WORKSHOP

CO SYS MO

CONSTRUCTIVE SYSTEMS ENGINEERING COST MODEL

8th Annual Practical Software and Systems Measurement Users' Group Conference
Keystone, CO
July 28 & 29, 2004

Dr. Barry W. Boehm – *USC Center for Software Engineering*
Chris Miller – *Software Productivity Consortium*
Gary Thomas – Raytheon Intelligence & Information Systems
Jo Ann Lane – *USC Center for Software Engineering*
Ricardo Valerdi – *USC Center for Software Engineering*

Workshop Agenda

Day 1 (1:45 PM – 5:30 PM 7/28)

- **Short COSYSMO tutorial (Valerdi)**
- **Develop size measurement constructs (Miller)**
- **Burning Issues (Valerdi/Miller)**
- **COSYSMO Delphi exercise (Valerdi)**

Day 2 (8:30 AM – 5:15 PM 7/29)

- ***myCOSYSMO* Tool demo (Thomas)**
- ***myCOSYSMO* case study #1 (Thomas)**
- ***myCOSYSMO* case study #2 (Thomas)**
- **COSOSIMO Delphi exercise (Lane)**

Assumptions

1. **At a minimum: You have read the "COSYSMO Primer" presentation provided in the read ahead material**
2. **Would be nice if: You downloaded *myCOSYSMO* onto your laptop**
3. **Even better if you: filled out the COSYSMO Delphi survey**

Burning Issues

HOT!

1. **Sizing**
   - what are the right levels to count REQS, I/F, SCEN?

BURN!

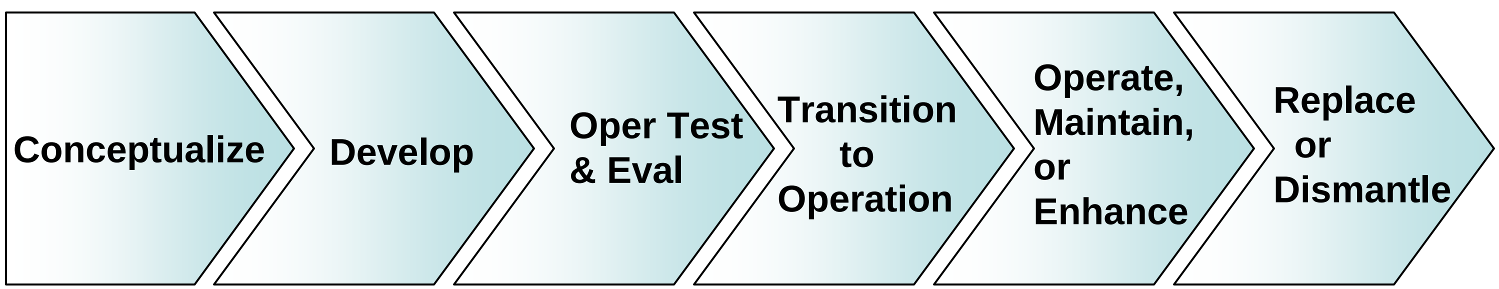
2. **Data for calibration**
   - Need at least 30 project data points
3. **Model unification**
   - With CII, COSOSIMO, et al
4. **SE activities from EIA/ANSI 632**
   - Which of the 33 requirements do we want to include in COSYSMO?

OUCH!

5. **Lifecycle extensions**

COSYSMO Overview

- Parametric model to estimate system engineering costs
- Includes 4 size & 14 cost drivers
- Covers full system engineering lifecycle
- Developed with USC-CSE Corporate Affiliate, PSM, and INCOSE participation



Central Proposition

There exists a subset of systems engineering activities for which it is possible to create a parametric model that will estimate systems engineering effort person months throughout the system life cycle

(a) for a specific system of interest, and

(b) with the same statistical criteria as the COCOMO suite of models at a comparable stage of maturity in time and effort

COSYSMO Data Collection Sources

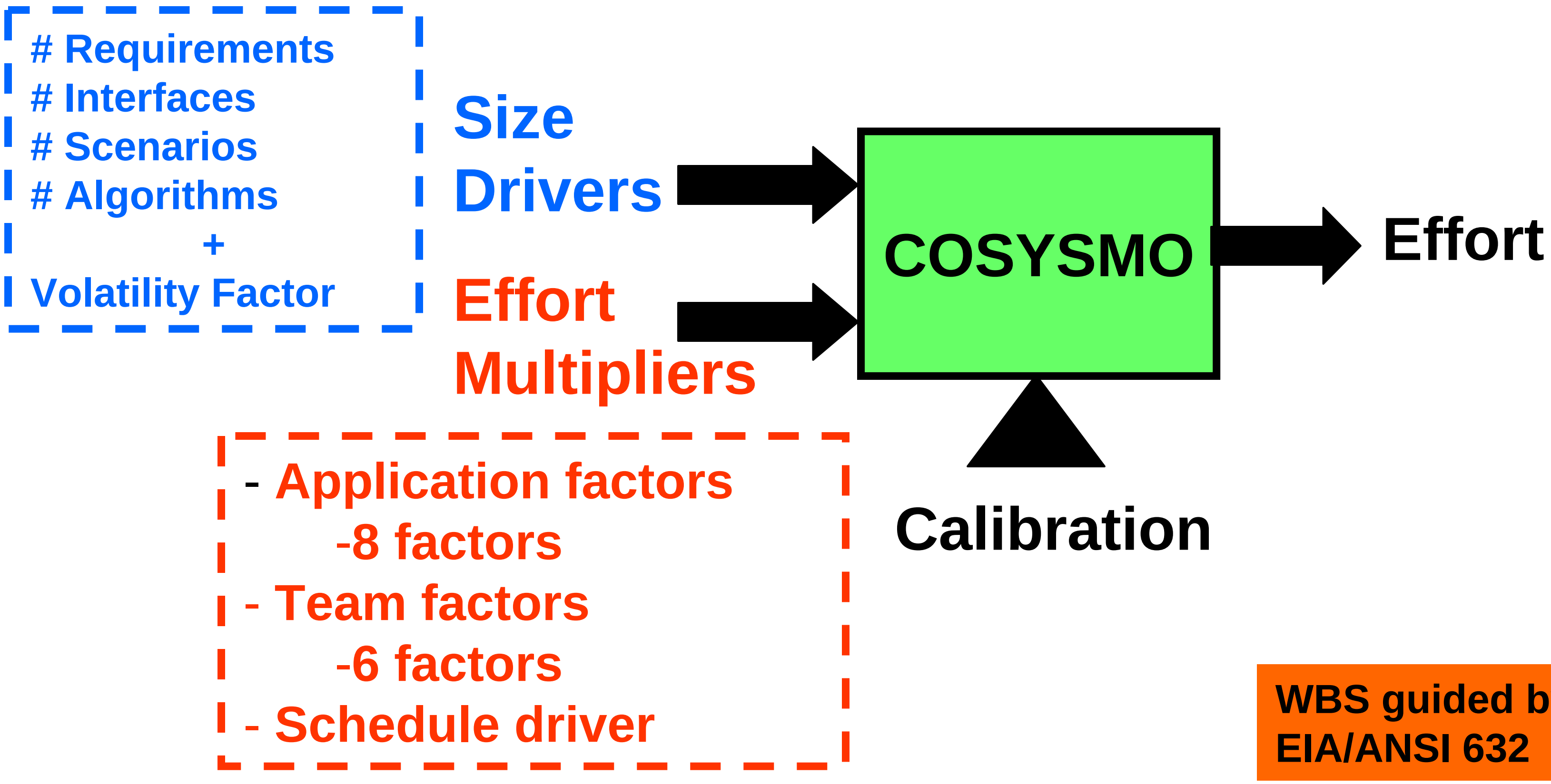
Organization	Expressed interest	Attended Working Group Meeting	Signed NDA	Filled Out Delphi	Contributed Data	Developed Local Calibration	Uses model as a sanity check
Raytheon	✓	✓	✓	✓	✓	✓	✓
BAE	✓	✓	✓	✓	✓		
Aero	✓	✓	✓	✓			
Northrop	✓	✓	✓	✓			
LMCO	✓	✓	✓	✓			
Gen Dyn	✓	✓	✓	✓	✓		
SAIC	✓	✓	✓	✓			
Boeing	✓	✓		✓			
L-3	✓	✓					

Data point sources: Raytheon (7), BAE Systems (3), General Dynamics (1)
In the pipeline: Lockheed Martin, Northrop Grumman, Aerospace Corp., SAIC

Model Differences

COCOMO II	COSYSMO
Software	Systems Engineering
Development phases	Entire Life Cycle
20+ years old	3 years old
200+ calibration points	~11 calibration points
23 Drivers	18 drivers
Variable granularity	Fixed granularity
3 anchor points	No anchor points
Size is driven by SLOC	Size is driven by requirements, I/F, etc

COSYSMO Operational Concept



WBS guided by EIA/ANSI 632

Model Form

$$PM_{NS} = A \cdot \left(\sum_{k} w_e \Phi_e + w_n \Phi_n + w_d \Phi_d \right)^E \cdot \prod_{j=1}^{14} EM_j$$

Where:

PM$_{NS}$ = effort in Person Months (Nominal Schedule)

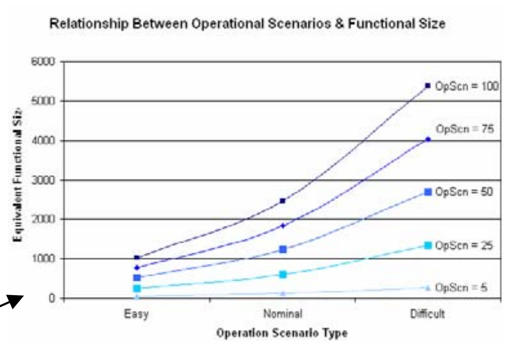
A = calibration constant derived from historical project data

k = {REQ, IF, ALG, SCN}

w_x = weight for "easy", "nominal", or "difficult" size driver

Φ_x = quantity of "k" size driver

E = represents diseconomy of scale (currently equals 1)

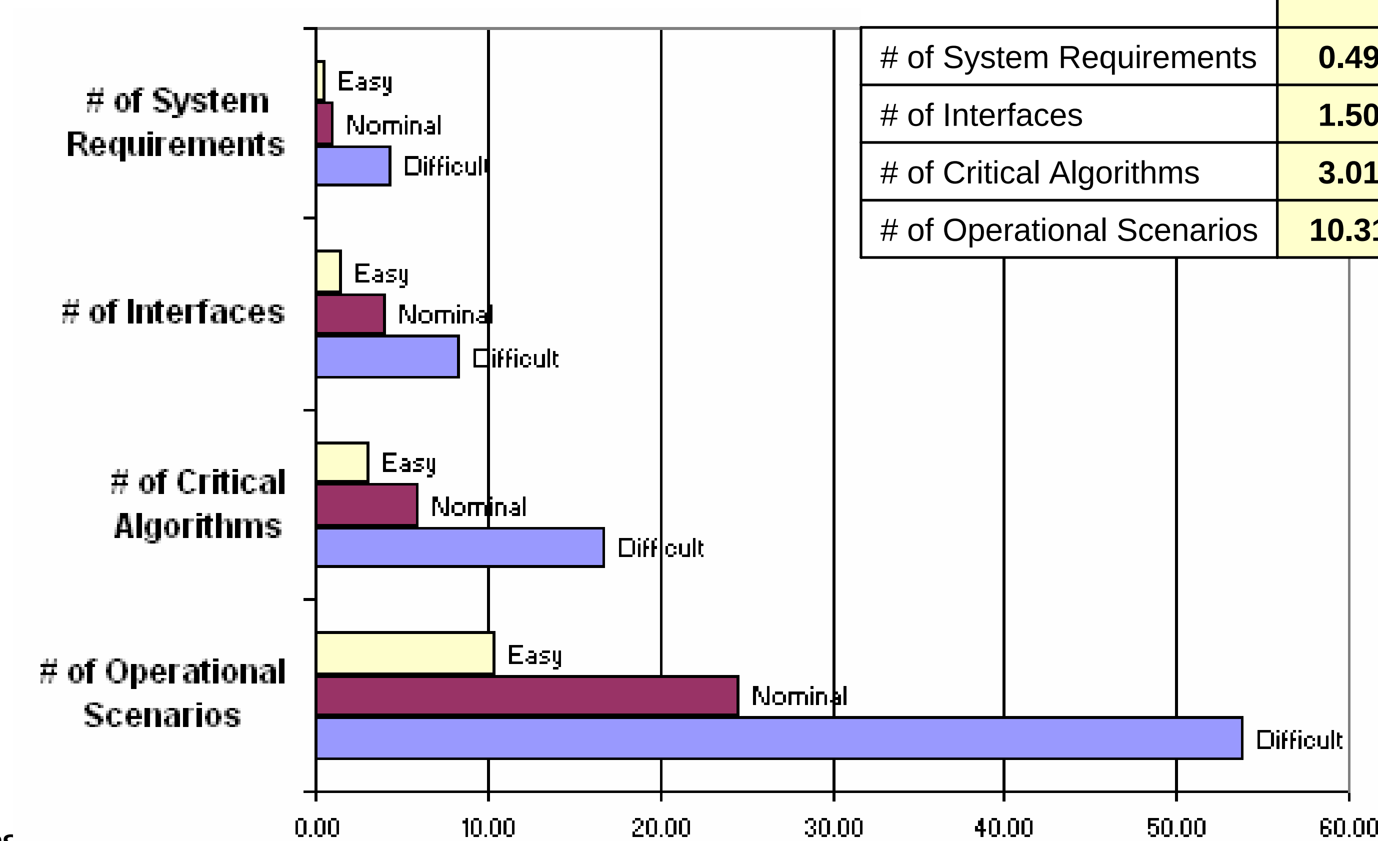


EM = effort multiplier for the j_{th} cost driver. The geometric product results in an overall effort adjustment factor to the nominal effort.

Size Driver Results

These four drivers help us determine how “big” a system is. The effort required for “nominal” # of system requirements serves as a basis for comparison to the other three size drivers. For example, the systems engineering effort required for difficult algorithms is 16.64 times greater than for nominal requirements.

	Easy	Nominal	Difficult
# of System Requirements	**0.49**	**1.00**	**4.23**
# of Interfaces	**1.50**	**3.92**	**8.21**
# of Critical Algorithms	**3.01**	**5.84**	**16.64**
# of Operational Scenarios	**10.31**	**24.58**	**53.85**



Cost Driver Results

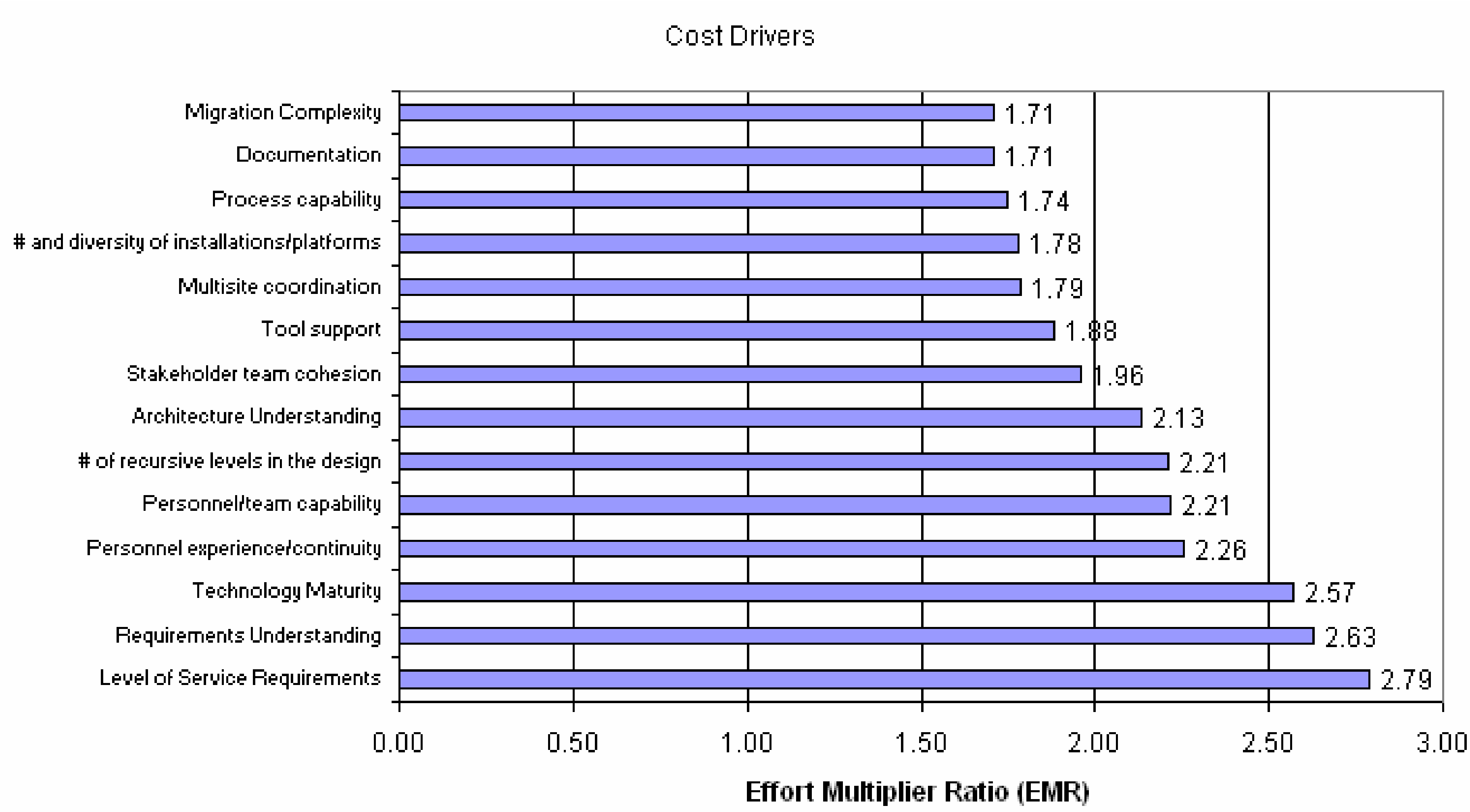
Note 1: The Effort Multiplier Ratio (EMR) is the ratio of the large value over the small one (i.e., Requirements Understanding EMR is 1.71/.65 = 2.63)

Note 2: Cost drivers are listed in order of appearance on the Delphi survey

Note 3: Intermediate values (Low, High, and Very High) were updated as geometric ratios rather than arithmetic differences. EMRs did not change.

	Very Low	Low	Nominal	High	Very High	Extra High	EMR
Requirements Understanding	1.71	1.31	1.00	0.81	0.65		2.63
Architecture Understanding	1.51	1.23	1.00	0.84	0.71		2.13
Level of Service Requirements	0.66	0.81	1.00	1.36	1.84		2.79
Migration Complexity			1.00	1.20	1.43	1.71	1.71
Technology Maturity	1.75	1.32	1.00	0.82	0.68		2.57
Documentation	0.77	0.88	1.00	1.15	1.32		1.71
# and diversity of installations/platforms			1.00	1.21	1.47	1.78	1.78
# of recursive levels in the design	0.67	0.82	1.00	1.22	1.48		2.21
Stakeholder team cohesion	1.45	1.20	1.00	0.86	0.74		1.96
Personnel/team capability	1.50	1.22	1.00	0.82	0.68		2.21
Personnel experience/continuity	1.54	1.24	1.00	0.82	0.68		2.26
Process capability	1.32	1.15	1.00	0.91	0.83	0.76	1.74
Multisite coordination	1.34	1.16	1.00	0.91	0.83	0.75	1.79
Tool support	1.39	1.18	1.00	0.86	0.74		1.88

Note: Cost drivers are listed in order of EMR value (or influence)



COSYSMO Delphi Round 3

- **Designed to help experts provide their opinion on size and cost driver weights**
- **Used in COCOMO suite of models**
- **Two previous COSYSMO Delphi rounds yielded 28 and 40 respondents, respectively**
- **Trying something new in Round 3: each cost driver with multiple viewpoints *may* have different rating scale values**
- **Other cost drivers *may* contain irrelevant viewpoints**

…now the survey

4 Size Drivers

1. Number of System Requirements
2. Number of Major Interfaces
3. Number of Operational Scenarios
4. Number of Critical Algorithms

- Each weighted by complexity, volatility, and degree of reuse

Number of System Requirements

This driver represents the number of requirements for the system-of-interest at a specific level of design. Requirements may be functional, performance, feature, or service-oriented in nature depending on the methodology used for specification. They may also be defined by the customer or contractor. System requirements can typically be quantified by counting the number of applicable "shall's" or "will's" in the system or marketing specification. Do not include a requirements expansion ratio – only provide a count for the requirements of the system-of-interest as defined by the system or marketing specification.

Easy	Nominal	Difficult
- Well specified	- Loosely specified	- Poorly specified
- Traceable to source	- Can be traced to source with some effort	- Hard to trace to source
- Little requirements overlap	- Some overlap	- High degree of requirements overlap

Number of Major Interfaces

This driver represents the number of shared major physical and logical boundaries between system components or functions (internal interfaces) and those external to the system (external interfaces). These interfaces typically can be quantified by counting the number of external and internal system interfaces among ISO/IEC 15288-defined system elements.

Easy	Nominal	Difficult
- Well defined	- Loosely defined	- Ill defined
- Uncoupled	- Loosely coupled	- Highly coupled
- Strong consensus	- Moderate consensus	- Low consensus
- Well behaved	- Predictable behavior	- Poorly behaved

Number of Critical Algorithms

This driver represents the number of newly defined or significantly altered functions that require unique mathematical algorithms to be derived in order to achieve the system performance requirements. As an example, this could include a complex aircraft tracking algorithm like a Kalman Filter being derived using existing experience as the basis for the all aspect search function. Another example could be a brand new discrimination algorithm being derived to identify friend or foe function in space-based applications. The number can be quantified by counting the number of unique algorithms needed to support each of the mathematical functions specified in the system specification or mode description document.

Easy	Nominal	Difficult
- Existing algorithms	- Some new algorithms	- Many new algorithms
- Basic math	- Algebraic by nature	- Difficult math (calculus)
- Straightforward structure	- Nested structure with decision logic	- Recursive in structure with distributed control
- Simple data	- Relational data	- Persistent data
- Timing not an issue	- Timing a constraint	- Dynamic, with timing issues
- Library-based solution	- Some modeling involved	- Simulation and modeling involved

Number of Operational Scenarios

This driver represents the number of operational scenarios that a system must satisfy. Such threads typically result in end-to-end test scenarios that are developed to validate the system and satisfy all of its requirements. The number of scenarios can typically be quantified by counting the number of unique end-to-end tests used to validate the system functionality and performance or by counting the number of use case sequence diagrams developed as part of the operational architecture.

Easy	Nominal	Difficult
- Well defined	- Loosely defined	- Ill defined
- Loosely coupled	- Moderately coupled	- Tightly coupled or many dependencies/conflicting requirements
- Timelines not an issue	- Timelines a constraint	- Tight timelines through scenario network

14 Cost Drivers

Application Factors (8)

1. Requirements understanding
2. Architecture understanding
3. Level of service requirements
4. Migration complexity
5. Technology Maturity
6. Documentation Match to Life Cycle Needs
7. # and Diversity of Installations/Platforms
8. # of Recursive Levels in the Design

Requirements understanding

This cost driver rates the level of understanding of the system requirements by all stakeholders including the systems, software, hardware, customers, team members, users, etc.

Very low	Low	Nominal	High	Very High
Poor, unprecedented system	Minimal, many undefined areas	Reasonable, some undefined areas	Strong, few undefined areas	Full understanding of requirements, familiar system

Architecture understanding

This cost driver rates the relative difficulty of determining and managing the system architecture in terms of platforms, standards, components (COTS/GOTS/NDI/new), connectors (protocols), and constraints. This includes tasks like systems analysis, tradeoff analysis, modeling, simulation, case studies, etc.

Very low	Low	Nominal	High	Very High
Poor understanding of architecture and COTS, unprecedented system	Minimal understanding of architecture and COTS, many undefined areas	Reasonable understanding of architecture and COTS, some weak areas	Strong understanding of architecture and COTS, few undefined areas	Full understanding of architecture, familiar system and COTS
>6 level WBS	5-6 level WBS	3-4 level WBS	2 level WBS	

Level of service requirements

This cost driver rates the difficulty and criticality of satisfying the ensemble of level of service requirements, such as security, safety, response time, interoperability, maintainability, the “ilities”, etc.

Viewpoint	Very low	Low	Nominal	High	Very High
Difficulty	**Simple**	**Low difficulty, coupling**	**Moderately complex, coupled**	**Difficult, coupled KPPs**	**Very complex, tightly coupled**
Criticality	**Slight inconvenience**	**Easily recoverable losses**	**Some loss**	**High financial loss**	**Risk to human life**

Migration complexity

This cost driver rates the extent to which the legacy system affects the migration complexity, if any. Legacy system components, databases, workflows, environments, etc., may affect the new system implementation due to new technology introductions, planned upgrades, increased performance, business process reengineering, etc.

Viewpoint	Nominal	High	Very High	Extra High
Legacy contractor	Self; legacy system is well documented. Original team largely available	Self; original development team not available; most documentation available	Different contractor; limited documentation	Original contractor out of business; no documentation available
Effect of legacy system on new system	Everything is new; legacy system is completely replaced or non-existent	Migration is restricted to integration only	Migration is related to integration and development	Migration is related to integration, development, architecture and design

Technology Risk

The maturity, readiness, and obsolescence of the technology being implemented. Immature or obsolescent technology will require more Systems Engineering effort.

Viewpoint	Very Low	Low	Nominal	High	Very High
Lack of Maturity	Technology proven and widely used throughout industry	Proven through actual use and ready for widespread adoption	Proven on pilot projects and ready to roll-out for production jobs	Ready for pilot use	Still in the laboratory
Lack of Readiness	Mission proven (TRL 9)	Concept qualified (TRL 8)	Concept has been demonstrated (TRL 7)	Proof of concept validated (TRL 5 & 6)	Concept defined (TRL 3 & 4)
Obsolescence			- Technology is the state-of-the-practice - Emerging technology could compete in future	- Technology is stale - New and better technology is on the horizon in the near-term	- Technology is outdated and use should be avoided in new systems - Spare parts supply is scarce

Documentation match to life cycle needs

The breadth and depth of documentation required to be formally delivered based on the life cycle needs of the system.

Viewpoint	Very low	Low	Nominal	High	Very High
Breadth	**General goals**	**Broad guidance, flexibility is allowed**	**Streamlined processes, some relaxation**	**Partially streamlined process, some conformity with occasional relaxation**	**Rigorous, follows strict customer requirements**
Depth	**Minimal or no specified documentati on and review requirements relative to life cycle needs**	**Relaxed documentation and review requirements relative to life cycle needs**	**Amount of documentation and reviews in sync and consistent with life cycle needs of the system**	**High amounts of documentation, more rigorous relative to life cycle needs, some revisions required**	**Extensive documentation and review requirements relative to life cycle needs, multiple revisions required**

 # and diversity of installations/platforms

The number of different platforms that the system will be hosted and installed on. The complexity in the operating environment (space, sea, land, fixed, mobile, portable, information assurance/security). For example, in a wireless network it could be the number of unique installation sites and the number of and types of fixed clients, mobile clients, and servers. Number of platforms being implemented should be added to the number being phased out (dual count).

Viewpoint	Nominal	High	Very High	Extra High
Sites/ installations	Single installation site or configuration	2-3 sites or diverse installation configurations	4-5 sites or diverse installation configurations	>6 sites or diverse installation configurations
Operating environment	Existing facility meets all known environmental operating requirements	Moderate environmental constraints; controlled environment (i.e., A/C, electrical)	Ruggedized mobile land-based requirements; some information security requirements. Coordination between 1 or 2 regulatory or cross functional agencies required.	Harsh environment (space, sea airborne) sensitive information security requirements. Coordination between 3 or more regulatory or cross functional agencies required.
Platforms	<3 types of platforms being installed and/or being phased out/replaced	4-7 types of platforms being installed and/or being phased out/replaced	8-10 types of platforms being installed and/or being phased out/replaced	>10 types of platforms being installed and/or being phased out/replaced
	Homogeneous platforms	Compatible platforms	Heterogeneous, but compatible platforms	Heterogeneous, incompatible platforms
	Typically networked using a single industry standard protocol	Typically networked using a single industry standard protocol and multiple operating systems	Typically networked using a mix of industry standard protocols and proprietary protocols; single operating systems	Typically networked using a mix of industry standard protocols and proprietary protocols; multiple operating systems

of recursive levels in the design

The number of levels of design related to the system-of-interest (as defined by ISO/IEC 15288) and the amount of required SE effort for each level.

Viewpoint	Very Low	Low	Nominal	High	Very High
Number of levels	1	2	3-5	6-7	>7
Required SE effort	Ad-hoc effort	Maintaining system baseline with few planned upgrades	Sustaining SE for the product line, introducing some enhancements of product design features or optimizing performance and/or cost	Maintaining multiple configurations or enhancements with extensive pre-planned product improvements or new requirements, evolving	Maintaining many configurations or enhancements with extensive pre-planned product improvements, new requirements rapidly evolving

14 Cost Drivers (cont.)

Team Factors (6)

1. Stakeholder team cohesion
2. Personnel/team capability
3. Personnel experience/continuity
4. Process capability
5. Multisite coordination
6. Tool support

Stakeholder team cohesion

Represents a multi-attribute parameter which includes leadership, shared vision, diversity of stakeholders, approval cycles, group dynamics, IPT framework, team dynamics, trust, and amount of change in responsibilities. It further represents the heterogeneity in stakeholder community of the end users, customers, implementers, and development team.

Viewpoint	Very Low	Low	Nominal	High	Very High
Culture	▪Stakeholders with diverse expertise, task nature, language, culture, infrastructure ▪Highly heterogeneous stakeholder communities	▪Heterogeneous stakeholder community ▪Some similarities in language and culture	▪Shared project culture	▪Strong team cohesion and project culture ▪Multiple similarities in language and expertise	▪Virtually homogeneous stakeholder communities ▪<u>Institutionalized</u> project culture
Communication	▪<u>Diverse</u> organizational objectives	▪<u>Converging</u> organizational objectives	▪<u>Common shared</u> organizational objectives	▪Clear roles & responsibilities	▪<u>High</u> stakeholder <u>trust</u> level

Personnel/team capability

Basic intellectual capability of a Systems Engineer (compared to the national pool of SEs) to analyze complex problems and synthesize solutions.

Very Low	Low	Nominal	High	Very High
15^{th} percentile	35^{th} percentile	55^{th} percentile	75^{th} percentile	90^{th} percentile

Personnel experience/continuity

The applicability and consistency of the staff at the initial stage of the project with respect to the domain, customer, user, technology, tools, etc.

	Very low	Low	Nominal	High	Very High
Experience	Less than 2 months	1 year continuous experience, other technical experience in similar job	3 years of continuous experience	5 years of continuous experience	10 years of continuous experience
Annual Turnover	**48%**	**24%**	**12%**	**6%**	**3%**

Process capability

The consistency and effectiveness of the project team at performing SE processes. This may be based on assessment ratings from a published process model (e.g., CMMI, EIA-731, SE-CMM, ISO/IEC15504). It can also be based on project team behavioral characteristics, if no assessment has been performed.

	Very low	Low	Nominal	High	Very High	Extra High
Assessment Rating (Capability or Maturity)	Level 0 (if continuous model)	Level 1	Level 2	Level 3	Level 4	Level 5
Project Team Behavioral Characteristics	Ad Hoc approach to process performance	Performed SE process, activities driven only by immediate contractual or customer requirements, SE focus limited	Managed SE process, activities driven by customer and stakeholder needs in a suitable manner, SE focus is requirements through design, project-centric approach – not driven by organizational processes	Defined SE process, activities driven by benefit to project, SE focus is through operation, process approach driven by organizational processes tailored for the project	Quantitatively Managed SE process, activities driven by SE benefit, SE focus on all phases of the life cycle	Optimizing SE process, continuous improvement, activities driven by system engineering and organizational benefit, SE focus is product life cycle & strategic applications

Multisite coordination

Location of stakeholders, team members, resources, corporate collaboration barriers.

Viewpoint	Very low	Low	Nominal	High	Very High	Extra High
Collocation	International, severe time zone impact	Multi-city and multi-national, considerable time zone impact	Multi-city or multi-company, some time zone effects	Same city or metro area	Same building or complex, some co-located stakeholders or onsite representation	Fully co-located stakeholders
Communications	Some phone, mail	Individual phone, FAX	Narrowband e-mail	Wideband electronic communication	Wideband electronic communication, occasional video conference	Interactive multimedia
Corporate collaboration barriers	Severe export and security restrictions	Mild export and security restrictions	Some contractual & Intellectual property constraints	Some collaborative tools & processes in place to facilitate or overcome, mitigate barriers	Widely used and accepted collaborative tools & processes in place to facilitate or overcome, mitigate barriers	Virtual team environment fully supported by interactive, collaborative tools environment

Tool support

Coverage, integration, and maturity of the tools in the Systems Engineering environment.

Very low	Low	Nominal	High	Very High
No SE tools	Simple SE tools, little integration	Basic SE tools moderately integrated throughout the systems engineering process	Strong, mature SE tools, moderately integrated with other disciplines	Strong, mature proactive use of SE tools integrated with process, model-based SE and management systems

Burning Issues

HOT!

1. **Sizing**
   - what are the right levels to count REQS, I/F, SCEN?

BURN!

2. **Data for calibration**
   - Need at least 30 project data points
3. **Model unification**
   - With CII, COSOSIMO, et al
4. **SE activities from EIA/ANSI 632**
   - Which of the 33 requirements do we want to include in COSYSMO?

OUCH!

5. **Lifecycle extensions**

Sizing: Problem Statement

- We need to formulate specific counting rules for the size drivers in COSYSMO
- This involves:
  - Developing specific descriptions of the desired level for counting requirements, interfaces, scenarios (what level is too high? just right? too low?)

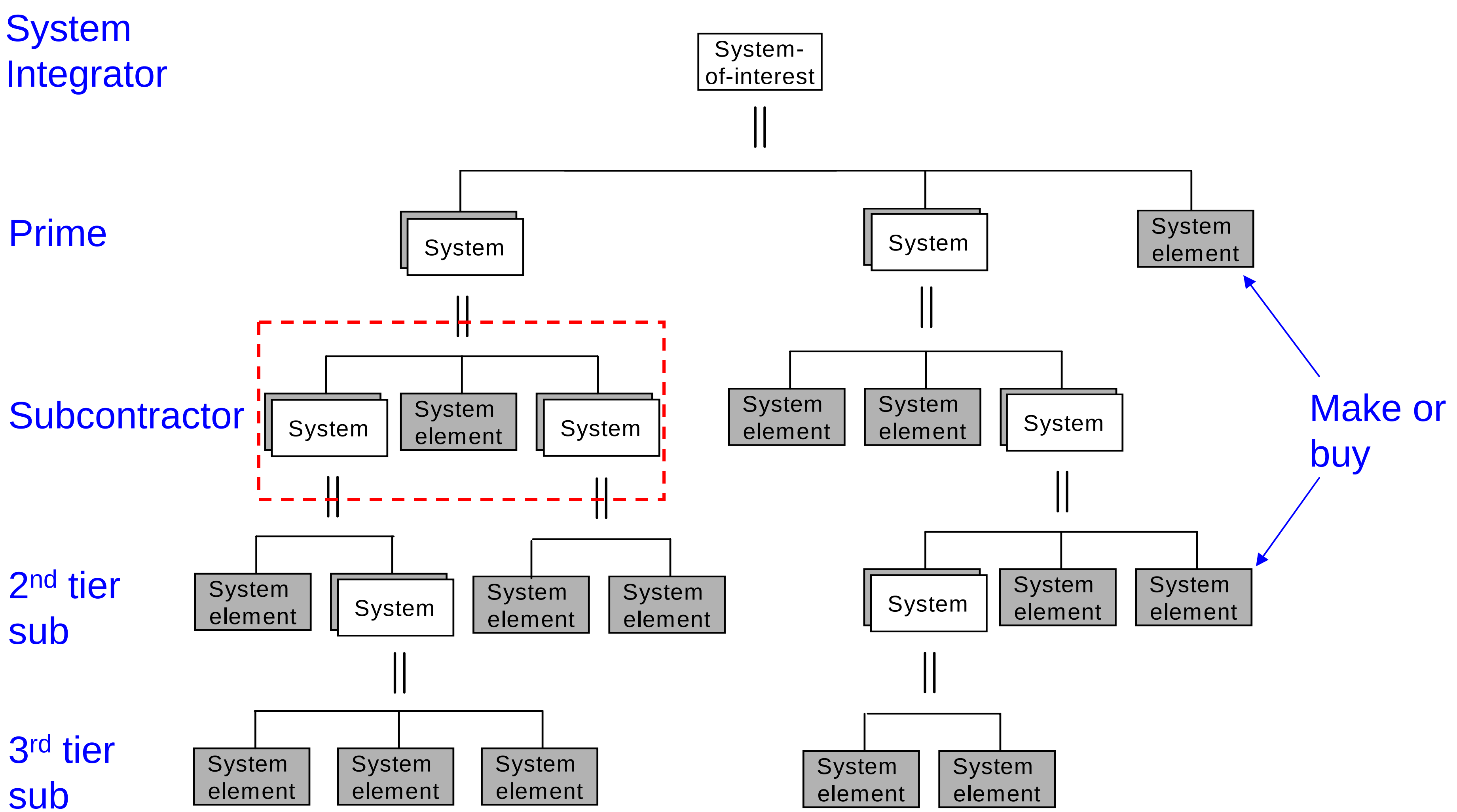
Proposed Approach

1. Determine the system of interest.
2. Decompose system objectives, capabilities, or measures of effectiveness into requirements that can be verified or designed.
3. Provide a graphical or narrative representation of the system of interest and how it relates to the rest of the system (if applicable).
4. Count the number of requirements in the system or marketing specification for the highest level of design in the desired system of interest. Make sure that all counted requirements are at the same design or bid level. Do not count the lower level requirements.

OR

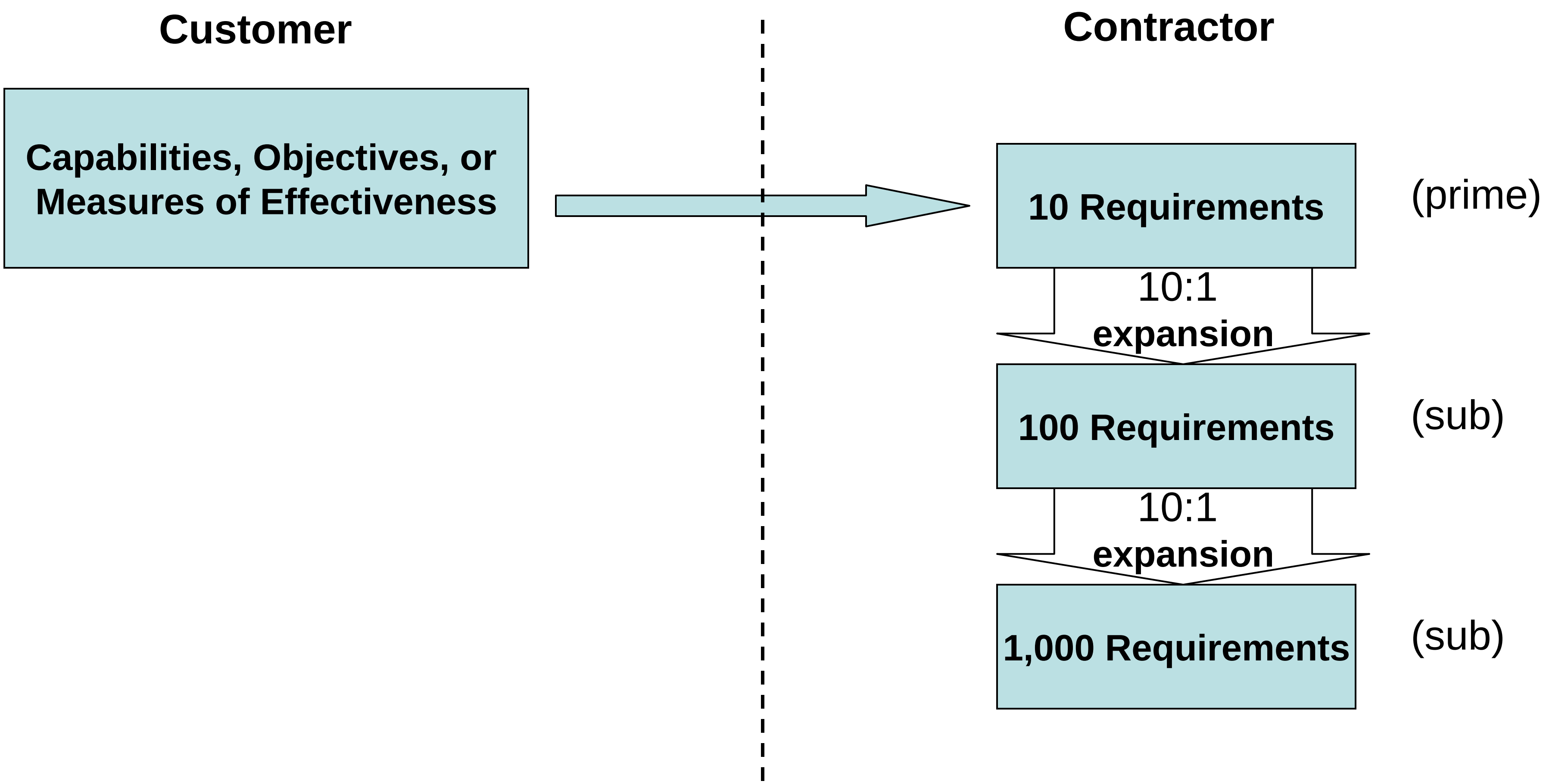
4. Count the number of requirements in your verification trace matrix for the highest level of design in the desired system of interest. Make sure that all counted requirements are at the same design or bid level. Do not count the lower level requirements.
5. Determine how many requirements are easy, nominal, or difficult.

Point #1: ISO/IEC 15288 System of Interest Structure



Source: ISO/IEC 15288.

Point #2: Decompose customer inputs into requirements



ERAM Example: Requirements

Customer specified requirement types:

The “Core” requirements are the minimum functional capabilities and performance required for acceptable operational suitability and effectiveness.

The “Extensible” requirements are the goals in functional capabilities and performance that the FAA desires to achieve in the future

Core Requirement example from the system specification:

	3	Requirements
	3.2	Functional Capabilities
	3.2.1	En Route – General
Too high?	3.2.1.0-16	The system **shall** check input messages to ensure message completeness and coherency
Just right?	3.2.1.0-16.0-1	The system **shall** provide format, logic, and validity checks for incoming data.
Too low?	3.2.1.0-16.1.0-1	???

Source: ERAM System Specification pp. 1-11

ERAM Example: Interfaces

3	Requirements
3.3	Integration Requirements
3.3.2	Interface Requirements
3.3.2.1	General
3.3.2.1.0-1	The system **shall** interface with the systems identified in Figure 3.3-1
3.3.2.1.0-1.0-1	See Figure 3.3-1 which contains 12 unidirectional interfaces and 14 bidirectional interfaces
3.3.2.1.0-1.0-1.0	???

Source: ERAM System Specification pp. 156-157

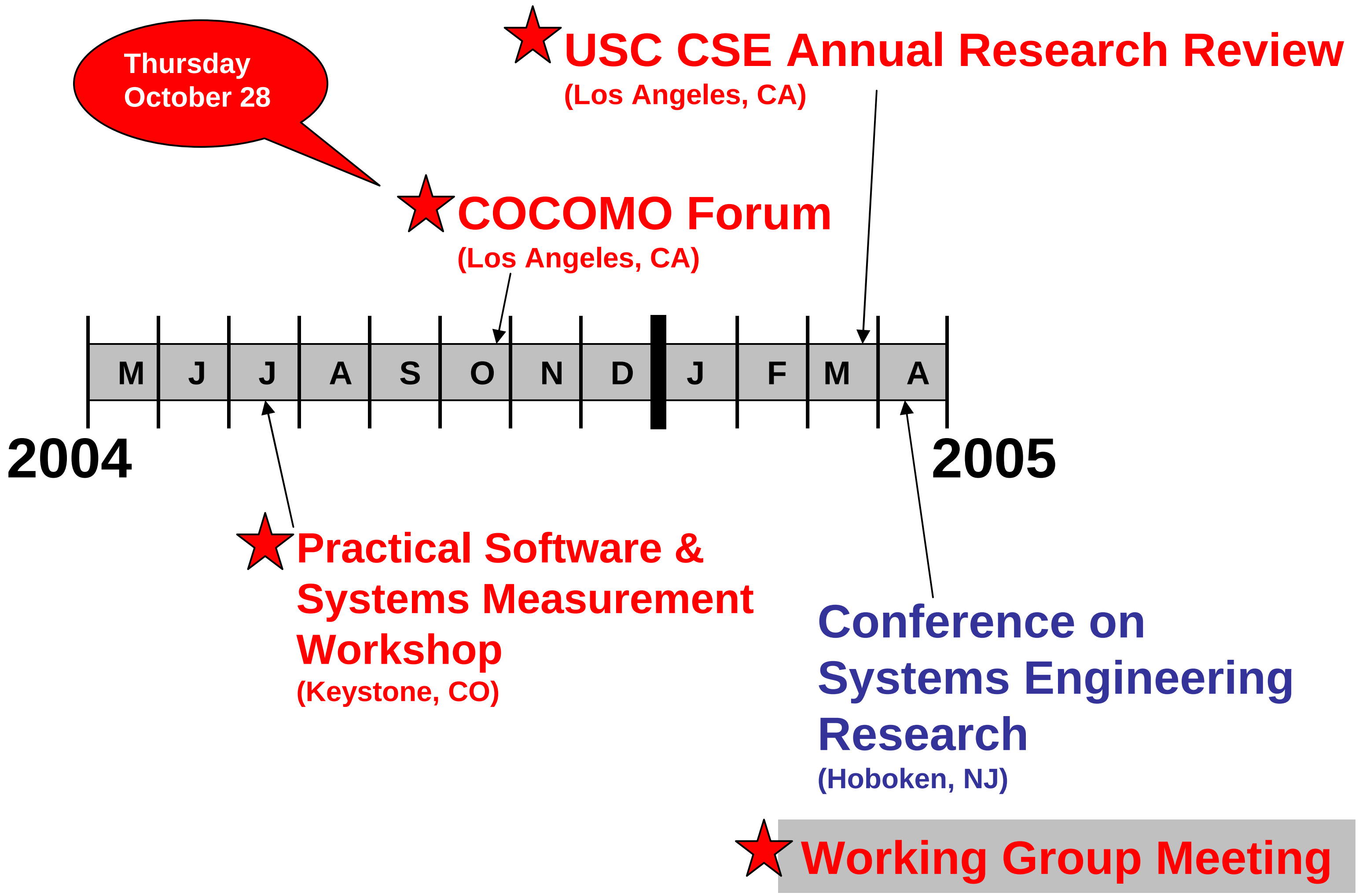
How is Systems Engineering Defined?

What is included from EIA/ANSI 632 "Processes for Engineering a System"?

- **Acquisition and Supply**
  - Supply Process
  - Acquisition Process
- **Technical Management**
  - Planning Process
  - Assessment Process
  - Control Process
- **System Design**
  - Requirements Definition Process
  - Solution Definition Process
- **Product Realization**
  - Implementation Process
  - Transition to Use Process
- **Technical Evaluation**
  - Systems Analysis Process
  - Requirements Validation Process
  - System Verification Process
  - End Products Validation Process

See worksheet "COSYSMO SCOPE – EIA632"
in *myCOSYSMO* tool

Calendar of Activities: 2004/05



Workshop Agenda

Day 1 (1:45 PM – 5:30 PM 7/28)

- **Short COSYSMO tutorial (Valerdi)**
- **Develop size measurement constructs (Miller)**
- **Burning Issues (Valerdi/Miller)**
- **COSYSMO Delphi exercise (Valerdi)**

Day 2 (8:30 AM – 5:15 PM 7/29)

- ***myCOSYSMO* Tool demo (Thomas)**
- ***myCOSYSMO* case study #1 (Thomas)**
- ***myCOSYSMO* case study #2 (Thomas)**
- **COSOSIMO Delphi exercise (Lane)**

Questions or Comments?

Dr. Barry Boehm

boehm@sunset.usc.edu

Ricardo Valerdi

rvalerdi@sunset.usc.edu

Websites

http://sunset.usc.edu

http://valerdi.com/cosysmo