Risk Exposure Leading Indicators

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Motivation

• Defense acquisition continues to experience time & cost overruns and reliability shortfalls

• GAO review of 85 MDAPs (FY2013)
  — 39% had unit cost growth of 25% or more
  — 27 month average delay in initial operating capability
  — 49% average increase in development cost vs initial estimate
  — 38% average increase in total acquisition cost vs initial estimate
  — Excludes programs that were cancelled, due to
    o Unacceptable reliability or performance in operational testing
    o Excessive cost growth
    o Change mission need during course of development

• 4 of 5 systems failed to meet reliability objectives (DA-AL&T, FY11)
**Research Organization**

**User Needs**

- **Materiel Solution Analysis**
- **Technology Development**
- **Engineering & Manufacturing Development**

**Pre-System Acquisition**
- Concept, scope, claims, estimates & plans

**System Acquisition**
- RFP & EMD execution

**Risk Exposure**: Uncertainty of / potential for later problems created by earlier decisions and actions or inactions

**Leading Indicators**: Evidence-based metrics related to magnitude, type and source, pointing to potential mitigations
• Collaboration with RT113, “ilities Tradespace and Affordability Project” (iTAP)

• Requirements for design margin for growth potential
  — Size, weight, power, cooling, computing, data transfer, etc. in excess of need
  — Tradeoffs among AUPC cost, upgrade cost, uncertain future upgrade needs and technology opportunities

• Functional performance requirements can be reduced in EMD
  — For increase in **design margins** to reduce development risk
  — For reduction in cost, other lifecycle burdens, or technology-specific risks

• Tradespace methods and tools under development to address design margin, cost, development risk, adversarial risk and lost opportunity costs
Related Research Collaboration
Model-Centric Engineering Risk

• Collaboration with RT118, “Transforming SE with Model-Centric Engineering”

• Risks in converting to model-centric engineering
  — Compliance evaluation of critical functions: flight safety and weapon release
  — Software-intensive cyber-physical systems
  — Control and behavior models embedded in cyber-physical systems
  — What was left out of system design and evaluation models?

• Risk mitigation through model-based balance of
  — Model-based “design of experiments” for cost-effective combination of simulation, surrogate testing, and subsystem testing
  — Family of models at different scope, scale, resolution, and fidelity
  — Models to interpret and extrapolate test results
Part 1: Pre-System Acquisition Risk Exposure Leading Indicators

- Motivation
- Guidelines
- Sources of Risk Exposure
- Example Risk Leading Indicators
- “Software-Intensive” Cyber-Physical Systems
- Next Steps
Motivation

• **75% of total life cycle cost is driven by pre-system acquisition decisions**
  

• Early decisions and actions can have consequences disproportionate to the time and resources expended

• Early decisions can expose the downstream program to risks that are difficult to mitigate later in the program
• Use data that can reasonably be expected to be available or producible pre-system acquisition

• Work with knowledge gaps expected in pre-system acquisition
  — “TBD/unknown” responses
  — Responses without substantiating evidence

• Are logically related to sources of risk and uncertainty

• Have account for variances in past programs

• Ask for the same data and evidence at MDD, MS-A and MS-B

• Provide useful insight into risk exposure sources for the Service Advocate or PM/SE organization

• Suggest or point to mitigation
Sources of Risk Exposure (1/3)

• Over-optimistic claims for cost, schedule and functional performance and life-cycle properties
  — Sets the program up for overrun
  — Incentivizes high-risk plans and strategies

• Limited Program Management and System Engineering team experience with programs of similar content and magnitude*

• Proceeding without adequate knowledge of the size, scope and inter-dependencies (system & development program)*
  — E.g., requirements validated by prototyping & preliminary design by MS-B

• Size, scope, inter-dependencies, and density
  — Non-linear impacts

* Especially for “software-intensive” cyber-physical systems with functionally integrated, embedded & distributed software & hardware
Sources of Risk Exposure (2/3)

- Limited time and resources planned for Developmental Testing and corrective action
  - Assuming problems will be small and rare
  - Not allocating reserve time and resources to correct problems
- Limited parallel pursuit of alternatives / fall-back positions
  - Cost-risk tradeoff
  - Competition incentivizes life-cycle cost control
- Optimistic technology and integration expectations
  - Planning to integrate subsystems that have not previously been integrated in a similar context
  - Expecting to benefit from novel technologies
  - Dependence on external development programs
  - Expecting to benefit from novel design and development methods, tools and procedures
Sources of Risk Exposure (3/3)

• Planning to employ concurrent engineering
  — Concurrent engineering is inherently a high-risk approach for parallel development of interdependent subsystems
    o Hopes the project can be divided into modules for parallel development, coordinated through an IPT team
    o Practice often sends junior members to the IPT meeting
    o Technical coordination through IPT is difficult and ad hoc, depending on the engineering organization, personnel and technical content
  — Needs skilled engineering management and subsystem lead engineer engagement in the IPT
  — Needs well-defined interface standards, resource & performance allocation guidelines

• Incomplete or benign operational conditions in the ICD, CDD and requirements
  — Overlooked conditions set up requirements changes and rework
Optimistic approaches to reduce time and cost, if “all goes according to plan” increase the likelihood and magnitude of overrun when things do not go according to plan.

<table>
<thead>
<tr>
<th></th>
<th>Aggressive</th>
<th>Conservative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Likelihood (ML)</td>
<td>1x</td>
<td>1.8x</td>
</tr>
<tr>
<td>Probability &gt; ML</td>
<td>77%</td>
<td>60%</td>
</tr>
<tr>
<td>Median (50th percentile)</td>
<td>2.7x</td>
<td>2.1x</td>
</tr>
<tr>
<td>Median if outcome &gt; ML</td>
<td>3.4x</td>
<td>2.7x</td>
</tr>
</tbody>
</table>

(Model: **Percentage increase** has normal distribution, vice absolute quantity increase)
Wide differences between CAPE and Service estimates indicate either high uncertainty or inconsistent assumptions.

Optimistic service estimates create risk exposure and encourage risky behavior.

EMD, Production and O&S Costs

Example: GCV

Service AUPC Cost Estimate
- $9M to $10.5M

CAPE AUPC Cost Estimate
- $16M to $17M

Data
Service Cost Estimate
- High-end (or TBD): _____
- Low-end (or TBD): _____

CAPE Cost Estimate
- High-end (or TBD): _____
- Low-end (or TBD): _____

Risk Indicator Calculation

Avg CAPE Estimate – Avg Service Estimate
______________________________ = 1.7
Avg Service Estimate

Avg CAPE Estimate – Avg Service Estimate
______________________________ = 5.4
Avg High – Avg Low
Performance vs Cost Estimates for Proposed vs Legacy System

High increases in performance relative to increase in cost suggest optimistic estimates.

Example: EFV vs AAV

<table>
<thead>
<tr>
<th>Factor</th>
<th>EFV</th>
<th>AAV</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUPC (1993 estimate)</td>
<td>$3.8M</td>
<td>$1M</td>
</tr>
<tr>
<td>Water speed</td>
<td>28MPH</td>
<td>8MPH</td>
</tr>
<tr>
<td>Water range</td>
<td>75 miles</td>
<td>20 miles</td>
</tr>
<tr>
<td>Off-road speed</td>
<td>30MPH</td>
<td>15MPH</td>
</tr>
<tr>
<td>Fuel economy (on road)</td>
<td>0.86 MPG</td>
<td>1.76 MPG</td>
</tr>
<tr>
<td>Intrinsic armor protection</td>
<td>14.5mmAP</td>
<td>7.62mmAP</td>
</tr>
<tr>
<td>Main gun caliber</td>
<td>30mm</td>
<td>12.7mm</td>
</tr>
<tr>
<td>Gun Stabilization</td>
<td>0.5 mils</td>
<td>unstabilized</td>
</tr>
</tbody>
</table>

Risk Indicator Calculation

\[ \frac{\sum \text{Performance Ratios}}{\text{Cost Ratio}} = 3.7 \]

Is it credible that the EFV will be 3.7 times as efficient at the AAV?

(By 2011, EFV AUPC estimate was $22M. AAV AUPC inflated to $2M-$2.5M)
Alternatives and fall-back options are standard risk reduction measures
- Principle of NAVY Set-Based Design

Evidence of broader and deeper consideration of capabilities, costs & risks

Limited fall-back positions increases exposure to risk of solution-specific problems

### GAO-09-665 Analysis of Alternatives

<table>
<thead>
<tr>
<th>% Cost Growth &amp; Schedule Delay</th>
<th># Alternatives in AoA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 to 5</td>
</tr>
<tr>
<td>&gt; 25%, &gt;12 m</td>
<td>61%</td>
</tr>
<tr>
<td>10 - 25%, 7 - 12 m</td>
<td>8%</td>
</tr>
<tr>
<td>&lt; 10%, &lt;7 m</td>
<td>31%</td>
</tr>
</tbody>
</table>

### Data
- Number of alternatives in the AoA
- Number of alternatives in TD Competitive Prototyping
- Number of EMD competitors

### JLTV Example
- 7 to 13 alternatives pre-screened for each of the 3 mission role variants
- 4 alternatives studied in the AoA for each of the 3 mission role variants
- 3 alternatives in TD Competitive Prototyping
- 3 EMD competitors
A new technology may need modification and/or pose unexpected difficulty when technologies that are “new to each other” have to interface – directly or indirectly – there is opportunity for error and unexpected difficulty.

**Example: F-35 JSF**
- Active, Electronically Scanned Array radar
- Distributed Aperture System
- Electro-Optical Targeting System
- Sensor Fusion
- Helmet Mounted Display
- Multifunction Advanced Data Link
- Communications, Navigation and Identification Integrated Avionics

**Data**
- Number of technologies not currently in the inventory on a similar system
- Number of new interfaces - pairs of technologies not previous integrated with each other on a similar system

**Risk Indicator Calculations**
- # new technologies - # with backup = 7
- Number of new interfaces = 13
Mission Density

Loading more missions onto a single system using multiple technologies in different combinations and conditions makes the system more complicated to estimate, design, and test, increasing uncertainty in cost and performance.

Example: F-35 JSF

4 systems replaced: F-16, A-10, F/A-18 Hornet and AV-8B Harrier

3 variants: conventional airfield landing, short takeoff and vertical landing, conventional carrier landing

9 missions: Close Air Support, Interdiction, Suppression and Destruction of Enemy Air Defense, Offensive and Defensive Counter Air, Air Interdiction, Assault Support Escort, Armed Reconnaissance, and electronic surveillance and intelligence

Data

Number of legacy systems replaced
Number of variants
Number of missions

Risk Indicator Calculation

Number of systems replaced + Number of variants + Number of missions = 16
Feature & Function Density

Loading features and functions subsystems, adds opportunities for conflict and competing demands on design, leading to greater difficulty in estimating development time and cost.

Uncertainty in the features and functions implies uncertainty in estimates.

**Example: F-35 JSF Subsystem Features and Functions**

- Active, Electronically Scanned Array radar: 6
- Distributed Aperture System: 7
- Electro-Optical Targeting System: 11
- Sensor Fusion: 4
- Helmet Mounted Display: 5
- Multifunction Advanced Data Link: 3
- Integrated Avionics: 27

**Risk Indicator Calculation**

\[ \sum \text{Number of features and functions} = 63 \]

**Data**

Numbers of distinctive, new or advanced features and functions of major subsystems.
An experienced PM and SE team is

- Less prone to errors of omission and commission
- Better prepared to make more accurate estimates
- More likely to exhibit healthy skepticism

**Data**

Previous programs the individual PM & SE team members have participated, and their role vice current role

**Risk Indicator Calculations**

**Example**

TBD

Fraction of team with *experience in their current PM/SE role* on a previous program

Fraction of team with PM/SE *experience on a similar program* (missions, functions, operating conditions and environment)

Number of *different comparable programs* the team members have participated on
More development testing early, with time and resources to recover, reduces the risk of bad outcomes in operational testing. If the Service advocate is planning for limited DT and fixes, planning is optimistic and the program is at risk.

Data
- Time and cost to allocate to DT during TD and EMD, as percent of planned total
- Time and cost to allocate to rework during TD and EMD, as proportions of planned time and cost

Risk Indicator Calculations
\[ \text{Min} \left( \%\text{Cost}_{\text{DT}} + \%\text{Cost}_{\text{Fix}}, \%\text{Time}_{\text{DT}} + \%\text{Time}_{\text{Fix}} \right) \]
## “TBD” and Unsubstantiated Data

Some of the data to assess risk exposure may be TBD or lack substantiating evidence early in the program.

Proceeding with lack of knowledge is a cause and evidence of risk exposure.

### Data Reporting

- Number of indicators with incomplete or TBD data and fraction of data provided
- Number of indicators with data provided, but without substantiation (and fraction)
- Number of risk leading indicators

### Risk Indicator Calculations: Fraction of Unknown Indicators and Data

<table>
<thead>
<tr>
<th>Example</th>
</tr>
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<tbody>
<tr>
<td>TBD</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th># of “TBD” Risk Indicators</th>
<th># of “Unsubstantiated Indicators”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Risk Indicators</td>
<td>Number of Risk Indicators</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \sum ) fraction of “TBD” Data</th>
<th>( \sum ) fraction of Unsubstantiated Data</th>
</tr>
</thead>
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<td>Number of Risk Indicators</td>
<td>Number of Risk Indicators</td>
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Software-Intensive Cyber-Physical Systems

• Systems with functionally integrated, embedded & distributed software & hardware

• All the “avionics”
  • Behavior logic and state transitions, real-time control, implementation software on distributed, embedded processors, FPGAs and other special processors, configuration data files, special circuitry, antennas, electro-mechanical (data/signal-physical) sensors and actuators

• New types of considerations
  • Safety-critical & mission-critical behaviors/states/transitions, information assurance, synchronization of distributed functions, potential “destructive interference” among different control elements, response times & capacities, scalability, accounting for noise and limits of sensors and actuators
Risk Exposure in Software-Intensive Cyber-Physical Systems

- PM and SE teams often have limited experience in software-intensive systems
- Proceeding without adequate knowledge of the eventual “software” role, functionality, size, scope, and interconnectedness exposes the program to risk
  - Unknown downstream implications of early decisions
- Flawed requirements account for 70% of safety- & mission-critical faults
  - Incomplete or wrong assumptions of correct state or control
  - Unspecified controlled-system state and environmental conditions
- Development effort increases non-linearly with size & interdependencies
  - Uncertainty increases even faster
- Identifying and handling “exception situations” is a major component of software development time and uncertainty
  - Late identification and handling of the exception cases
- Experience of the downstream software development team has a large impact
- Procedures and standards for software development “best practices” do not address risk exposure due to requirements, experience and organization
Can Software Effort Models Estimate Early Risk Exposure?

• E.g., COCOMO II “Early Design” stage model
• Estimates time and cost AFTER software specifications
  • Calibrated to ~200 software projects
  • Estimation uncertainty for any given project is due to
    • Inherent project uncertainty
    • Calibrating to diverse types of projects and executing organizations
• Use for pre-system acquisition risk leading indicators?
  • Count number of “TBD” input data items as an indicator
  • Sample/simulate from low to high values over all “TBD” input data items to estimate the uncertainty range
• Limitations Needs
  • Extension to full cyber-physical “avionics”
  • Calibration to relevant programs
COCOMO II “Early Design” Model

Inputs

- Sizing Data (5 types of “function points”, 3 inputs for each function point)
  - # external inputs
  - # external outputs
  - # internal logical files
  - # external interface files
  - # external query types
  - and # of data elements and # file types for each (low, med, high)

- 5 Scale Factors (rating scale)
  - Application novelty
  - Development flexibility
  - Architecture resolution
  - Team cohesion
  - Process maturity (CMMI)

- 6 Effort Multipliers (rating scale)
  - Personnel capability
  - Product reliability & complexity
  - Reusability required
  - Platform difficulty
  - Personnel experience
  - Facilities
  - Development schedule
Alternative Approach

• Provide a series of questions that will help lead to clarification of the embedded software and avionics
  • Roles, functionality, criticality, interfaces, distribution, states, etc.

• The number of “TBD” answers are the risk leading indicator data indicating the depth of understanding of the system
  • Different “weights” for different questions, depending on stage of development at MDD, MS-A, MS-B

• Calibrate a parametric model (similar to COCOMO II)
  • Numbers of functions, states, interfaces, etc. are inputs
  • Sample from low to high range of inputs to estimate uncertainty

• Risk exposure mitigation is simply developing the information
Software-Intensive Cyber-Physical Systems
Early Scoping and Risk Exposure Indicators

- Questions to help conceptualize the major subsystems, interactions, and software/avionics characteristics (inspired by DODAF views and models)
  - What are the main system roles, capabilities and characteristics?
  - What external interfaces are required?
  - What are the main subsystems and their functions?
  - Which subsystems functions interface or interact with each other?
  - Which subsystem functions need to be synchronized with each other?
  - Which capabilities & characteristics depend on which functions?
  - What are the automatic feedback control loops, man-in-the-loop control, and interactive manual and automatic control?
  - What are the data fusion, synthesis, and perception/decision support functions?
  - What are the system/subsystem states, transitions, events, and event sequences?
  - Which of the above are safety-critical? Which are mission-critical?
- Numbers of “TBD” and unsubstantiated answers measure of system understanding
- Calibrate a parametric model to estimate time and cost uncertainty
  - Sample low to high range for data that are “TBD”
  - Combine with the inherent uncertainty in the model
- Developing the evidence to provide the answers mitigates risk
Next Steps

• Complete leading indicators for remaining types and sources
  — *Special attention for “software-intensive” cyber-physical systems*

• Finalize data and evidence questionnaire & refine indicators

• Validate with historical data
  — Confirm data can be available
  — Confirm leading indicators differentiate between programs with large overruns and re-baselining or restructuring from those that did not

• Calibrate to historical data
  — By leading indicator and in aggregate
  — Scoring
    • **High**: similar to programs with large overruns, re-baselining or restructuring
    • **Low**: similar to programs with small overruns, no re-baselining or restructuring
    • **Indeterminate**: not clearly high or low
Part 2: System Development
Risk Exposure Leading Indicators

- Motivation
- Guidelines
- Sources of Risk Exposure
- Examples Risk Leading Indicators
- Next Steps
Motivation

• Methods, procedures and tools are needed to detect embedded risk exposure and risky practices
  — Evidence of risk exposure from program and systems engineering data
  — Estimate bias and dispersion between actual and planned time and cost for IMS activities, by WBS element and IMP element
  — Integrate maturity advancement, cost, schedule and performance risk

• To alert and inform Program Management
  — When the program has elevated or increasing exposure to risk
  — Which technical areas are contributing most to risk exposure
  — What evidence and type of risk exposure
  — In time for proactive investigation and mitigation

• Complementing other risk assessment and management practices
  — Only one component of overall program risk management
Guidelines

• Reflect PMO risk-reward tradeoffs and considerations in the EMD RFP
  — Engineering, manufacturing and RAM maturity stages are the touchstone
    o Maturity progress relative to actual and budgeted time and cost
    o Maturity state relative to remaining time and cost

• Quantitative and evidence-based methods using standard program management and systems engineering reports & data

• Integrate cost, schedule, EMD progress and product risk & diagnose at WBS 3

• Build on prior research, e.g.,
  — NDIA System Development leading indicators
  — GAO “Best Practices” in cost, schedule and technical program assessment

• “Self-calibrate” for the specific program and contractor
  — Avoid difficulties sharing data across programs and contractors
  — Keep relevance to the specific program and team
Sources of Risk Exposure in EMD

- Risks inherited from Pre-System Acquisition
- Lack of visibility in development vs projected vs actual time & cost
  - Design, Manufacturing, & RAM maturity staged
- Instability, Inconsistency, Incompleteness, Interdependency in plans and engineering baselines
- Unknown unknowns – interactions, dependencies – detected by their effects, but that were not anticipated
- Contractor program management, systems engineering, and lead design engineering experience and stability
- “Gaming the system” to meet incentive and performance metrics, expecting to recover later
Sources of Risk Exposure in EMD

- Limited visibility into maturity advancement vs cost and schedule creates risk exposure
  — “You can’t manage what you don’t measure”

- Instability, Inconsistency, Incompleteness, Interdependency in plans and engineering baselines – evidence of engineering or management deficiency & potentially cause rework

- Past performance on a program can predict future performance
  — If the root causes have not changed, overruns will continue
  — Lagging indicators become effective leading indicators
• IMP is the framework linking schedule, cost & maturity reporting

• Risk Leading Indicators
  — Objective metrics computed from program management and system engineering baselines and updates providing evidence of risk exposure
  — Diagnosis by WBS and IMP
  — Input data from IMS and EVM

• Risk Estimating Relationships - Past predicts future performance
  — If the root causes have not changed, overruns will continue
  — Lagging indicators become effective leading indicators
  — Calibrate leading indicators to individual program maturation, cost and schedule
    o Parametric models, similar to Cost Estimating Relationships
  — Learn from data accumulated during EMD to estimate and localize risk
  — Programs have individual technical, organizational, and personnel issues
  — One program does not predict another, & sharing detailed program data is difficult
EMD Maturity

- Maturity levels are accomplishments with objective criteria on the progression to product delivery for LRIP

- Maturity is a key concept in proposal evaluation, broken out by
  - Design and engineering maturity
  - Manufacturing maturity & manufacturing cost maturity
  - RAM maturity

- Maturity advancement is not a standard reporting element, but is key to linking technical progress to time, cost, and RLI

- Inserting maturity advancement events into the IMP produces visibility
  - Integrates technical progress, time, cost and IMS network reporting
  - Ensures visibility for technical progress risk exposure early warning
  - Breakout by WBS level-3 supports risk exposure area diagnosis
  - Provides traceability to proposal evaluation criteria
Leveraging the Integrated Master Plan

• Government-specified three-level hierarchy of events, accomplishments and objective criteria

• Basis for the Integrated Master Schedule and EVM reporting

• Guidelines and processes to embed engineering, manufacturing, and RAM maturation stages into the IMP will create linkage to cost and schedule reporting
  — Providing integrated technical, cost and schedule progress vs plan data to calibrate contractor performance by WBS element
EMD Risk Leading Indicator Organization

- **Requirements**
  - Interdependency
  - Stability

- **Maturity**
  - Maturity levels
  - Deviation from scheduled advancement
  - Completeness at current level

- **Margins**
  - System design margins
  - Program cost and schedule

- **Architecture & Behavior**
  - Scale
  - Interdependency
  - Completeness
  - Stability

- **Compliance**
  - Verification status & trend
  - Verification schedule

- **Schedule**
  - Scale and interdependency
  - Activity margins
  - Performance
  - Stability
Example Risk Leading Indicators in Observable Program Data

- **Requirements Stability**
  - % requirements added/deleted/changed per reporting period

- **Compliance Verification Completeness**
  - % requirements that have been verified
  - % requirements fully/partially/not compliant

- **Architecture Size and Interdependence**
  - (# elements) * (# interfaces)
  - (# interfaces) / (# elements)

- **Verification Schedule & Trends**
  - % V&V activities completed on schedule
  - Minimum time from V&V activity to next milestone
  - Bias and dispersion of actual vs planned IMS activity time and cost
Next Steps

- Pilot application in collaboration with a specific ACAT I program
- “On-Hold” during Source Selection
Acknowledgements

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“The most serious mistakes are not made as a result of wrong answers. The truly dangerous thing is asking the wrong question.” – Peter Drucker

“There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.” – Donald Rumsfeld

“It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so.” – Mark Twain

“In God we trust; all others bring data.” “You can’t manage what you don’t measure.” – W. Edwards Demming

“Short cuts make long delays.” – Peregrin Took