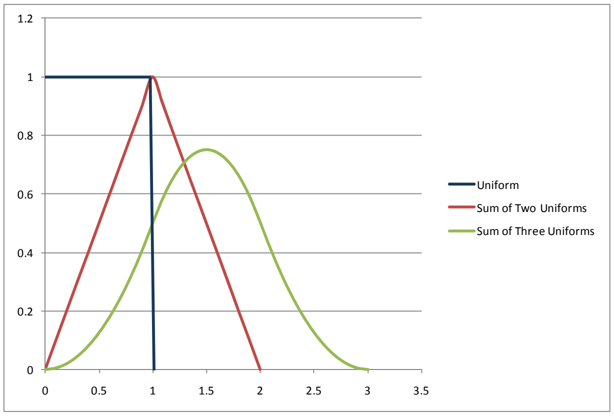
Central Limit Theorem

- However, unless you are modeling all your risk with normal distributions, the total mean and variance will not exactly match that of a normal distribution
- However, given a sufficiently large WBS and relatively weak correlation among WBS elements, a normal distribution should be a good approximation for the total risk
- This is due to the Central Limit Theorem
  - Under certain conditions, the sum of independent random variables approaches a normal distribution
  - One of the most important theorems in probability theory
  - Note there is no restriction on the distributions involved in this summation
  - Convergence is faster for symmetric distributions than asymmetric distributions

Summing Distributions

- The sum of two independent uniforms is a triangular
- The sum of three independent uniforms appears to be bell-shaped



Method of Moments in Practice

- The Method of Moments is used to aggregate risk in the FRISK approach pioneered by Book and Young of the Aerospace Corporation
- Also the aggregation method used in the NASA/Air Force Cost Model
  - Is computationally as simple as possible while still providing accurate estimates
  - Calculates the correct top-level means and standard deviations
  - Is faster than Monte Carlo
  - Allows full access to the correlation matrix
    - Users can set individual inter- and intra-subsystem correlations to any desired value in the range (-1,1), unlike PRICE, SEER, and ACE-IT

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Accuracy of Method of Moments

- Studies by SAIC, MCR, and Tecolote comparing the Method of Moments with Monte Carlo simulation show similar results

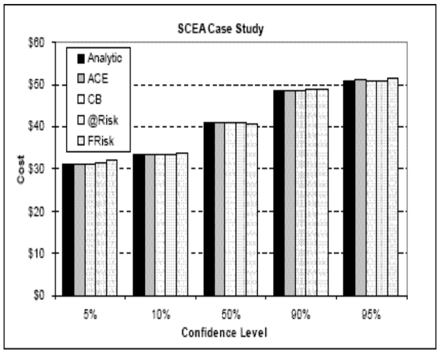

Figure 12: Comparing Risk Simulation Tools Based Upon 10,000 LHC Iterations.

Reference: SCEA Presentation "Cost Risk Analysis 'For the Masses'" by Tecolote Research, 2004.

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Comparative Risk Model Outputs for 2002 MCR Case Study

Table 6: MCR Case Study

	Sd	5%	10%	50%	90%	95%
ACE	487.2	1,043	1,156	1,708	2,438	2,630
CB	486.1	1,044	1,157	1,704	2,441	2,626
@Risk	489.9	1,039	1,150	1,705	2,448	2,640
Normal	491.8	947	1,126	1,756	2,386	2,565
FRISK	491.8	1,076	1,189	1,691	2,405	2,657
Beta	491.8	994	1,121	1,729	2,431	2,610

•Reference: SCEA Presentation "Cost Risk Analysis 'For the Masses'" by Tecolote Research, 2004.