Development of COSYSMO 3.0: An Extended, Unified Cost Estimating Model for Systems Engineering

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Agenda

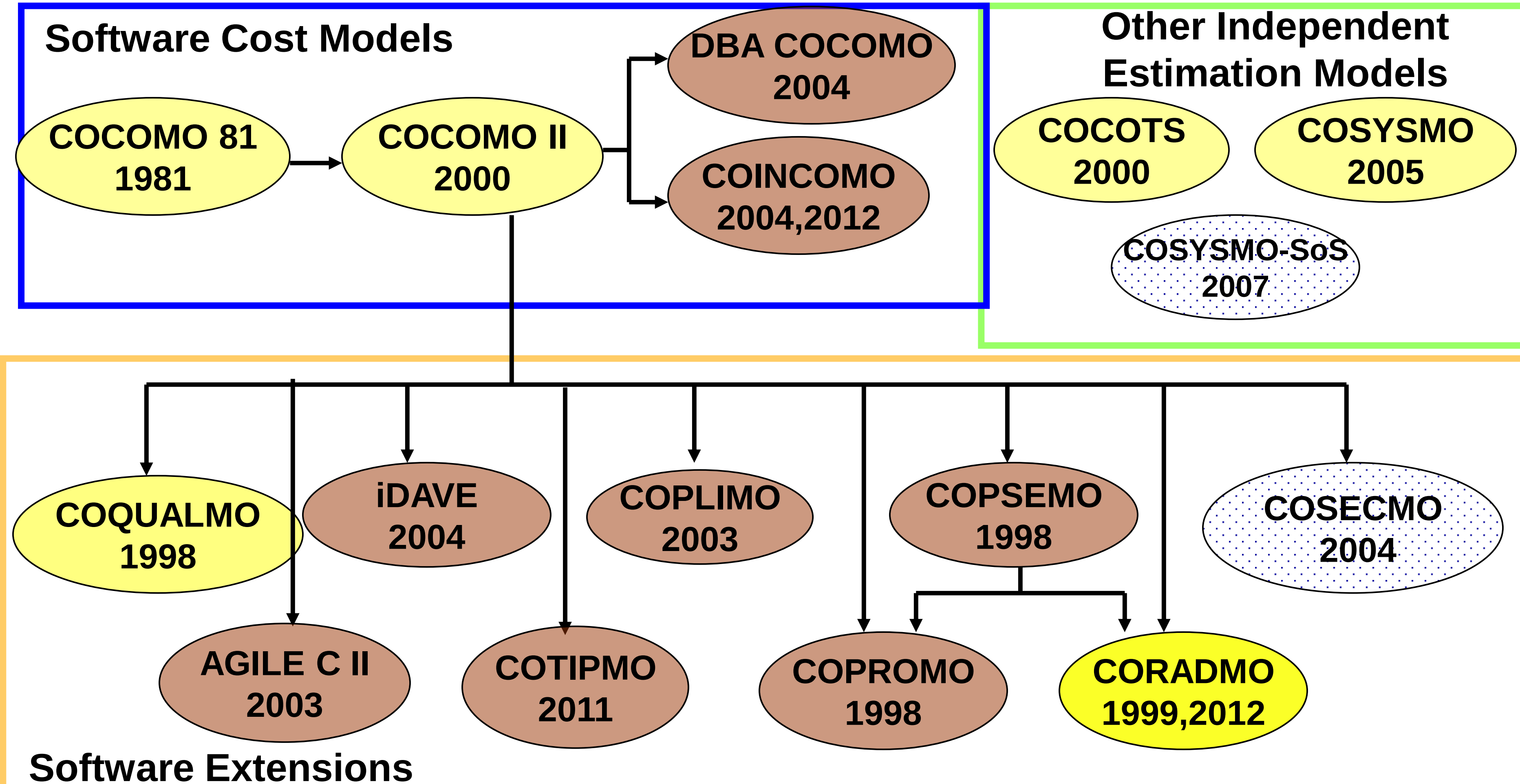
Agenda:

- **Preliminaries: motivation, history, research hypothesis, & methodology**
- **The priors; the COSYSMO 3.0 formula**
- **Closing: Developing the Final Model; future research**
- **Appendices: Bibliography; backup slides**

COSYSMO 3.0 Motivation

- **Context:**
  - Current and future trends create challenges for full-system cost estimation
    - Emergent requirements, rapid change, net-centric systems of systems, COTS, clouds, apps, widgets, high assurance with agility, multi-mission systems
  - Current development practices can minimize cost of one phase, such as development, while raising full-system cost
- **COSYSMO 3.0 is being developed to mitigate this situation by supporting accurate estimates of systems engineering costs, with benefits including:**
  - Allowing thoughtful system-level systems engineering during development, which can result in, for example, choosing new technologies that reduce total system cost
  - Allowing thoughtful engineering of systems to support life-cycle flexibility

COCOMO Family of Cost Models



Legend:
Model has been calibrated with historical project data and expert (Delphi) data
Model is derived from COCOMO II
Model has been calibrated with expert (Delphi) data

Dates indicate the time that the first paper was published for the model

History of COSYSMO Models

COSYSMO 1.0
Valerdi, 2005

- Identifies form of model
- Identifies basic cost drivers
- Identifies Size measure

With Reuse
Wang et al, 2008

- Adds weights to Size elements, reducing net Size in the presence of reuse

Req'ts Volatile
Pena, 2012

- Adds scale factor based on requirements volatility

For Reuse
Wang et al, 2014

- Adds weights to Size elements, reducing net Size when artifacts are only partially completed

Sys of Sys
Lane et al, 2011

- Allocates SE effort to SoS and constituent systems. Adds effort multiplier when in the presence of system-of-systems.

COSYSMO 3.0
Alstad, 2018

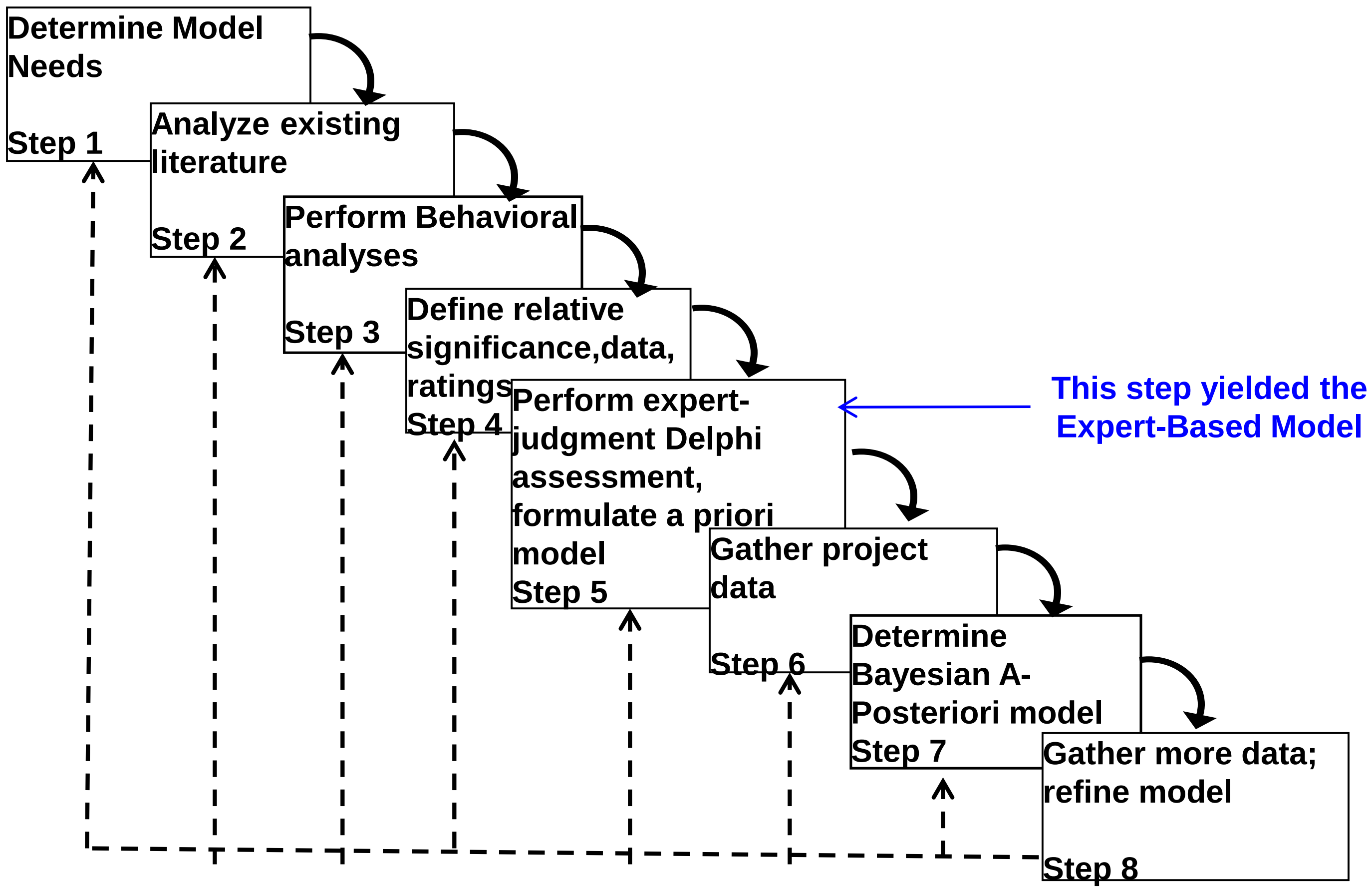
- Integrates features of previous models

Research Hypothesis

- It is possible to develop a systems engineering cost estimating model ("COSYSMO 3.0") with these properties:
  - Is applicable to a wide range of systems engineering projects;
  - Includes all the major features of COSYSMO 1.0 and its extension models, except for interoperability;
  - Provides continuity to users of previous COSYSMO-family models;
  - When calibrated to data from a particular organization, estimates actual systems engineering costs with a PRED(.30) accuracy of 50%.

USC-CSSE Modeling Methodology

Figure 4.1 from [22]



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Developing the Prior Model

I led COSYSMO 3.0 Wideband Delphi workshops at 4 conferences over the period August 2015-March 2016

- **Purpose: To develop consensus expert opinion on the numerical value of COSYSMO 3.0 parameters**
- **Delphi = anonymous voting; Wideband = group discussion**
- **Protocol for a parameter:**
  - I state a starting value for a parameter
  - Each expert fills in a paper ballot with a recommended value
  - I collect ballots & announce average value
  - I lead a discussion; if there is not consensus, another round of voting is held
- **Resulted in 26 expert ballots**
  - Experts represented 21 organizations
  - With 19.6 average years of SysEng experience
- **Result was "Expert-Based COSYSMO 3.0"**

COSYSMO 3.0
Top-Level Model

$$PH = A \times (AdjSize)^{E} \times \prod_{j=1}^{13} EM_j$$

Elements of the COSYSMO 3.0 model:

- **Calibration parameter A**
- **Adjusted Size model**
  - **eReq submodel, where 4 products contribute to size**
  - **Reuse submodel**
- **Exponent (E) model**
  - **Accounts for diseconomy of scale**
  - **Constant and 3 scale factors**
- **Effort multipliers EM**
  - **13 cost drivers**

COSYSMO 3.0 Size Model

$$AdjSize_{C3} = \sum_{SizeDrivers} eReq(Type(SD), Difficulty(SD)) \times PartialDevFactor(AL_{Start}(SD), AL_{End}(SD), RType(SD))$$

- ***SizeDriver*** **is one of the system engineering products that determines size in the COSYSMO family (per [2]). Any product of these types is included:**
  - **System requirement**
  - **System interface**
  - **System algorithm**
  - **Operational scenario**
- **There are two submodels:**
  - **Equivalent nominal requirements (“eReq”)**
    - **Raw size**
  - **Partial development**
    - **Adjusts size for reuse**

Size Model – eReq Submodel

- **The eReq submodel is unchanged from [2].**
- **The submodel computes the size of a *SizeDriver*, in units of eReq ("equivalent nominal requirements")**
- **Each *SizeDriver* is evaluated as being easy, nominal, or difficult.**
- **The following table contains conversion factors for the conversion of a *SizeDriver* to a number of eReq:**

Size Driver Type	Easy	Nominal	Difficult
System Requirement	0.5	1.0	4.5
System Interface	1.9	4.0	9.0
System Algorithm	1.9	3.8	9.8
Operational Scenario	6.4	13.6	26.3

How Reuse Is Addressed

Reuse operates in two directions [1]:

- **Development with reuse (DWR): previously developed artifacts are reused on the current project**
  - **Addressed completely by the DWR partial development model**
- **Development for reuse (DFR): the current project is creating artifacts to be reused on other projects**
  - **One aspect of DFR development is that DFR costs more than ordinary development**
    - **Addressed by the DFR cost driver (covered there)**
  - **Another aspect of DFR is that the artifacts may be only partially completed, as during an IR&D project**
    - **Addressed by the DFR partial development model**

Size Model – Partial Development Submodel

- **(Concepts here are simplified a little)**
- **The basic DWR concept:**
  - **If a reused *SizeDriver* is being brought in, that saves effort, and so we adjust the size by multiplying the raw size by a *PartialDevFactor* less than 1.**
  - **The value of *PartialDevFactor* is based on the maturity of the reused *SizeDriver*, and is looked up in a table [24].**
    - **How fully developed was the *SizeDriver*?**
  - **If there is no reuse for this *SizeDriver*, then *PartialDevFactor* = 1 (no adjustment).**

DWR Activity Level:	New	Design Modified	Design Im-plemented	Adapted for Integration	Adopted for Integration	Managed
DWR % for this AL through end	100.00%	83.00%	70.13%	56.88%	37.82%	17.50%

- **The basic development-for-reuse (DFR) concept is analogous:**
  - **A product to be reused may be not be taken through the full development cycle (e.g., an IR&D project)**

DFR Activity Level:	Conceptualized for Reuse	N/A	Designed for Reuse	Constructed for Reuse	N/A	Validated for Reuse
DFR % from start through this AL	31.96%		54.60%	78.06%		90.69%

COSYSMO 3.0
Exponent Model

- **Exponent model is expanded from Peña [4, 9]**

$$E = E_{Base} + SF_{ROR} + SF_{PC} + SF_{RV}$$

Where:

- **E_{Base} = A minimum exponent for diseconomy of scale**
- **SF = scale factor**
- ***ROR* = Risk/Opportunity Resolution**
- ***PC* = Process Capability**
- ***RV* = Requirements Volatility**

The effect of a large exponent is more pronounced on bigger projects

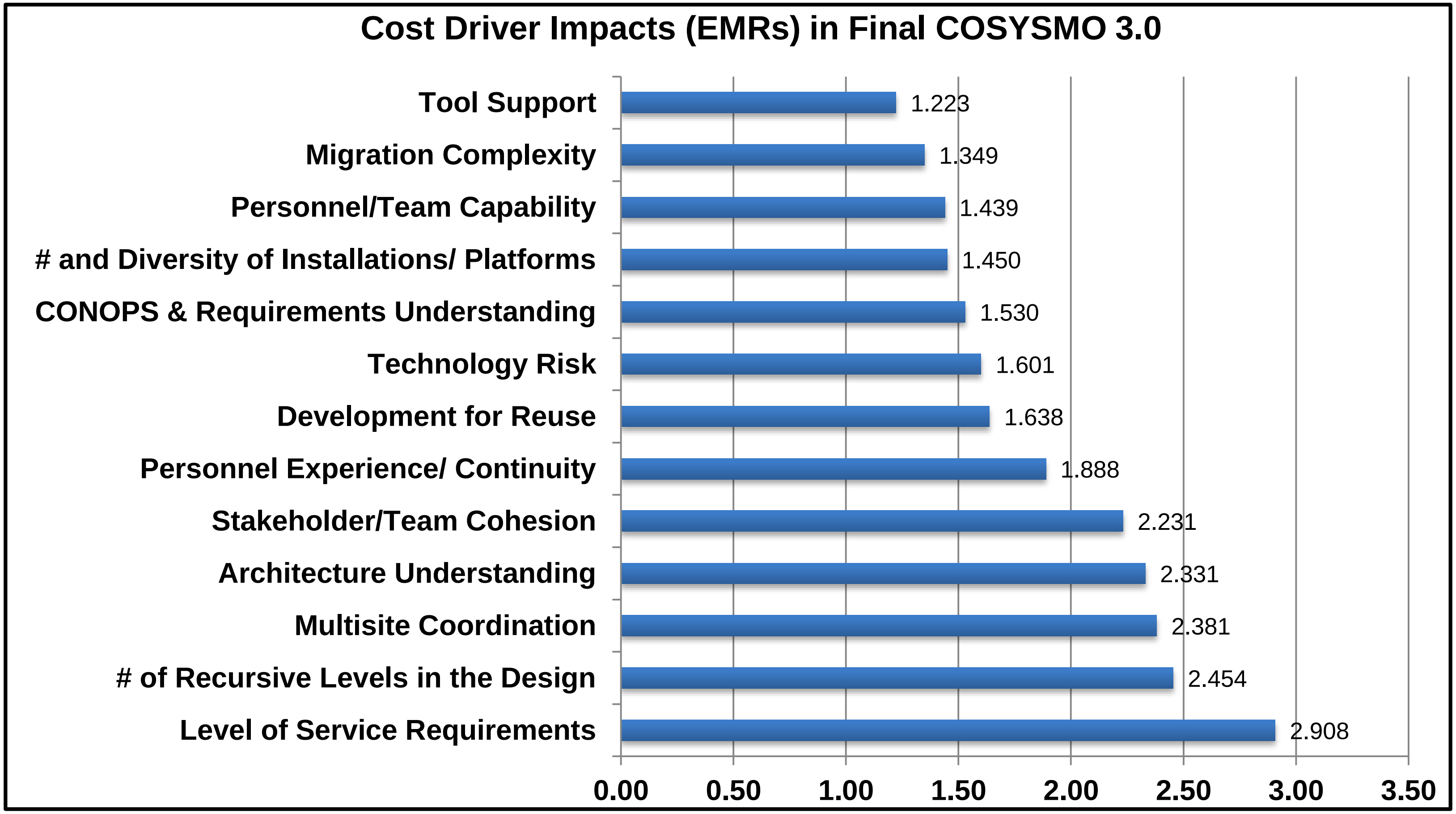
Cost Drivers

- **Here are the 13 COSYSMO 3.0 cost drivers:**

	Driver Name	Data Item
UNDR	CONOPS & requirements understanding	Subjective assessment of the CONOPS & the system requirements
UNDR	Architecture understanding	Subjective assessment of the system architecture
UNDR	Stakeholder team cohesion	Subjective assessment of all stakeholders
CMPX	Level of service requirements	Subjective difficulty of satisfying the key performance parameters
CMPX	Technology risk	Maturity, readiness, and obsolescence of technology
CMPX	# of Recursive levels in the design	Number of applicable levels of the Work Breakdown Structure
CMPX	Development for reuse	Is this project developing artifacts for later reuse?
OPRN	# and Diversity of installations/platforms	Sites, installations, operating environment, and diverse platforms
OPRN	Migration complexity	Influence of legacy system (if applicable)
PERS	Personnel/team capability	Subjective assessment of the team's intellectual capability
PERS	Personnel experience/continuity	Subjective assessment of staff consistency
ENVR	Multisite coordination	Location of stakeholders and coordination barriers
ENVR	Tool support	Subjective assessment of SE tools

- **Relative to COSYSMO 1.0 cost drivers, this model:**
  - **Drops Documentation**
  - **Adds Development for Reuse**
  - **Changes Process Capability to scale factor**

Cost Driver Impacts



The EMR (Effort Multiplier Ratio) of a cost driver is its maximum possible value divided by its minimum possible value; this is the impact of the cost driver.

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Development of the Final Model

- I obtained a dataset of about 40 projects from an aerospace company
  - I fit a model to that via linear regression, using the Delphi results as Bayesian priors
    - Had to drop the planned Interoperabilty cost driver, due to not being addressed in the dataset
  - Also used recommendation to reduce impact of cost drivers as a Bayesian prior [11]
  - The result is the Final Model of COSYSMO 3.0
- Calibrating the model to the dataset and achieving PRED(.30) >= 50% took some imagination
  - A simple-minded fit resulted in either:
    - Some non-credible parameter values; or
    - PRED(.30) < 50%.
  - I was able to calibrate by:
    - Dropping a few outliers; and
    - Using a hill-climbing algorithm to find suitable parameter values.

Future Of COSYSMO 3.0

- Hope that existence of the model improves practice of systems engineering
  - Model is open—parameter values & definitions, estimating spreadsheet, etc are publically available
  - Model captures more project attributes than previous models
  - Easy to retrofit a database of existing projects
  - Hope that model enables production of a systems engineering cost estimate as standard practice
    - Developers, acquirers
- Future research topix:
  - Create a validated model for interoperability
    - Existing COSYSMO 3.0 work provides an excellent foundation
  - Create tailored models for different types of project
    - “Tailored” = some driver values are pre-filled in
    - Defense, software-intensive, ...
  - Estimating model for total development cost, based primarily on COSYSMO 3.0 drivers
    - Some work already done at Lockheed-Martin
  - Better integrate activity levels between DWR and DFR
  - Strengthen validation via additional datasets
    - 2nd dataset has PRED(.30) = 84%

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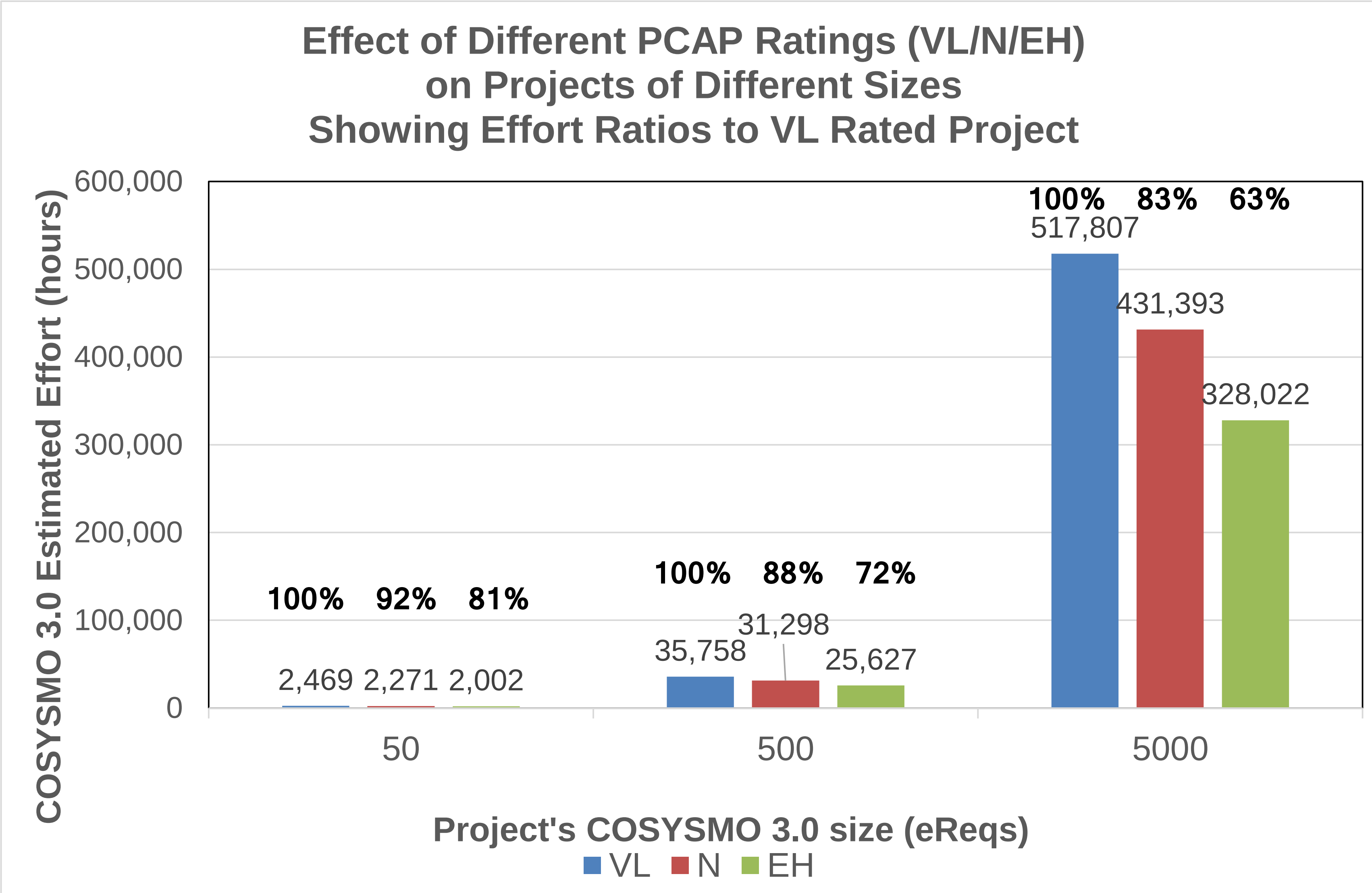
Backup Slides

- Impact of PCAP in COSYSMO 3.0
- Example parameter definition
- Numerical parameters of the Final Model
- Placing Process Capability: cost driver or scale factor?
- Continuity and the Rosetta Stone
- Coordination with COCOMO III


Effect of Different PCAP Ratings (VL/N/EH)
on Projects of Different Sizes
Showing Effort Ratios to VL Rated Project
COSYSMO 3.0 Estimated Effort (hours)
600,000
500,000
400,000
300,000
200,000
100,000
0
100% 92% 81%
2,469 2,271 2,002
100% 88% 72%
35,758 31,298 25,627
100% 83% 63%
517,807
431,393
328,022
50
500
5000
Project's COSYSMO 3.0 size (eReqs)
VL N EH

Example Cost Driver: Dev. For Reuse

Definition

- **Text definition: Is the project (or subproject) developing artifacts to be reused on later project(s)? ("Development for Reuse", or "DFR".) If so, what is the extent of the planned reuse?**
- **Rating scale:**

Low	Nominal	High	Very High	Extra High
No reuse at all.	Artifacts will be reused only on the current project.	Artifacts will be reused across the program.	Artifacts will be reused across a product line.	Artifacts will be reused across multiple product lines.

Cost Driver and Scale Factor Ratings

	Text Rating:	Very Low	Low	Nominal	High	Very High	Extra High
	Numeric Rating:	-2.0	-1.0	0.0	1.0	2.0	3.0
Cost Driver	**Step Size**	**Effort Multipliers**					
CONOPS & Requirements Understanding	0.765	1.71	1.31	1.00	0.76	0.59	(Invalid)
Architecture Understanding	0.805	1.54	1.24	1.00	0.81	0.65	(Invalid)
Stakeholder Team Cohesion	0.802	1.55	1.25	1.00	0.80	0.64	(Invalid)
Level of Service Requirements	1.277	0.61	0.78	1.00	1.28	1.63	(Invalid)
Technology Risk	1.262	0.63	0.79	1.00	1.26	1.59	(Invalid)
# of Recursive Levels in the Design	1.179	0.72	0.85	1.00	1.18	1.39	(Invalid)
# and Diversity of Installations/ Platforms	1.238	(Invalid)	(Invalid)	1.00	1.24	1.53	1.90
Migration Complexity	1.252	(Invalid)	(Invalid)	1.00	1.25	1.57	1.96
Personnel/Team Capability	0.831	1.45	1.20	1.00	0.83	0.69	(Invalid)
Personnel Experience/ Continuity	0.858	1.36	1.17	1.00	0.86	0.74	(Invalid)
Multisite Coordination	0.812	1.52	1.23	1.00	0.81	0.66	0.54
Tool Support	0.892	1.26	1.12	1.00	0.89	0.80	(Invalid)
Scale Factor	**Step Size**	**Scale Factor Values**					
Risk & Opportunity Management	-0.0120	0.0602	0.0482	0.0361	0.0241	0.0120	0.0000
Process Capability	-0.0107	0.0536	0.0429	0.0322	0.0214	0.0107	0.0000
Requirements Volatility	0.0095	0.0000	0.0095	0.0189	0.0284	0.0379	(Invalid)

COSYSMO 3.0 Final Model Constants

A	Productivity Factor	26.33
EBase	Exponent Base	1.0332

Placement of Process Capability (1/2)

- Process Capability (PROC) was a cost driver in COSYSMO 1.0, but there were arguments that it should be a scale factor instead
- With an earlier version of the model, I generated this table:

	PROC as CD	PROC as SF
Cost Driver Fit		
Standard Error of Residuals	0.4829	0.4994
R squared	0.9890	0.9882
F-statistic	570.80	571.20
Scale Factor Fit		
Standard Error of Residuals	0.3985	0.1930
R squared	0.9911	0.9979
F-statistic	3946	11280

- One argument in favor of "scale factor" is that its cost driver fit is only slightly worse, but its scale factor fit is much better

Placement of Process Capability (2/2)

- **A second argument is that members of the Working Group have the intuition that "scale factor" is likely correct, as a poor process would have a proportionally greater impact on a larger project**
- **A third argument is that "scale factor" would agree with its placement in COCOMO II (and, apparently, COCOMO III)**

Definition Modifications & the Rosetta Stone

- **Users of previous versions of COSYSMO want to carry forward as much of their estimation database as possible ("continuity"). So support is provided via a Rosetta Stone document which provides instructions on how to re-rate existing drivers under COSYSMO 3.0.**

Degree of Definition Change	Rosetta Stone Instruction for How To Change Old Rating
No change	"No change"
Moderate change	"No change"
Substantial change	"Decrement old rating by x steps"

Excerpts from the Rosetta Stone

Element Type Key:
CD = Cost Driver
SF = Scale Factor
Color (Degree of Change) Key:

No Change in Definition	No Change in Rating	Rating Change	New or Deleted

Element from COSYSMO 1.0 (or other model as shown)	COSYSMO 3.0 Element	Instructions for 3.0 Rating	Justification (for Working Group members)
CD: Requirements Understanding	CD: CONOPS and Requirements Understanding	Same rating.	1.0 CD is now a viewpoint in a larger 3.0 CD; the 1.0 rating should be carried forward in that context, without any mis-rating.
CD: Documentation Match to Life Cycle Needs	Dropped		
CD: # and Diversity of Installations/Platforms	(same)	Same rating.	Same definition.
CD: Personnel/Team Capability	(same)	Same rating.	Minor text definition improvement should allow the 1.0 rating to carry forward to a 3.0 rating.
CD: Process Capability	(same)	Same rating.	Same definition.
CD: Personnel Experience/Continuity	(same)	Decrement old rating by half a level.	One of two viewpoints has been "shifted up" one level; e.g., 3 years' experience was Nominal, but in 3.0 it's Low.
CD: Multisite Coordination	(same)	Same rating.	Same definition.
CD: Tool Support	(same)	Decrement old rating by a level.	The rating scale has been "shifted up" one level; e.g., "Strong, mature tools" was rated High, but in 3.0 it's Nominal. In addition, the topic of life cycle coverage was added to the rating scale. Decrementation by a level should not result in a significant mis-rating.

Coordination with COCOMO III (1/2)

The Final Model has been coordinated with Brad Clark's in-progress COCOMO III definition effort, with these results:

- **Essentially identical definitions of Risk/Opportunity Management scale factor.**
- **Essentially identical definitions of Multi-Site Development cost driver.**
- **COSYSMO 3.0 Development for Reuse cost driver taken from COCOMO II.**
- **COSYSMO 3.0 Personnel/Team Capability cost driver definition modified to agree with COCOMO II's.**

Coordination with COCOMO III (2/2)

- **A 2012 paper* was published distinguishing the scopes of COCOMO and COSYSMO in a project; Brad and the COSYSMO 3.0 Working Group coordinated on an (unpublished) update (”COCOMO – COSYSMO Estimation Boundaries")**

***Wang, G., Valerdi, R., Roedler, G., Ankrum, A., Gaffney, J. E., “Harmonizing Systems and Software Cost Estimation,” International Journal of Computer Integrated Manufacturing, Volume 25, 2012 - Issue 4-5: Special Issue: Through Life Cost Estimating.**