Leading Indicators for Systems Engineering Effectiveness

Presentation for NDIA SE Conference
October 28, 2009

Garry Roedler
Lockheed Martin
Growing Interest in SE Effectiveness

• Questions about the effectiveness of the SE processes and activities are being asked
  - DoD
  - INCOSE
  - Others

• Key activities and events have stimulated interest
  - DoD SE Revitalization
  - AF Workshop on System Robustness

• Questions raised included:
  - How do we show the value of Systems Engineering?
  - How do you know if a program is doing good systems engineering?

• Sessions included SE Effectiveness measures and Criteria for Evaluating the Goodness of Systems Engineering on a Program
Background of the Systems Engineering Leading Indicators Project

“SE Leading Indicators Action Team” formed in late 2004 under Lean Aerospace Initiative (LAI) Consortium in support of Air Force SE Revitalization

The team is comprised of engineering measurement experts from industry, government and academia, involving a collaborative partnership with INCOSE, PSM, and several others

- Co-Leads: Garry Roedler, Lockheed Martin & Donna Rhodes, MIT ESD/LAI Research Group
- Leading SE and measurement experts from collaborative partners volunteered to serve on the team

The team held periodic meetings and used the ISO/IEC 15939 and PSM Information Model to define the indicators.

PSM (Practice Software and Systems Measurement) has developed foundational work on measurements under government funding; this effort uses the formats developed by PSM for documenting the leading indicators.
A Collaborative Industry Effort

... and several others
Objectives of the project

1. Gain common understanding of the needs and drivers of this initiative
2. Identify information needs underlying the application of SE effectiveness
   - Address SE effectiveness and key systems attributes for systems, SoS, and complex enterprises, such as robustness, flexibility, and architectural integrity
3. Identify set of leading indicators for SE effectiveness
4. Define and document measurable constructs for highest priority indicators
   - Includes base and derived measures needed to support each indicator, attributes, and interpretation guidance
5. Identify challenges for implementation of each indicator and recommendations for managing implementation
6. Establish recommendations for piloting and validating the new indicators before broad use
SE Leading Indicator Definition

- A measure for evaluating the effectiveness of how a specific SE activity is applied on a program in a manner that provides information about impacts that are likely to affect the system performance objectives
  - An individual measure or collection of measures that are predictive of future system performance
    - Predictive information (e.g., a trend) is provided before the performance is adversely impacted
  - Measures factors that may impact the system engineering performance, not just measure the system performance itself
  - Aids leadership by providing insight to take actions regarding:
    - Assessment of process effectiveness and impacts
    - Necessary interventions and actions to avoid rework and wasted effort
    - Delivering value to customers and end users
Leading Indicators

Sources of ignition

Engineering Capability

Causes

Need to monitor drivers and triggers

Smoke detectors

Performance not meeting plans

Fire alarms

Product not maturing fast enough

Fires

Behind schedule, unpredictable

Financial Indicators

Copyright 2009, YorkMetrics
Interactions Among Factors

Adapted from J. McGarry, D.Card, et al., Practical Software Measurement, Addison Wesley, 2002
Criteria of Leading Indicators

- Early in activity flow
- In-process data collection
- In time to make decisions
  - Actionable
  - Key decisions
- Objective
- Insight into goals / obstacles
- Able to provide regular feedback
- Can support defined checkpoints
  - Technical reviews, etc.
- Confidence
  - Quantitative (Statistical)
  - Qualitative
- Can clearly/objectively define decision criteria for interpretation
  - Thresholds
- Tailorable or universal

Used criteria to prioritize candidates for inclusion in guide
**Systems Engineering Leading Indicators**

Thirteen leading indicators defined by SE measurement experts

Beta guide released December 2005 for validation

- Pilot programs conducted
- Workshops conducted
- Survey conducted
  - 106 responses
  - Query of utility of each indicator
  - No obvious candidates for deletion

Version 1.0 released in June 2007

**Objective:** Develop a set of SE Leading Indicators to assess if program is performing SE effectively, and to enhance proactive decision making
List of Indicators

- Requirements Trends (growth; correct and complete)
- System Definition Change Backlog Trends (cycle time, growth)
- Interface Trends (growth; correct and complete)
- Requirements Validation Rate Trends (at each level of development)
- Requirements Verification Trends (at each level of development)
- Work Product Approval Trends
  - Internal Approval (approval by program review authority)
  - External Approval (approval by the customer review authority)
- Review Action Closure Trends (plan vs actual for closure of actions over time)
- Technology Maturity Trends (planned vs actual over time)
  - New Technology (applicability to programs)
  - Older Technology (obsolescence)
- Risk Exposure Trends (planned vs, actual over time)
- Risk Handling Trends (plan vs, actual for closure of actions over time)
- SE Staffing and Skills Trends: # of SE staff per staffing plan (level or skill - planned vs. actual)
- Process Compliance Trends
- Technical Measurement Trends: MOEs (or KPPs), MOPs, TPMs, and margins

Current set has 13 Leading Indicators
Fields of Information Collected for Each Indicator

- Information Need/Category
- Measurable Concept
- Leading Information Description
- Base Measures Specification
  - Base Measures Description
  - Measurement Methods
  - Units of Measure
- Entities and Attributes
  - Relevant Entities (being measured)
  - Attributes (of the entities)
- Derived Measures Specification
  - Derived Measures Description
  - Measurement Function
- Indicator Specification
  - Indicator Description and Sample
  - Thresholds and Outliers
  - Decision Criteria
  - Indicator Interpretation
- Additional Information
  - Related SE Processes
  - Assumptions
  - Additional Analysis Guidance
  - Implementation Considerations
  - User of the Information
  - Data Collection Procedure
  - Data Analysis Procedure

Derived from measurement guidance of PSM and ISO/IEC 15939, Measurement Process
Guide Contents

1. About This Document
2. Executive Summary
   • Includes Table 1 with overview of indicators and mapping to life cycle phases/stages
3. Leading Indicators Descriptions
   • Includes a brief narrative description of each indicator, description of the leading information provided and example graphics
4. Information Measurement Specifications
   • Detailed definitions of each indicators, including all fields of information

SYSTEMS ENGINEERING LEADING INDICATORS GUIDE

Version 1.0
June 15, 2007
Supersedes Beta Release, December 2005

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Developed and Published by Members of

<http://www.incose.org/ProductsPubs/products/seleadingIndicators.aspx>
3.1. **Requirements Trends**

This indicator is used to evaluate the trends in the growth, change, completeness, and correctness of the definition of the system requirements. This indicator provides insight into the rate of maturity of the system definition against the plan. Additionally, it characterizes the stability and completeness of the system requirements which could potentially impact design and production. The interface trends can also indicate risks to quality and impact of architecture, design, implementation, verification, and validation, as well as potential impact to cost and schedule.

An example of how such an indicator might be reported is shown below. Refer to the measurement information specification in Section 4.1 for the details regarding this indicator; the specification includes the general information which would be tailored by each organization to suit its needs and organizational practices.

**Requirements Trends.** The graph illustrates growth trends in the number of requirements in respect to planned number of requirements (which is typically based on expected value based on historical information of similar projects as well as the nature of the program). Based on actual data, a projected number of requirements will also be shown on a graph. In this case, we can see around PDR that there is a significant variance in actual versus planned requirements, indicating a growing problem. An organization would then take corrective action—where we would expect to see the actual growth move back toward the planned subsequent to this point. The requirements growth is an indicator of potential impacts to cost, schedule, and complexity of the technical solution. It also indicates risks of change to and quality of architecture, design, implementation, verification, and validation.

**Requirements Volatility.** The graph illustrates the rate of change of requirements over time. It also provides a profile of the types of change (new, deleted, or revised) which allows root-cause analysis of the change drivers. By monitoring the requirements volatility trend, the program team is able to predict the readiness for the System Requirements Review (SRR) milestone. In this example, the program team initially selected a calendar date to conduct the SRR, but in subsequent planning made the decision to have the SRR be event driven, resulting in a new date for the review wherein there could be a successful review outcome.

**TBD/TBR Discovery Rate.** The graphs show the cumulative requirement TBDs/TBRs vs. the ratio of cumulative TBDs/TBRs over cumulative time. The plot provides an indication of the convergence and stability of the TBDs/TBRs over the life cycle of the project. The graph on the left shows a desirable trend of requirement TBD/TBR stability, as the ratio of decreases and the cumulative number of TBDs/TBRs approaches a constant level. This “fold-over” pattern is the desirable trend to look for especially in the later stages of project life cycle. In contrast, the graph on the right shows an increasing number of TBDs/TBRs even as the program approaches later stages of its life cycle; this is a worrisome trend in system design stability. An advantage of this plot is that by shape of the graph without having to read...
4.1. **Requirements Trends**

<table>
<thead>
<tr>
<th><strong>Requirements Trends</strong></th>
<th><strong>Information Need Description</strong></th>
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<tbody>
<tr>
<td><strong>Information Need</strong></td>
<td>• Evaluate the stability and adequacy of the requirements to understand the risks to other activities towards providing required capability, on-time and within budget.</td>
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<td></td>
<td>• Understand the growth, change, completeness and correctness of the definition of the system requirements.</td>
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<tr>
<td><strong>Information Category</strong></td>
<td>1. Product size and stability – Functional Size and Stability</td>
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<tr>
<td></td>
<td>2. Also may relate to Product Quality and Process Performance (relative to effectiveness and efficiency of validation)</td>
</tr>
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</table>

**Measurable Concept and Leading Insight Provided**

- Indicates whether the system definition is maturing as expected.
- Indicates risks of change to and quality of architecture, design, implementation, verification, and validation.
- Indicates schedule and cost risks.
- Greater requirements growth, changes, or impacts than planned or lower closure rate of TBDs/TBRs than planned indicate these risks.
- May indicate future need for different level or type of resources/skills.

**Base Measure Specification**

| **Base Measures** | 1. # Requirements |
|                  | 2. # Requirement TBDs/TBRs (by selected categories: interval, milestone) |
|                  | 3. # Requirement defects (by selected categories; e.g., type, cause, severity) |
|                  | 4. # Requirements changes (by selected categories; e.g., type, cause) |
|                  | 5. Impact of each requirement change (in estimated effort hours or range of hours) |
|                  | 6. Start/complete times of change |

| **Measurement Methods** | 1. Count the number of requirements |
|                        | 2. Count the number of requirements TBDs/TBRs |
|                        | 3. Count the number of requirements defects per category |
|                        | 4. Count the number of requirements changes per category |
|                        | 5. Estimate the effort hours or range of effort hours expected for each change. |
|                        | 6. Record from actual dates & times of requirements complete in the CM system |

| **Unit of Measurement** | 1. Requirements |
|                       | 2. TBDs/TBRs |
|                       | 3. Defects |
|                       | 4. Changes |
|                       | 5. Effort Hours |
|                       | 6. Date and Time (Hours, Minutes) |

**Entities and Attributes**

- **Relevant Entities**: Requirements
  - Requirement TBDs/TBRs
  - Requirement Defects
  - Requirement Changes
  - Time interval (e.g., monthly, quarterly, phase)

**Derived Measure Specification**

| **Derived Measure** | 1. % Requirements approved |
|                     | 2. % Requirements Growth |
|                     | 3. % TBDs/TBRs closure variance per plan |
|                     | 4. % Requirements Modified |
|                     | 5. Estimated Impact of Requirements Changes for time interval (in Effort hours) |
|                     | 6. Defect profile |
|                     | 7. Defect density |
|                     | 8. Defect leakage (or escapes) |
|                     | 9. Cycle time for requirement changes (each and average) |

**Indicator Specification**

**Indicator Description and Sample**

- Line or bar graphs that show trends of requirements growth and TBD/TBR closure per plan. Stacked bar graph that shows types, causes, and impact/severity of changes. Show thresholds of expected values based on experimental data. Show key events along the time axis of the graphs.

| **Thresholds and Outliers** | Organization dependent. |
|                            | Investigate and, potentially, take corrective action when the requirements growth, requirements change impact, or defect density/distribution exceeds established thresholds <fill in organization specific threshold> or a trend is observed per established guidelines <fill in organizational specific>. |

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**Output**

- **Example of Section 4 Contents**

- **Derived Measure Specification**

- **Indicator Specification**

- **Thresholds and Outliers**

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## Example of Section 4 Contents (Cont’d)

<table>
<thead>
<tr>
<th>Indicator Interpretation</th>
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<tbody>
<tr>
<td>• Used to understand impact on system definition and impact on production.</td>
</tr>
<tr>
<td>• Analyze this indicator for process performance and other relationships that may provide more &quot;leading perspective&quot;.</td>
</tr>
<tr>
<td>• Ops Concept quality may be a significant leading indicator of the requirements stability (may be able to use number of review comments; stakeholder coverage in defining the Ops Concept).</td>
</tr>
<tr>
<td>• Care should be taken that the organization does not create incentives driving perceptions that all requirements change is undesirable. Note: Requirements changes may be necessary to accommodate new functionality.</td>
</tr>
<tr>
<td>• Review of this indicator can help determine the adequacy of:</td>
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<tr>
<td>o Quantity and quality of Systems Engineers</td>
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<tr>
<td>o Infrastructure</td>
</tr>
<tr>
<td>o Process maturity (acquirer and supplier)</td>
</tr>
<tr>
<td>o Interface design capability</td>
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<tr>
<td>o Stakeholder collaboration across life cycle</td>
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<tr>
<td>Funding by customer; financial challenge by the program management</td>
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</tbody>
</table>

### Additional Information

<table>
<thead>
<tr>
<th>Related Processes</th>
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<tbody>
<tr>
<td>Stakeholder Requirements, Requirements Analysis, Architectural Design</td>
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</table>

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<tr>
<th>Assumptions</th>
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<tbody>
<tr>
<td>Requirements Database, Change Control records, and defect records are maintained &amp; current.</td>
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</table>

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<tr>
<th>Additional Analysis Guidance</th>
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<tbody>
<tr>
<td>• May also be helpful to track trends based on severity/priority of changes</td>
</tr>
<tr>
<td>• Defect leakage - identify the phases in which defect was inserted and found for each defect recorded.</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Implementation Considerations</th>
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<tbody>
<tr>
<td>• Requirements that are not at least at the point of a draft baseline should not be counted.</td>
</tr>
<tr>
<td>• Usage is driven by the correctness and stability of interfaces definition and design.</td>
</tr>
<tr>
<td>o Lower stability means higher risk of impact to other activities and other phases, thus requiring more frequent review.</td>
</tr>
<tr>
<td>o Applies throughout the life cycle, based on risk.</td>
</tr>
<tr>
<td>o Track this information per baseline version to track the maturity of the baseline as the system definition evolves.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>User of Information</th>
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<tbody>
<tr>
<td>• Program Manager (PM)</td>
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<tr>
<td>• Chief Systems Engineer (CSE)</td>
</tr>
<tr>
<td>• Product Managers</td>
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<tr>
<td>• Designers</td>
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</tbody>
</table>

<table>
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<tr>
<th>Data Collection Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>• See Appendix A</td>
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</tbody>
</table>

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<thead>
<tr>
<th>Data Analysis Procedure</th>
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</thead>
<tbody>
<tr>
<td>• See Appendix A</td>
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</tbody>
</table>
# Systems Engineering Leading Indicators Application to Life Cycle Phases/ Stages

## Table 1 - SYSTEMS ENGINEERING LEADING INDICATORS OVERVIEW

<table>
<thead>
<tr>
<th>Leading Indicator</th>
<th>Insight Provided</th>
<th>Phases / Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Requirements Trends</strong></td>
<td>Rate of maturity of the system definition against the plan. Additionally, characterizes the stability and completeness of the system requirements which could potentially impact design and production.</td>
<td>P1 P2 P3 P4 P5 S1 S2 S3 S4 S5</td>
</tr>
<tr>
<td><strong>System Definition Change Backlog Trend</strong></td>
<td>Change request backlog which, when excessive, could have adverse impact on the technical, cost and schedule baselines.</td>
<td></td>
</tr>
<tr>
<td><strong>Interface Trends</strong></td>
<td>Interface specification closure against plan. Lack of timely closure could pose adverse impact to system architecture, design, implementation and/or V&amp;V any of which could pose technical, cost and schedule impact.</td>
<td>P1 P2 P3 P4 P5 S1 S2 S3 S4 S5</td>
</tr>
<tr>
<td><strong>Requirements Validation Trends</strong></td>
<td>Progress against plan in assuring that the customer requirements are valid and properly understood. Adverse trends would pose impacts to system design activity with corresponding impacts to technical, cost &amp; schedule baselines and customer satisfaction.</td>
<td>P1 P2 P3 P4 P5 S1 S2 S3 S4 S5</td>
</tr>
<tr>
<td><strong>Requirements Verification Trends</strong></td>
<td>Progress against plan in verifying that the design meets the specified requirements. Adverse trends would indicate inadequate design and rework that could impact technical, cost and schedule baselines. Also, potential adverse operational effectiveness of the system.</td>
<td>P1 P2 P3 P4 P5 S1 S2 S3 S4 S5</td>
</tr>
<tr>
<td><strong>Work Product Approval Trends</strong></td>
<td>Adequacy of internal processes for the work being performed and also the adequacy of the document review process, both internal and external to the organization. High reject count would suggest poor quality work or a poor document review process each of which could have adverse cost, schedule and customer satisfaction impact.</td>
<td>P1 P2 P3 P4 P5 S1 S2 S3 S4 S5</td>
</tr>
<tr>
<td><strong>Review Action Closure Trends</strong></td>
<td>Responsiveness of the organization in closing post-review actions. Adverse trends could forecast potential technical, cost and schedule baseline issues.</td>
<td>P1 P2 P3 P4 P5 S1 S2 S3 S4 S5</td>
</tr>
</tbody>
</table>
## Indicator’s Usefulness for Gaining Insight to the Effectiveness of Systems Engineering

(1 of 3)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Critical</th>
<th>Very Useful</th>
<th>Somewhat Useful</th>
<th>Limited Usefulness</th>
<th>Not Useful</th>
<th>Usefulness Rating *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements Trends</td>
<td>24%</td>
<td>35%</td>
<td>11%</td>
<td>3%</td>
<td>3%</td>
<td>4.1</td>
</tr>
<tr>
<td>System Definition Change Backlog Trend</td>
<td>7</td>
<td>11</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3.9</td>
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<tr>
<td>Interface Trends</td>
<td>14</td>
<td>12</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>4.3</td>
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<tr>
<td>Requirements Validation Trends</td>
<td>22</td>
<td>16</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>4.4</td>
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<tr>
<td>Requirements Verification Trends</td>
<td>37</td>
<td>23</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>4.4</td>
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<tr>
<td>Work Product Approval Trends</td>
<td>7</td>
<td>19</td>
<td>21</td>
<td>2</td>
<td>0</td>
<td>3.9</td>
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<tr>
<td>Review Action Closure Trends</td>
<td>5</td>
<td>33</td>
<td>21</td>
<td>5</td>
<td>0</td>
<td>3.9</td>
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<tr>
<td>Risk Exposure Trends</td>
<td>14</td>
<td>37</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>4.3</td>
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<tr>
<td>Risk Handling Trends</td>
<td>6</td>
<td>25</td>
<td>11</td>
<td>1</td>
<td>0</td>
<td>4.1</td>
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<tr>
<td>Technology Maturity Trends</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>4.1</td>
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<tr>
<td>Technical Measurement Trends</td>
<td>21</td>
<td>27</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>4.4</td>
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<tr>
<td>Systems Engineering Staffing &amp; Skills Trends</td>
<td>11</td>
<td>27</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>4.2</td>
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<tr>
<td>Process Compliance Trends</td>
<td>6</td>
<td>14</td>
<td>11</td>
<td>1</td>
<td>0</td>
<td>4.0</td>
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*Defined on the Slide.  
Somewhat Useful  | Very Useful

Percentages shown are based on total survey responses. Not all indicator responses total to 100% due to round-off error or the fact that individual surveys did not include responses for every question.
Indicator’s Usefulness for Gaining Insight to the Effectiveness of Systems Engineering (2 of 3)

Usefulness Ratings defined via the following guidelines:

- **4.6-5.0 = Critical**: Crucial in determining the effectiveness of Systems Engineering
- **4.0-4.5 = Very Useful**: Frequent insight and/or is very useful for determining the effectiveness of Systems Engineering
- **3.0-3.9 = Somewhat Useful**: Occasional insight into the effectiveness of Systems Engineering
- **2.0-2.9 = Limited Usefulness**: Limited insight into the effectiveness of Systems Engineering
- **Less than 2.0 = Not Useful**: No insight into the effectiveness of Systems Engineering
Looking Forward – What Next?
Next Steps/Action Items

- Revision to SELI Guide revision planned for release in December
- Continue to conduct SELI telecons every 3 weeks
  - Contact Howard Schimmoller, Garry Roedler, or Cheryl Jones for information
New Indicators

- New indicators
  1. Test Completeness
  2. Resource Volatility
  3. Defect and Error Trends
  4. System Affordability
  5. Architecture Trends
  6. Algorithm & Scenario Trends
  7. Complexity Change Trends
  8. Concept Development – May want to consider based on needs identified by UARC EM task
  9. 2 other indicators are being contributed for consideration

Will include those that have matured by late November
Additional Information on Specific Application and Relationships

1. Cost-effective sets of Base Measures that support greatest number of indicators
2. Indicators vs. SE Activities of ISO/IEC 15288
3. Application of the SE Leading Indicators for Human System Integration (HSI)
4. Application of the SE Leading Indicators for Understanding Complexity
### SELI versus SE Activities of ISO/IEC 15288

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<td>6.3 Project Processes</td>
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<td>6.3.1 Project Planning Process</td>
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<td>6.3.1.3.a Define the project</td>
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<td>6.3.1.3.b Plan the project resources</td>
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<td>6.3.1.3.c Plan the project technical and quality management</td>
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NAVAIR Applied Leading Indicators (ALI) Methodology

- Systematically analyzes multiple data elements for a specific information need to determine mathematically valid relationships with significant correlation
  - These are then identified as Applied Leading Indicators

- Provides a structured approach for:
  - Validation of the LI's
  - Identifying most useful relationships

- Unanimous agreement to include this in the SELI guide

- NAVAIR (Greg Hein) to summarize the methodology for incorporation into the SELI Guide revision as an appendix
  - Summary will include links to any supplementary information and guidance
Interaction with SERC SE Effectiveness Measurement Project

- SE Leading Indicators Guide is pointed to from SERC SE Effectiveness Measurement (EM) project for quantitative measurement perspective

- SERC EM contribution:
  - Short-term:
    - Mapping of SE Effectiveness Measurement Framework to SE Leading Indicators (SELI)
      - 51 Criteria => Critical Success Factors => Questions => SELI
        - Critical Success Factors serve as Information Needs
        - Questions serve as Measurable Concepts
    - Mapping of 51 Criteria to SELI
    - Review to ensure consistency of concepts and terminology
  - Longer-term:
    - Work with OSD to get infrastructure in place to support data collection and analysis
      - Tie to SRCA DB (TBR)
      - May require government access and analysis
QUESTIONS?