Quantifying Uncertainty in Early Lifecycle Cost Estimation for DOD Major Defense Acquisition Programs

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James McCurley
Senior Technical Staff

Jim McCurley is a Senior Member of the Technical Staff at the Software Engineering Institute (SEI). During his 15 years at the SEI, his areas of expertise have included data analysis, statistical modeling, and empirical research methods. For the last several years, he has worked with various DoD agencies involved with the acquisition of large scale systems. From 1999-2005, Jim also worked as a member of the Technical Analysis Team for the CERT Analysis Center.
Robert Stoddard

Senior Technical Staff

Robert Stoddard is a Senior Member of the Technical Staff at the Software Engineering Institute (SEI). Robert earned a BS in Business, an MS in Systems Management and is a certified Motorola Six Sigma Master Black Belt. He delivers measurement courses in public and client offerings and provides measurement consulting to external clients.
Early cost estimation methods often result in highly inaccurate program cost predictions – and it continues to worsen.

| Table 1: Analysis of DOD Major Defense Acquisition Program Portfolios |
|--------------------------|--------------------------|--------------------------|
| Number of programs       | 75                       | 91                       | 95                       |
| Total planned commitments | $790 Billion             | $1.5 Trillion            | $1.6 Trillion            |
| Commitments outstanding  | $380 Billion             | $887 Billion             | $858 Billion             |
| **Portfolio performance**|                          |                          |                          |
| Change to total RDT&E costs from first estimate | 27 percent | 33 percent | 40 percent |
| Change in total acquisition cost from first estimate | 6 percent | 18 percent | 26 percent |
| Estimated total acquisition cost growth | $42 Billion | $202 Billion | $295 Billion |
| Share of programs with 25 percent or more increase in program acquisition unit cost | 37 percent | 44 percent | 44 percent |
| Average schedule delay in delivering initial capabilities | 16 months | 17 months | 21 months |

Source: GAO analysis of DOD data.
“DOD’s flawed funding process is largely driven by decision makers’ willingness to accept unrealistic cost estimates and DOD’s commitment to more programs than it can support. DOD often underestimates development costs—due in part to a lack of knowledge and optimistic assumptions about requirements and critical technologies.”

*Source: A Knowledge-Based Funding Approach Could Improve Major Weapon System Program Outcomes, GAO Report to the Committee on Armed Services, U.S. Senate s, U.S. Senate, July, 2008 GAO-08-619*
Functional reasons for cost overruns

Source: December 2009 SAR; analysis by CSIS Defense-Industrial Initiatives Group

*Cost and Time Overruns for Major Defense Acquisition Programs*, 2010
DoD Acquisition Lifecycle

Acquisition Phases and Decision Milestones

- Materiel Solution
- Technology Development
- Engineering & Manufacturing
- Production & Deployment

Cost Estimate
Based on:
- Analogies
- Expert Judgment
- Limited Information

Delay

Approval

Cost Growth

FCS Program 2003 vs 2009
- Status – program terminated
- Cost estimate grew by $70B
- Schedule grew from 7.5 to 12.3 yrs
- Lines of code grew from 34M to 114M
Source: GAO-10-406

Ground Combat Vehicle Delay Due to Reconciling Cost Estimates
- 4 months delay in obtaining approval to proceed
- Rework to conduct a new Analysis of Alternatives and to produce a new cost estimate
Source: GAO-12-181T
Information Flow for Early Lifecycle Estimation

Information from Analogous Programs/Systems

Proposed Material Solution & Analysis of Alternatives

Program Execution Change Drivers

System Characteristics
- Trade-offs
  - KPP selection
  - Systems Design
  - Sustainment issues

Operational Capability
- Trade-offs
  - Mission / CONOPS
  - Capability Based Analysis

Technology Development
- Strategy
  - Production Quantity
  - Acquisition Mgt
  - Scope definition/responsibility
  - Contract Award

Driver States & Probabilities

Plans, Specifications, Assessments

Probabilistic Modeling (BBN) & Monte Carlo Simulation

Cost Estimates
- analogy
- parametric
- engineering
- CERs

Program Execution Scenarios with conditional probabilities of drivers/states

Expert Judgements
Create a Method for Quantifying the Uncertainty of Cost Estimation Inputs and Resulting Estimates

Elements of Innovation

1. Identify Change Drivers & States
   Explicit identification of domain specific program change drivers.

2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques
   Unique application of Dependency Structure Matrix techniques for cost estimation.

3. Assign Conditional Probabilities to BBN Model
   BBN modeling of a larger number of program change drivers for estimation than previous research.

4. Calculate Cost Factor Distributions for Program Execution Scenarios
   Scenario modeling of alternate program executions to assess influence of various underlying assumptions.

5. Monte Carlo Simulation to Compute Cost Distribution
   Monte Carlo simulation applied to estimation input parameters rather than output values.

Technical Problem

- Complexity Reduction
- Modeling Uncertainty
# Materiel Solution Analysis Phase – Pre Milestone Estimate

1. Identify Change Drivers & States
2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques
3. Assign Conditional Probabilities to BBN Model
4. Calculate Cost Factor Distributions for Program Execution Scenarios
5. Monte Carlo Simulation to Compute Cost Distribution

## Step 1: Identify Change Drivers and States

### Domain-Specific Program Change Drivers Identified

<table>
<thead>
<tr>
<th>Change Driver</th>
<th>Nominal State</th>
<th>Alternative States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope Definition</td>
<td>Stable</td>
<td>Users added</td>
</tr>
<tr>
<td>Mission / CONOPS</td>
<td>As defined</td>
<td>New condition</td>
</tr>
<tr>
<td>Capability Definition</td>
<td>Stable</td>
<td>Addition</td>
</tr>
<tr>
<td>Funding Schedule</td>
<td>Established</td>
<td>Funding delays tie up resources {e.g. operational test}</td>
</tr>
<tr>
<td>Advocacy Change</td>
<td>Stable</td>
<td>Joint service program loses participant</td>
</tr>
<tr>
<td>Closing Technical Gaps (CBA)</td>
<td>Selected Trade studies are sufficient</td>
<td>Technology does not achieve satisfactory performance</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>
Step 2: Reduce Cause and Effect Relationships via Design Structure Matrix Techniques

Materiel Solution Analysis Phase – Pre Milestone Estimate

1. Identify Change Drivers & States
2. Reduce complexity of Cause and Effect relationships via matrix techniques
3. Assign Conditional Probabilities to BBN Model
4. Calculate Cost Factor Distributions for Program Execution Scenarios
5. Monte Carlo Simulation to Compute Cost Distribution

Capturing interrelationships among change drivers and reducing the complexity of the network
# Step 2: Reduce Cause and Effect Relationships via Dependency Structure Matrix Techniques

## Change Drivers - Cause & Effects Matrix

<table>
<thead>
<tr>
<th>Causes</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission / CONOPS</td>
<td></td>
</tr>
<tr>
<td>Change in Strategic Vision</td>
<td></td>
</tr>
<tr>
<td>Capability Definition</td>
<td></td>
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<tr>
<td>Advocacy Change</td>
<td></td>
</tr>
<tr>
<td>Closing Technical Gaps (CBA)</td>
<td></td>
</tr>
<tr>
<td>Building Technical Capability &amp; Capacity (CBA)</td>
<td></td>
</tr>
<tr>
<td>Interoperability</td>
<td></td>
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<tr>
<td>Systems Design</td>
<td></td>
</tr>
<tr>
<td>Interdependency</td>
<td></td>
</tr>
<tr>
<td>Functional Measures</td>
<td></td>
</tr>
<tr>
<td>Scope Definition</td>
<td></td>
</tr>
<tr>
<td>Functional Solution Criteria (measure)</td>
<td></td>
</tr>
<tr>
<td>Funding Schedule</td>
<td></td>
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<tr>
<td>Acquisition Management</td>
<td></td>
</tr>
<tr>
<td>Program Mgmt - Contractor Relations</td>
<td></td>
</tr>
<tr>
<td>Project Mgt Structure</td>
<td></td>
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<tr>
<td>Manning at program office</td>
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<tr>
<td>Scope Responsibility</td>
<td></td>
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<tr>
<td>Standards/Certifications</td>
<td></td>
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<tr>
<td>Supply Chain Vulnerabilities</td>
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<tr>
<td>Information sharing</td>
<td></td>
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<tr>
<td>PO Process Performance</td>
<td></td>
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<tr>
<td>Sustainment Issues</td>
<td></td>
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<tr>
<td>Contract Award</td>
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<tr>
<td>Production Quantity</td>
<td></td>
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<tr>
<td>Data Ownership</td>
<td></td>
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<tr>
<td>Industry Company Assessment</td>
<td></td>
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<tr>
<td>Cost Estimate</td>
<td></td>
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<tr>
<td>Test &amp; Evaluation</td>
<td></td>
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<tr>
<td>Contractor Performance</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td></td>
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<tr>
<td>Project Challenge</td>
<td></td>
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<tr>
<td>Product Challenge</td>
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### Below diagonal

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<th>Tots</th>
<th>0 0 6 4 1 9 5 12 8 7 13 4 10 15 18 7 17 0 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</th>
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</table>
Step 3: Assign Conditional Probabilities to BBN Model

Materiel Solution Analysis Phase – Pre Milestone Estimate

1. Identify Change Drivers & States
2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques
3. Assign Conditional Probabilities to BBN Model
4. Calculate Cost Factor Distributions for Program Execution Scenarios
5. Monte Carlo Simulation to Compute Cost Distribution

Capability Definition is affected by CONOPS and Strategic Vision

Quantifying the uncertainty of change drivers and the cascading effects
Step 4: Calculate Cost Factor Distributions for Program Execution Scenarios

Materiel Solution Analysis Phase – Pre Milestone Estimate

1. Identify Change Drivers & States
2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques
3. Assign Conditional Probabilities to BBN Model
4. Calculate Cost Factor Distributions for Program Execution Scenarios
5. Monte Carlo Simulation to Compute Cost Distribution

An example scenario with 4 drivers in nominal state

BBN model enables computation of different scenarios of program execution on cost model factors
### Step 5a: Monte Carlo Simulation to Compute Cost Distribution

#### Materiel Solution Analysis Phase – Pre Milestone Estimate

1. Identify Change Drivers & States
2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques
3. Assign Conditional Probabilities to BBN Model
4. Calculate Cost Factor Distributions for Program Execution Scenarios
5. Monte Carlo Simulation to Compute Cost Distribution

#### BBN output distributions mapped to COCOMO input values

<table>
<thead>
<tr>
<th>Drivers</th>
<th>XL</th>
<th>VL</th>
<th>L</th>
<th>N</th>
<th>H</th>
<th>VH</th>
<th>XH</th>
<th>Product</th>
<th>Project</th>
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<tbody>
<tr>
<td>PREC</td>
<td>6.20</td>
<td>4.96</td>
<td>3.72</td>
<td>2.48</td>
<td>1.24</td>
<td>0.00</td>
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<tr>
<td>FLEX</td>
<td>5.07</td>
<td>4.05</td>
<td>3.04</td>
<td>2.03</td>
<td>1.01</td>
<td>0.00</td>
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<tr>
<td>RESL</td>
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<td>5.65</td>
<td>4.24</td>
<td>2.83</td>
<td>1.41</td>
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<tr>
<td>TEAM</td>
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#### Effort Multipliers

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<th>PDIF</th>
<th>PDIF</th>
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**Probability distribution used for input to cost estimation model links uncertainty of program change drivers to cost drivers**
COCOMO “Architecture” Parameter Mapping

Product challenge factors represent uncertainty in performance criteria and technology.

- PREC: Is this application unprecedented?
- FLEX: How stringent are the product goals, scope and objectives?
- RCPX: What is required product reliability and complexity?
- RUSE: Must we design for re-usability?
- RESL: Have we addressed technology & architecture risk?

Project challenge factors represent difficulty in managing the workforce.

- PREX: Personnel capability and experience?
- SCED: How much schedule pressure is applied to this development?
- FCIL: Are facilities adequate? Includes tools and multi-site development.
- TEAM: Do we have a cohesive development team?
- PMAT: Does the organization have a mature process?
Monte Carlo simulation using program change factor distributions uses uncertainty on the input side to determine the cost estimate distribution.
Monte Carlo Simulation

We will use Monte Carlo simulation to connect the BBN output node distributions to the COCOMO input parameter distributions.

The animation on the next slide depicts the essence of Monte Carlo simulation when we need to work with distributions rather than single numbers.
Crystal Ball uses a random number generator to select values for A and B.

Crystal Ball then allows the user to analyze and interpret the final distribution of C!

Crystal Ball causes Excel to recalculate all cells, and then it saves off the different results for C!
An Example Output of Monte Carlo Simulation

200,000 Trials

Person-Months

Frequency View

199,650 Displayed

- Infinity

Certainty: 90.0000%

1,854.48
Develop Efficient Techniques To Calibrate Expert Judgment of Program Uncertainties

Solution

**Step 1:** Virtual training using reference points

**Step 2:** Iterate through a series of domain specific tests

**Step 3:** Feedback on test performance

**Outcome:** Expert renders calibrated estimate of size

---

DoD Domain-Specific reference points

1) Size of ground combat vehicle targeting feature xyz in 2002 consisted of 25 KSLOC Ada
2) Size of Army artillery firing capability feature abc in 2007 consisted of 18 KSLOC C++
3) …

---

Calibrated = more realistic size and wider range to reflect true expert uncertainty

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Polling Question 1

Do you find that your current cost estimation process relies heavily on expert judgment?

1. Yes
2. No
3. Not Sure
Experts Tend to Be Over-Confident

Most people are significantly **overconfident** about their estimates, especially educated professionals

(AIE = Hubbard Generic Calibration Training)

<table>
<thead>
<tr>
<th>Group</th>
<th>Subject</th>
<th>% Correct (target 90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvard MBAs</td>
<td>General Trivia</td>
<td>40%</td>
</tr>
<tr>
<td>Chemical Co. Employees</td>
<td>General Industry</td>
<td>50%</td>
</tr>
<tr>
<td>Chemical Co. Employees</td>
<td>Company-Specific</td>
<td>48%</td>
</tr>
<tr>
<td>Computer Co. Managers</td>
<td>General Business</td>
<td>17%</td>
</tr>
<tr>
<td>Computer Co. Managers</td>
<td>Company-Specific</td>
<td>36%</td>
</tr>
</tbody>
</table>

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Experiments confirm that calibrated judgment can be taught.
Future Research Activities
Create A Repository for Quantifying Program Execution Uncertainties

Subject Matter Experts need DoD MDAP data about uncertainty to quantify relationships of program change drivers and their impact on program execution.

Why Hard? Empirical data need to be identified, accessed, extracted and analyzed from a myriad of sources. Data about program change is not structured nor quantified for use in estimation.

DoD Need: Quantified information about cost driver uncertainty should inform estimates.
For C2 systems, how often does Strategic Vision change?

Records show that Strategic Vision changed in 45% of the MDAPS.

The Materiel Solution of a global network command and control system anticipates a possible change in Strategic Vision which will include allied participation.

Sharing information with allies creates new encryption requirements (a change in Mission/CONOPs).

These changes lead to changes in Capability.
If Strategic Vision changes, what else changes?

70% of the time the Mission/CONOPS changes

Repository identifies cascading effects of change in MDAP cost drivers.

The Materiel Solution of a global network command and control system anticipates a possible change in Strategic Vision which will include allied participation.

Sharing information with allies creates new encryption requirements (a change in Mission/CONOPs).

The Materiel Solution of a global network command and control system anticipates a possible change in Strategic Vision which will include allied participation.
The Materiel Solution of a global network command and control system anticipates a possible change in Strategic Vision which will include allied participation.

Sharing information with allies creates new encryption requirements (a change in Mission/CONOPs).

These changes lead to changes in Capability Definition.

Joint Conditional Probabilities can be calculated for downstream changes.
QUELCE Summary

QUELCE includes the effects of uncertainty in the resulting estimate by:

- Making visible the quantified uncertainties that exist in basic assumptions.
- Calculating uncertainty of the input factors to the model rather than adjusting the output factors.
- Using scenario planning to calculate how specific changes might affect outcomes.

The method utilizes subjective and objective data as input

- Historical data can be used to populate the BBN nodes and establish the connections between the BBN and cost model inputs.
- Expert judgments are documented and made explicit.
- Information typically not used for estimation purposes can be leveraged.

The method explicitly includes factors that have been documented as sources of program failure in the past but are not typically captured by cost models.
For More Information

QUELCE Technical Report:
http://www.sei.cmu.edu/library/abstracts/reports/11tr026.cfm

SEI Blog
http://blog.sei.cmu.edu

• “Improving the Accuracy of Early Cost Estimates for Software-Reliant Systems, First in a Two-Part Series”


• “Quantifying Uncertainty in Early Lifecycle Cost Estimation (QUELCE): An Update”

Journal of Software Technology
http://journal.thedacs.com/issue/64/207

• “An Innovative Approach to Quantifying Uncertainty in Early Lifecycle Cost Estimation”
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As projects continue to grow in scale and complexity, effective collaboration across geographical, cultural, and technical boundaries is increasingly prevalent and essential to system success. SATURN 2012 will explore the theme of "Architecture: Catalyst for Collaboration." Join the Measurement and Analysis Forum on LinkedIn at http://www.linkedin.com/groups/Measurement-Analysis-Forum-2758144