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

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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
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]

Step 1: Determine Model Needs

Step 2: Analyze existing literature

Step 3: Perform Behavioral analyses

Step 4: Define relative significance, data, ratings

Step 5: Perform expert-judgment Delphi assessment, formulate a priori model

Step 6: Gather project data

Step 7: Determine Bayesian A-Posteriori model

Step 8: Gather more data; refine model

This step yielded the Expert-Based Model
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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

\[ PH = A \cdot (AdjSize)^E \cdot \prod_{j=1}^{15} EM_j \]

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

\[
\text{AdjSize}_{C3} = \sum_{\text{SizeDrivers}} e\text{Req}(\text{Type}(SD), \text{Difficulty}(SD)) \times \text{PartialDevFactor}(AL_{\text{Start}}(SD), AL_{\text{End}}(SD), R\text{Type}(SD))
\]

- **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:

<table>
<thead>
<tr>
<th>Size Driver Type</th>
<th>Easy</th>
<th>Nominal</th>
<th>Difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Requirement</td>
<td>0.5</td>
<td>1.0</td>
<td>4.5</td>
</tr>
<tr>
<td>System Interface</td>
<td>1.9</td>
<td>4.0</td>
<td>9.0</td>
</tr>
<tr>
<td>System Algorithm</td>
<td>1.9</td>
<td>3.8</td>
<td>9.8</td>
</tr>
<tr>
<td>Operational Scenario</td>
<td>6.4</td>
<td>13.6</td>
<td>26.3</td>
</tr>
</tbody>
</table>
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).

<table>
<thead>
<tr>
<th>DWR Activity Level:</th>
<th>New</th>
<th>Design Modified</th>
<th>Design Implemented</th>
<th>Adapted for Integration</th>
<th>Adopted for Integration</th>
<th>Managed</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWR % for this AL through end</td>
<td>100.00%</td>
<td>83.00%</td>
<td>70.13%</td>
<td>56.88%</td>
<td>37.82%</td>
<td>17.50%</td>
</tr>
</tbody>
</table>

• 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)

<table>
<thead>
<tr>
<th>DFR Activity Level:</th>
<th>Conceptualized for Reuse</th>
<th>N/A</th>
<th>Designed for Reuse</th>
<th>Constructed for Reuse</th>
<th>N/A</th>
<th>Validated for Reuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFR % from start through this AL</td>
<td>31.96%</td>
<td>54.60%</td>
<td>78.06%</td>
<td>90.69%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Exponent Model

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

\[ E = E_{\text{Base}} + SF_{ROR} + SF_{PC} + SF_{RV} \]

Where:
- \( E_{\text{Base}} \) = 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
Here are the 13 cost drivers:

<table>
<thead>
<tr>
<th>Driver Name</th>
<th>Data Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONOPS &amp; requirements understanding</td>
<td>Subjective assessment of the CONOPS &amp; the system requirements</td>
</tr>
<tr>
<td>Architecture understanding</td>
<td>Subjective assessment of the system architecture</td>
</tr>
<tr>
<td>Stakeholder team cohesion</td>
<td>Subjective assessment of all stakeholders</td>
</tr>
<tr>
<td>Level of service requirements</td>
<td>Subjective difficulty of satisfying the key performance parameters</td>
</tr>
<tr>
<td>Technology risk</td>
<td>Maturity, readiness, and obsolescence of technology</td>
</tr>
<tr>
<td># of Recursive levels in the design</td>
<td>Number of applicable levels of the Work Breakdown Structure</td>
</tr>
<tr>
<td>Development for reuse</td>
<td>Is this project developing artifacts for later reuse?</td>
</tr>
<tr>
<td># and Diversity of installations/platforms</td>
<td>Sites, installations, operating environment, and diverse platforms</td>
</tr>
<tr>
<td>Migration complexity</td>
<td>Influence of legacy system (if applicable)</td>
</tr>
<tr>
<td>Personnel/team capability</td>
<td>Subjective assessment of the team’s intellectual capability</td>
</tr>
<tr>
<td>Personnel experience/continuity</td>
<td>Subjective assessment of staff consistency</td>
</tr>
<tr>
<td>Multisite coordination</td>
<td>Location of stakeholders and coordination barriers</td>
</tr>
<tr>
<td>Tool support</td>
<td>Subjective assessment of SE tools</td>
</tr>
</tbody>
</table>
Cost Driver Impacts (EMRs) in Final COSYSMO 3.0

<table>
<thead>
<tr>
<th>Cost Driver</th>
<th>EMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Support</td>
<td>1.223</td>
</tr>
<tr>
<td>Migration Complexity</td>
<td>1.349</td>
</tr>
<tr>
<td>Personnel/Team Capability</td>
<td>1.439</td>
</tr>
<tr>
<td># and Diversity of Installations/ Platforms</td>
<td>1.450</td>
</tr>
<tr>
<td>CONOPS &amp; Requirements Understanding</td>
<td>1.530</td>
</tr>
<tr>
<td>Technology Risk</td>
<td>1.601</td>
</tr>
<tr>
<td>Development for Reuse</td>
<td>1.638</td>
</tr>
<tr>
<td>Personnel Experience/ Continuity</td>
<td>1.888</td>
</tr>
<tr>
<td>Stakeholder/Team Cohesion</td>
<td>2.231</td>
</tr>
<tr>
<td>Architecture Understanding</td>
<td>2.331</td>
</tr>
<tr>
<td>Multisite Coordination</td>
<td>2.381</td>
</tr>
<tr>
<td># of Recursive Levels in the Design</td>
<td>2.454</td>
</tr>
<tr>
<td>Level of Service Requirements</td>
<td>2.908</td>
</tr>
</tbody>
</table>

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 projects from an aerospace company
  – Fit a model to that, using the Delphi results as Bayesian priors
    • Had to drop the planned Interoperability cost driver, due to not being addressed in the dataset
  – 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 Research Topix

• 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
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Backup Slides

• 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
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:

<table>
<thead>
<tr>
<th>Low</th>
<th>Nominal</th>
<th>High</th>
<th>Very High</th>
<th>Extra High</th>
</tr>
</thead>
<tbody>
<tr>
<td>No reuse at all.</td>
<td>Artifacts will be reused only on the current project.</td>
<td>Artifacts will be reused across the program.</td>
<td>Artifacts will be reused across a product line.</td>
<td>Artifacts will be reused across multiple product lines.</td>
</tr>
</tbody>
</table>
### Cost Driver and Scale Factor Ratings

<table>
<thead>
<tr>
<th>Cost Driver</th>
<th>Step Size</th>
<th>Effort Multipliers</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CONOPS &amp; Requirements Understanding</td>
<td>0.765</td>
<td>1.71</td>
<td>1.31</td>
<td>1.00</td>
<td>0.76</td>
<td>0.59</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Architecture Understanding</td>
<td>0.805</td>
<td>1.54</td>
<td>1.24</td>
<td>1.00</td>
<td>0.81</td>
<td>0.65</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stakeholder Team Cohesion</td>
<td>0.802</td>
<td>1.55</td>
<td>1.25</td>
<td>1.00</td>
<td>0.80</td>
<td>0.64</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level of Service Requirements</td>
<td>1.277</td>
<td>0.61</td>
<td>0.78</td>
<td>1.00</td>
<td>1.28</td>
<td>1.63</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology Risk</td>
<td>1.262</td>
<td>0.63</td>
<td>0.79</td>
<td>1.00</td>
<td>1.26</td>
<td>1.59</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of Recursive Levels in the Design</td>
<td>1.179</td>
<td>0.72</td>
<td>0.85</td>
<td>1.00</td>
<td>1.18</td>
<td>1.39</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># and Diversity of Installations/Platforms</td>
<td>1.238</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Migration Complexity</td>
<td>1.252</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personnel/Team Capability</td>
<td>0.831</td>
<td>1.45</td>
<td>1.20</td>
<td>1.00</td>
<td>0.83</td>
<td>0.69</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personnel Experience/Continuity</td>
<td>0.858</td>
<td>1.36</td>
<td>1.17</td>
<td>1.00</td>
<td>0.86</td>
<td>0.74</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multisite Coordination</td>
<td>0.812</td>
<td>1.52</td>
<td>1.23</td>
<td>1.00</td>
<td>0.81</td>
<td>0.66</td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool Support</td>
<td>0.892</td>
<td>1.26</td>
<td>1.12</td>
<td>1.00</td>
<td>0.89</td>
<td>0.80</td>
<td>(Invalid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 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

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Productivity Factor</td>
<td>26.33</td>
</tr>
<tr>
<td>EBase</td>
<td>Exponent Base</td>
<td>1.0332</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th></th>
<th>PROC as CD</th>
<th>PROC as SF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost Driver Fit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Error of Residuals</td>
<td>0.4829</td>
<td>0.4994</td>
</tr>
<tr>
<td>R squared</td>
<td>0.9890</td>
<td>0.9882</td>
</tr>
<tr>
<td>F-statistic</td>
<td>570.80</td>
<td>571.20</td>
</tr>
<tr>
<td><strong>Scale Factor Fit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Error of Residuals</td>
<td>0.3985</td>
<td>0.1930</td>
</tr>
<tr>
<td>R squared</td>
<td>0.9911</td>
<td>0.9979</td>
</tr>
<tr>
<td>F-statistic</td>
<td>3946</td>
<td>11280</td>
</tr>
</tbody>
</table>

- 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.
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.

<table>
<thead>
<tr>
<th>Degree of Definition Change</th>
<th>Rosetta Stone Instruction for How To Change Old Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>No change</td>
<td>“No change”</td>
</tr>
<tr>
<td>Moderate change</td>
<td>“No change”</td>
</tr>
<tr>
<td>Substantial change</td>
<td>“Decrement old rating by x steps”</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Element from COSYSMO 1.0 (or other model as shown)</th>
<th>COSYSMO 3.0 Element</th>
<th>Instructions for 3.0 Rating</th>
<th>Justification (for Working Group members)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD: Requirements Understanding</td>
<td>CD: CONOPS and Requirements Understanding</td>
<td>Same rating.</td>
<td>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.</td>
</tr>
<tr>
<td>CD: Documentation Match to Life Cycle Needs</td>
<td>Dropped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD: # and Diversity of Installations/Platforms</td>
<td>(same)</td>
<td>Same rating.</td>
<td>Same definition.</td>
</tr>
<tr>
<td>CD: Personnel/Team Capability</td>
<td>(same)</td>
<td>Same rating.</td>
<td>Minor text definition improvement should allow the 1.0 rating to carry forward to a 3.0 rating.</td>
</tr>
<tr>
<td>CD: Process Capability</td>
<td>(same)</td>
<td>Same rating.</td>
<td>Same definition.</td>
</tr>
<tr>
<td>CD: Personnel Experience/Continuity</td>
<td>(same)</td>
<td>Decrement old rating by half a level.</td>
<td>One of two viewpoints has been &quot;shifted up&quot; one level; e.g., 3 years' experience was Nominal, but in 3.0 it's Low.</td>
</tr>
<tr>
<td>CD: Multisite Coordination</td>
<td>(same)</td>
<td>Same rating.</td>
<td>Same definition.</td>
</tr>
<tr>
<td>CD: Tool Support</td>
<td>(same)</td>
<td>Decrement old rating by a level.</td>
<td>The rating scale has been &quot;shifted up&quot; one level; e.g., &quot;Strong, mature tools&quot; 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.</td>
</tr>
</tbody>
</table>
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")