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The Budding SV3: Estimating the Cost of Architectural Growth Early in the Life Cycle

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Panel 22. Enhancing Cost Estimating Techniques

Thursday, May 15, 2014	
3:30 p.m. – 5:00 p.m.	**Chair: Daniel A. Nussbaum,** Naval Postgraduate School, former Director, Naval Center for Cost Analysis ***A Robust Design Approach to Cost Estimation: Solar Energy for Marine Corps Expeditionary Operations*** Susan Sanchez, Naval Postgraduate School Matthew M. Morse, United States Marine Corps Stephen Upton, Naval Postgraduate School Mary L. McDonald, Naval Postgraduate School Daniel A. Nussbaum, Naval Postgraduate School ***The Budding SV3: Estimating the Cost of Architectural Growth Early in the Life Cycle*** Matthew Dabkowski, U.S. Army/University of Arizona Ricardo Valerdi, University of Arizona ***Using Cost Estimating Relationships to Develop A Price Index for Tactical Aircraft*** Stanley Horowitz, Institute for Defense Analyses Bruce Harmon, Institute for Defense Analyses Daniel Levine, Institute for Defense Analyses

The Budding SV3: Estimating the Cost of Architectural Growth Early in the Life Cycle

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Abstract[1]

As the systems engineering community continues to mature model-based approaches, exciting opportunities for sophisticated, computational analysis grow. Among these possibilities, we posit and demonstrate a novel algorithm for estimating the cost of architectural changes early in the system life cycle when uncertainty is high. In particular, by treating the DoD Architecture Framework (DoDAF) Systems View 3 (SV3) as an adjacency matrix, we leverage concepts from network science to analyze the impact of architectural changes that result from the addition of a subsystem. Following this growth, we estimate the marginal increase in systems engineering effort via an explicit connection between the open academic cost model COSYSMO (Constructive Systems Engineering Cost Model) and the SV3. Based on its stochastic nature, this procedure is further implemented as a Monte Carlo simulation, allowing us to generate distributions of potential cost growth. Theoretically, this work serves as a proof of concept for further research on the integration of network science and systems engineering. Practically, the methodology provides a means for practitioners to accelerate the accuracy and fidelity of their "should cost" and "will cost" analyses early in the systems life cycle.

Introduction

On August 2, 2011, President Barack Obama signed the Budget Control Act (2011) into law. Driven by a need to reign in federal spending and curtail the growth of the national debt, the law contained a provision for a decade's worth of automatic, wide-sweeping, and substantial budget cuts, if Congress failed to pass a deficit reduction bill (Heniff, Rybicki, &

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[1] This work is derived from papers presented at the Conference of Systems Engineering Research (CSER) over the past two years (Dabkowski, M., Estrada, J., Reidy, B., & Valerdi, R., 2013; Dabkowski, M., Valerdi, R., & Farr, J., 2014). In particular, material in the sections titled "COSYSMO—A Tool for Costing Architectural Complexity," "Network Science—A Mechanism for Generating Unforeseen Architectural Growth," and "Estimating the Cost of Architectural Growth" originally appeared in Elsevier's *Procedia Computer Science* (with copyright retained by the authors). With this in mind, the first three sections of this paper add substantial political context and acquisition background, while the last few sections cover new limitations and possibilities for future work.

Mahan, 2011, pp. 2-3). Dubbed sequestration, the provision was intended as a forcing function to generate congressional consensus (Heniff et al., 2011, p. 27); it failed. Thus, on March 1, 2013, President Obama implemented the cuts (Sequestration, 2013), and the Department of Defense (DoD) absorbed an immediate, unanticipated 23% reduction in its Fiscal Year 2013 budget (Office of the Secretary of Defense, 2011), as well as a combined $492 billion loss in funding over the next 10 years (Heniff et al., 2011, p. 30).

Of course, the impact of this loss on defense acquisition is substantial, as the combined services and the industrial base face furloughs, reduced production, and difficult modernization decisions (On Impacts, 2013). That said, according to Dr. William LaPlante (Principal Deputy Assistant Secretary of the Air Force [Acquisition]) and Lieutenant General (LTG) Michael Moeller (United States Air Force Deputy Chief of Staff, Strategic Plans and Programs), the "single largest impact of sequestration and current budgetary unknowns is [their effect on] . . . the meticulous cost and schedule planning mandated in numerous public laws and DoD acquisition policy directives" (On Impacts, 2013, p. 70).

To be sure, Dr. LaPlante and LTG Moellers' assertion has tremendous, historical support. After all, even in the best of times, cost estimation (and its correlate scheduling) is difficult. For example, consider that between 1997 and 2009, 47 major defense acquisition programs (MDAPs) experienced cost overruns of at least 15% or 30% over their current or original baseline estimates, respectively (GAO, 2011, p. 2). Known formally as a Nunn-McCurdy breach, the reasons for this excessive growth are myriad, although nearly 70% of the cases identified engineering and design issues as a contributing factor (GAO, 2011, p. 5).

In sum, our defense budget is uncertain and presumably shrinking; uncertain funding frustrates cost planning; and cost planning (however meticulous) is already difficult and often based on incomplete information. Unfortunately, in an uncertain environment, the need to plan well is paramount. Indeed, we find ourselves in challenging times.

Pre-Milestone A Cost Estimation—Filled With Potential and Fraught With Peril

While the fiscal emergencies of the past several years have placed a spotlight on defense acquisition and spending in general, Congress legislatively acknowledged the need for change in 2009 with the passage of the Weapon Systems Acquisition Reform Act (WSARA, 2009). Generally speaking, the WSARA aims to reduce cost overruns and schedule delays through a collection of four major organizational changes and seven procedural adjustments (Berteau, Hofbauer, & Sanok, 2010, p. 4). For the purpose of this section, several stand out.

First, the WSARA increased the rigor and accountability of Pre-Milestone A (Pre-MS A) analysis and certification. For example, as directed by Ashton Carter, the former Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]), "the [Milestone Decision Authority] MDA for an MDAP shall sign a memorandum with the subject 'Milestone A Program Certification,' prior to signing the [acquisition decision memorandum] ADM to approve MS A" (Under Secretary of Defense [AT&L], 2009, p. 11). Additionally, as part of this process, the MDA must include the following language in the ADM: "At any time prior to MS B approval, the [program manager] PM shall notify me immediately if the projected cost of the program exceeds the cost estimate for the program at the time of MS A certification [emphasis added] by at least 25 percent" (Under Secretary of Defense [AT&L], 2009, p. 11). Moreover, if such growth and notification occurs, then the MDA must notify Congress and either (a) defend the program and recommend its continuation or (b) suggest a plan for termination (Under Secretary of Defense [AT&L], 2009, p. 12). Simply put, as per the WSARA, Pre-MS A cost estimation is a critical go/no go decision point.

Next, the WSARA established a new position known as the Performance Assessments and Root Cause Analysis (PARCA) official. [2] Functionally, the PARCA conducts reviews of an MDAP's cost, schedule, and performance, as well as root cause analysis *"including the role of . . . excessive manufacturing or integration risk [and] unanticipated design, engineering, manufacturing, or integration issues* [emphasis added]" (Under Secretary of Defense [AT&L], 2009, pp. 7–8). Moreover, the WASRA required the Director of Defense Research and Engineering (DDR&E) to develop "standards that will be used to measure and assess the maturity of critical technologies and *integration risk* [emphasis added] in MDAPs" (Under Secretary of Defense [AT&L], 2009, p. 9). In short, the WSARA is quite clear—assessing integration and design risk matters!

With the exceptions of a PARCA root cause analysis following critical cost growth and a DDR&E technological maturity evaluation prior to MS B, the timing of the PARCA and DDR&Es' assessments are somewhat vague, being described as "periodic," "at key stages," or "upon request" (Under Secretary of Defense [AT&L], 2009, pp. 7–9). That said, given (a) the increased emphasis on Pre-MS A cost estimation and integration risk and (b) the recurring role of engineering and design issues in excessive cost growth, it seems reasonable to require an assessment of integration and design risk Pre-MS A. This conclusion is implicitly reinforced by additional WSARA guidance mandating that Analysis of Alternatives (AoA) give "[f]ull consideration of possible trade-offs among cost, schedule, and performance objectives for each alternative considered" (Under Secretary of Defense [AT&L], 2009, p. 3; Under Secretary of Defense [AT&L], 2013b, p. 122).

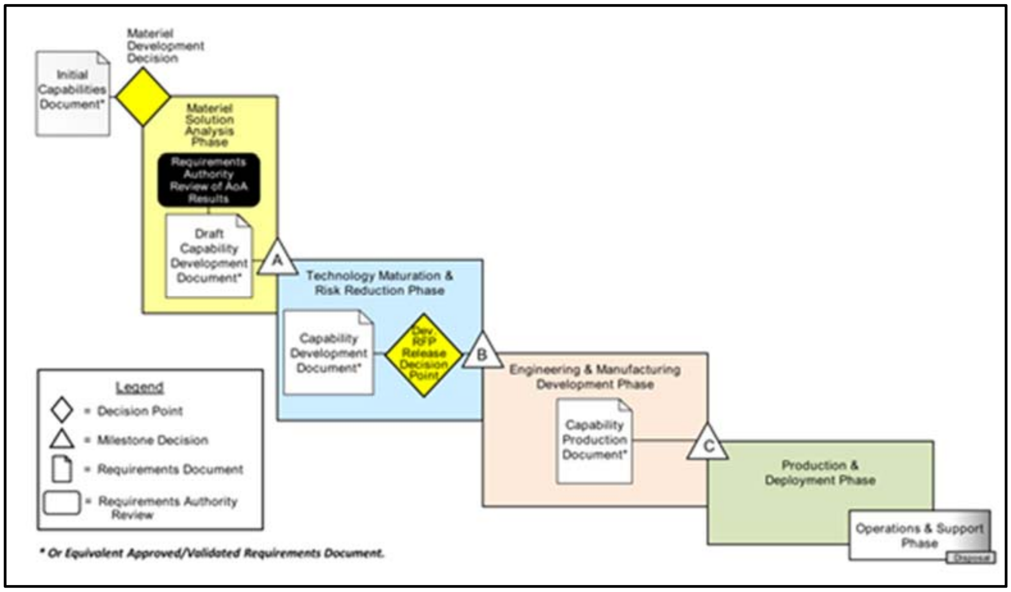

Figure 1. Illustration of the Interaction Between the Capability Requirements Process and the Acquisition Process

(Under Secretary of Defense [AT&L], 2013b, p. 5)

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[2] The WSARA also established a Director of Cost Assessment and Program Evaluation (DCAPE), Director of Development Test and Evaluation (DT&E), and a Director of Systems Engineering (SE) (WSARA, 2009); however, these positions are less relevant to this section.

Conceptually, conducting an assessment of integration and design risk Pre-MS A is appealing. After all, as shown in Figure 1, Pre-MS A is commensurate with the Material Solution Analysis Phase, during which "affordability analysis, risk analysis, and planning for risk mitigation are key activities" (Under Secretary of Defense [AT&L], 2013b, p. 15). Moreover, during a system's conceptual or preliminary design phase, the majority of a program's future, life-cycle costs are often (and perhaps unwittingly) committed (Blanchard & Fabrycky, 1998, p. 37; Dowlatshahi, 1992, p. 1803). Put another way, today's design decisions, driven by current requirements, determine tomorrow's debts, and the implication is obvious—make better design decisions now.

Unfortunately, this is easier said than done. Specifically, while the early life cycle contains substantial opportunities for future cost savings, it is characterized by uncertainty, notably in what will ultimately be required. For example, based on workshops conducted between 2010 and 2011 involving "27 participants . . . [with] an average of 23 years of experience in variety of industries but with specific emphasis on aerospace and defense," an average of 28% of a system's baseline requirements will change over the course of its life cycle, with roughly 43% of these changes occurring in the development phase (Peña & Valerdi, 2014, pp. 16–18). In the parlance of the Defense Acquisition System (DAS) and as seen in Figure 1, these changes occur Post-MS B. Furthermore, when system requirements change, this change manifests itself as the modification of an existing requirement or the addition of a new requirement 86% of the time (Peña & Valerdi, 2014, p. 17).

Quite bluntly, experience suggests we are much more likely to add than take away (i.e., scope creep), and these changes often carry substantial costs. For instance, in their meticulous RAND study, Bolten, Leonard, Arena, Younossi, and Sollinger carefully examined the Selected Acquisition Reports (SARs) of 35 MDAPs, attributing differences between their current and MS B cost estimates to one of 13 categories (2008, pp. 14–15). Among these categories is requirements volatility (dubbed "requirements"), which captures requirement changes that occur "at any point after MS B . . . [and normally] add capabilities to the system" (Bolten et al., 2008, p. 17). For the 35 MDAPs analyzed, requirements volatility accounted for an average of 21.5% of a program's total cost growth over its MS B estimate, making it the second largest source of cost growth (RAND, 2008, p. 27). Occasionally, as evidenced by the C130J "Super Hercules," a change in requirements can necessitate the addition of a subsystem, and the resulting cost growth can be extreme.

> The program originally was envisioned as a nondevelopmental aircraft acquisition with a negligible [Research, Development, Test, and Evaluation] RDT&E effort planned. Several years into the program, the decision was made to install the Global Air Traffic Management system, adding several hundred million dollars to development and causing the total development cost growth to climb upward of 2,000 percent. (Under Secretary of Defense [AT&L], 2013a, p. 25)

With this in mind, it is no surprise that Pre-MS A cost estimation is challenging, and its complications have been duly noted by analysts in the Office of the Deputy Assistant Secretary of the Army for Cost and Economics (ODASA-CE; Hull, 2009; Roper, 2010) as well as Carnegie Mellon's Software Engineering Institute (SEI) (Ferguson, Goldenson, McCurley, Stoddard, Zubrow, & Anderson, 2011, pp. 6–7). Collectively, these issues stem from a lack of system specification prior to MS A, making traditional, bottom-up estimation difficult at best. As such, ODASA-CE developed a parametric method known as capability-based cost analysis, where the cost to acquire a desired set of capabilities is estimated from the historical cost of acquiring them (Hull, 2009; Roper, 2010). Taking a multimethodology approach, SEI developed QUELCE (Quantifying Uncertainty in Early Lifecycle Cost

Estimation), which incorporates expert opinion, Bayesian belief networks, parametric cost models, and Monte Carlo simulation (Ferguson et al., 2011).

While these methods are tremendously valuable and should continue to be refined, the DoD's current push to require more system specification earlier in the lifecycle has created an opportunity for an alternative approach. In particular, while the USD(AT&L) previously specified that the initial submission of an MDAP's Capability Development Document (CDD) was prior to MS B (Under Secretary of Defense [AT&L], 2008, p. 19), the recently signed interim DoD Instruction 5000.02 now requires a "draft" or DoD component-approved CDD prior to MS A (see Figure 1; Under Secretary of Defense [AT&L], 2013b, p. 46). Moreover, according to the current *Manual for the Operation of the Joint Capabilities Integration and Development System* (JCIDS), CDDs must contain 25 of the 31 DoD Architecture Framework (DoDAF) models ever required by JCIDS (CJCS, 2012a, p. B-F-6), and these models are the same set required by the Capability Production Document (CPD), which is submitted just prior to an MDAP entering production (see Figure 1; CJCS, 2012a, p. B-F-6).[3] Of course, the Pre-MS A, draft CDD can and likely will change, but the conclusion is clear—more information is available earlier, most notably detailed architectural models.

Systems Engineering—A Discipline With Promise

Given the bevy of DoDAF models now available Pre-MS A, the natural question is "What, if anything, can these draft diagrams tell us about cost?" While an exhaustive answer to this query requires a thorough examination of each of the 25 models, our intent is to provide a proof of concept. Accordingly, we focus on one—the Systems Viewpoint 2 (SV2): Systems Resource Flow Description.

As a matter of definition, the SV2 documents "details of the physical pathways or network patterns that implement interfaces" (Department of Defense Deputy Chief Information Officer, 2010, p. 205). Graphically, this normally takes the form of a block diagram, and an example is given in Figure 2, which documents the flow of resources between devices in the Ocean Observatories Initiative's (OOI) Portland site.[4] As this example shows, the SV2 visually captures how the subsystems of a larger system (or program) connect.

That said, as a system's complexity or size increases, the SV2 can quickly become unwieldy and unreadable, forcing the architect to generate a library of smaller SV2s. In such situations, the larger number of program-wide interfaces can be more compactly represented in the Systems Viewpoint 3 (SV3): Systems-Systems Matrix. The SV3 for the OOI Portland site is given in Figure 3, where shaded cells indicate that the subsystems in the corresponding rows and columns are connected.

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[3] Although the current *Manual for the Operation of the Joint Capabilities Integration and Development System* (dated January 19, 2012) does not require a "DIV-3: Physical Data Model" for the CDD but does require it for the CPD, this is an error (CJCS, 2012b, p. 3). It is required for both.

[4] The OOI is a National Science Foundation project that will ultimately provide a "networked infrastructure of science-driven sensor systems to measure the physical, chemical, geological and biological variables in the ocean and seafloor" (Ocean Observatories Initiative, 2013).

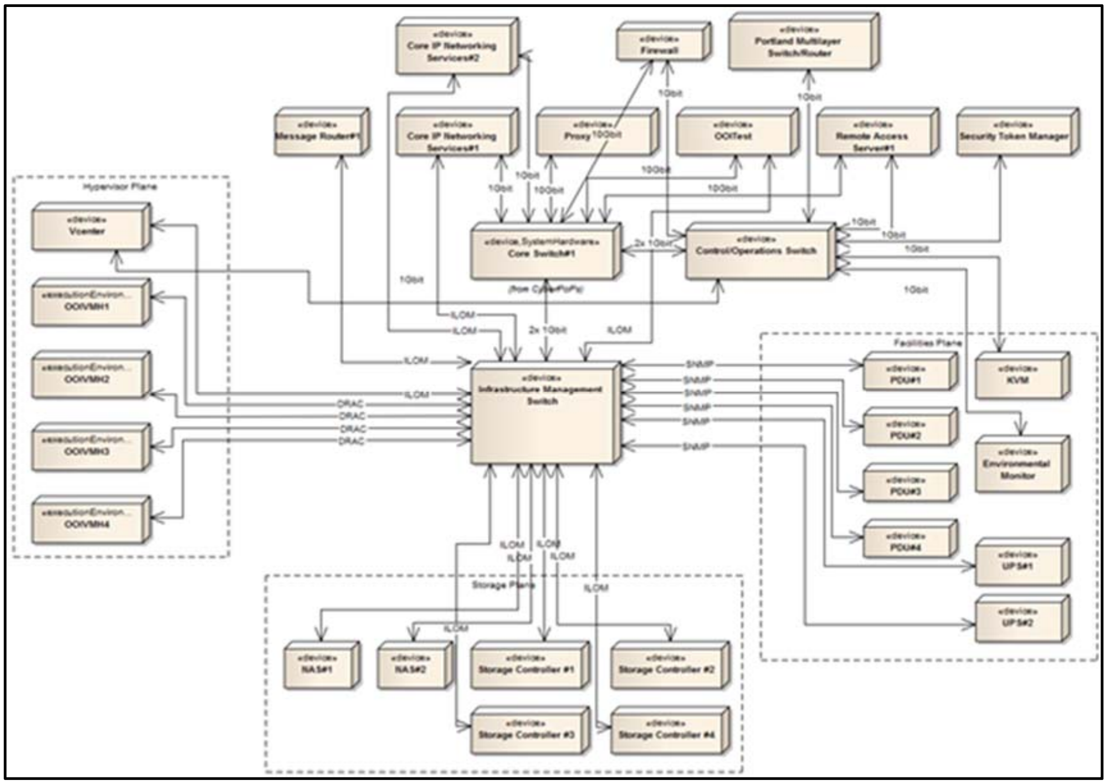
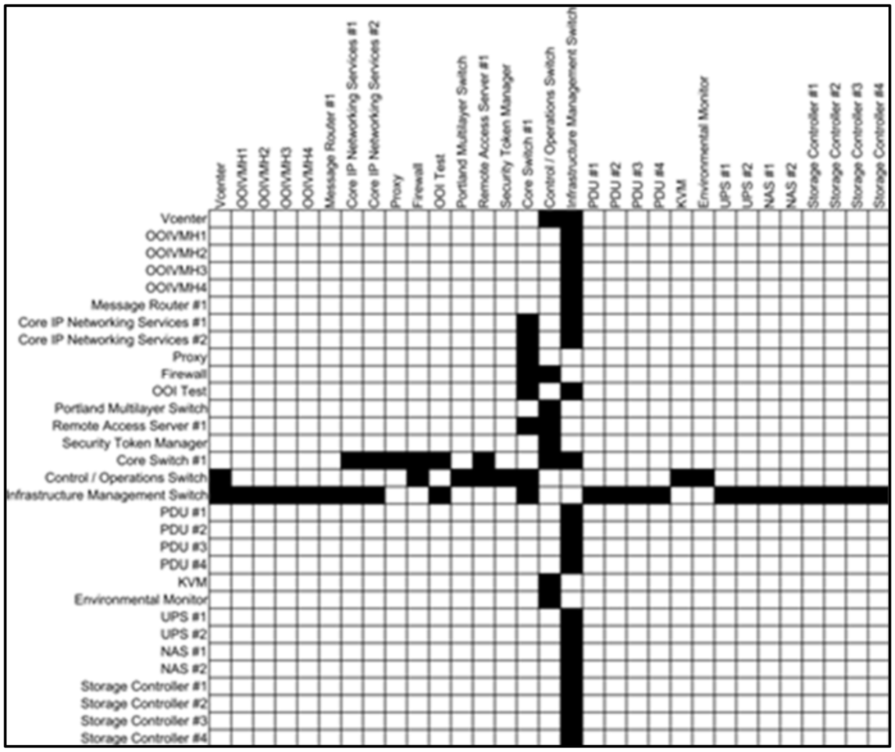


Figure 2. **SV2 Documenting the Flow of Resources for OOI's Portland Site**
(Farcas, 2011)



	Vcenter	OOIVMH1	OOIVMH2	OOIVMH3	OOIVMH4	Message Router #1	Core IP Networking Services #1	Core IP Networking Services #2	Proxy	Firewall	OOI Test	Portland Multilayer Switch	Remote Access Server #1	Security Token Manager	Core Switch #1	Control / Operations Switch	Infrastructure Management Switch	PDU #1	PDU #2	PDU #3	PDU #4	KVM	Environmental Monitor	UPS #1	UPS #2	NAS #1	NAS #2	Storage Controller #1	Storage Controller #2	Storage Controller #3	Storage Controller #4
Vcenter																■	■														
OOIVMH1																	■														
OOIVMH2																	■														
OOIVMH3																	■														
OOIVMH4																	■														
Message Router #1																	■														
Core IP Networking Services #1															■		■														
Core IP Networking Services #2															■		■														
Proxy															■																
Firewall															■	■															
OOI Test															■		■														
Portland Multilayer Switch																■															
Remote Access Server #1															■	■															
Security Token Manager																■															
Core Switch #1							■	■	■	■	■		■			■	■														
Control / Operations Switch	■									■		■	■	■	■							■	■								
Infrastructure Management Switch	■	■	■	■	■	■	■	■			■				■			■	■	■	■			■	■	■	■	■	■	■	■
PDU #1																	■														
PDU #2																	■														
PDU #3																	■														
PDU #4																	■														
KVM																■															
Environmental Monitor																■															
UPS #1																	■														
UPS #2																	■														
NAS #1																	■														
NAS #2																	■														
Storage Controller #1																	■														
Storage Controller #2																	■														
Storage Controller #3																	■														
Storage Controller #4																	■														

Figure 3. **SV3 Summarizing the OOI Portland Site's SV2**

Professionally speaking, the SV2 and SV3 fall within the purview of systems engineering (SE), a discipline repeatedly identified as a means to control program cost. For example, in the Government Accountability Office’s (GAO) 2011 report DoD Cost Overruns, “early and continued systems engineering analysis” is the first of five tools recommended for containing cost growth (p. 7). Similarly, in a 2008 National Research Council (NRC) report, the authors state that the “application of SE to decisions made in the pre-Milestone A period is critical to avoiding (or at least minimizing) cost and schedule overruns” (p. 3). These assertions are empirically backed-up by data from historical, software-intensive systems, where the return on investment for greater SE effort can be as high as 8:1 (Boehm, B., Valerdi, R., & Honour, E., 2008, p. 232). Legislatively, Congress acknowledged the value of SE in 2009 by adding a Director of Systems Engineering to the USD(AT&L)’s staff (WSARA, 2009, p. 1710).

With SE’s cost saving potential firmly established, the aforementioned NRC report identifies six primary “seeds of [cost, schedule, and performance] failure” addressable by SE, including incomplete requirements at MS B, system complexity (via internal, architectural design), and external interface complexity (via network-centric operations or “systems of systems” constructs; 2008, pp. 82–85). Abstractly, the SV3 provides a compact representation of all three, as requirements (however incomplete) drive the selection of subsystems and, thus, spawn their attendant interfaces, both internal and external. Therefore, formally evaluating the interfaces portrayed in the SV3 and subsequently estimating their cost holds promise. Accordingly, we turn our attention to the Constructive Systems Engineering Cost Model (COSYSMO).

COSYSMO—A Tool for Costing Architectural Complexity

Developed by the second author in 2005, COSYSMO is a parametric, open academic cost model that estimates the systems engineering effort (in person months) required to bring a system to fruition (Valerdi, 2005). Consisting of four size drivers (i.e., number of requirements, number of interfaces, number of algorithms, and number of operational scenarios) and 14 effort multipliers, it has been used by a variety of organizations (Valerdi, 2008; Wang, Valerdi, Roedler, Ankrum, & Gaffney, 2012), and it utilizes the cost estimating relationship (CER) given in Equation 1 below (Valerdi, 2005):

$$PM_{NS} = A \cdot \underbrace{\left(\sum_{i \in \{e,n,d\}} \sum_{k=1}^{4} w_{i_k} \Phi_{i_k} \right)^{E}}_{\text{size}} \cdot \underbrace{\prod_{j=1}^{14} EM_j}_{\text{effort}} \tag{1}$$

where

PM_{NS} = system engineering effort (nominal schedule),

A = calibration constant derived from historical project data (assume as 0.25),

W_{ik} = weight for the ith complexity level of the kth size driver ($i \in \{e\ (\text{easy}), n\ (\text{nominal}), d\ (\text{difficult})\}$),

Φik = quantity of the kth size driver with complexity level i ($k \in \{1\ (\text{requirements})$, 2 (interfaces), 3 (algorithms) and 4 (operational scenarios)}),

E = diseconomies of scale constant (assume as 1.06), and

EM_j = systems engineering effort multiplier for the jth cost driver (assume product is 0.89).

With respect to costing architectural complexity via the SV3, we are primarily concerned with the "number of interfaces" size driver, where system interfaces are defined as "shared major physical and logical boundaries between system components or functions (internal interfaces) and those external to the system (external interfaces)" (Valerdi, 2005, p. 282). Additionally, from a complexity (and thus effort) standpoint, all interfaces are not created equal; therefore, we categorize, count, and weigh them according to the taxonomy given in Table I (Valerdi, 2014, p. 284).

Table 1. COSYSMO's Interface Rating Scale and Relative Weights[5]

	Complexity Level		
Characteristics	Easy	Nominal	Difficult
Message complexity	Simple	Moderate	Complex
Coupling level	Uncoupled	Loose	Tight
Stakeholder consensus	Strong	Moderate	Low
Behavior	Well behaved	Predictable	Emergent
Relative weight (w_{ik})	1.1	2.8	6.3

Armed with COSYSMO's CER and its corresponding interface rating scale, consider a hypothetical system with the SV3 portrayed Figure 4.

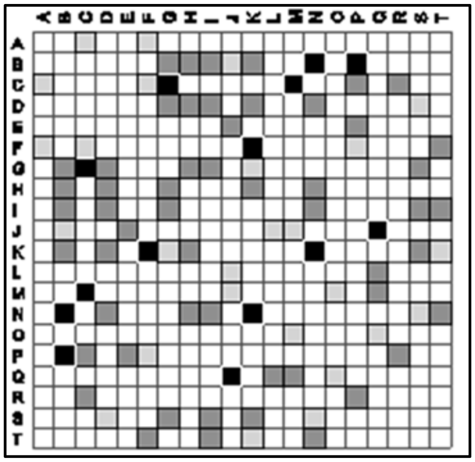


Figure 4. SV3 for a Hypothetical System Where the Shading of the Cells Indicates Interface Complexity (Light Gray ⇒ Easy, Medium Gray ⇒ Nominal, Black ⇒ Difficult)

Consisting of 20 subsystems (labeled **A** through **T**) and 47 interfaces, assume the system is mature enough for interface complexity to be assessed. Moreover, without loss of generality, assume there are 200 easy, 200 nominal, and 50 difficult requirements, as well as 5 difficult critical algorithms. Using additional w_{ik} and EM_j data obtained from Valerdi (2014, p. 284), we apply Equation 1 to obtain an initial estimate of PMNS as follows:

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[5] The relative weights in Table 1 have been obtained through industry calibration.

$$PM_{NS} = 0.25 \cdot \left(\underbrace{(0.5 \times 200 + 1.0 \times 200 + 5.0 \times 50)}_{\text{requirements}} + \underbrace{(11.5 \times 5)}_{\text{algorithms}} + \underbrace{(1.1 \times 13 + 2.8 \times 27 + 6.3 \times 7)}_{\text{interfaces}} \right)^{1.06} \cdot 0.89 = 245.27 \quad (2)$$

As such, we conclude that 245.27 PM of SE effort are required, and, if we further assume that each PM costs $20,000, this equates to $4,905,400. In a perfect world, our Pre-MS A requirements would be well-defined, our architecture would hold, and this estimate would suffice. Reality, however, is rarely this kind, as our earlier discussion on requirements volatility attests. Nonetheless, if revised requirements prompt the elimination or introduction of new subsystems and interfaces, the resultant cost impact can be easily quantified since there is an explicit connection between the SV3 and COSYSMO.

Network Science—A Mechanism for Generating Unforeseen Architectural Growth

While the above methodology is useful, it fails to provide decision makers with a sense of how costly architectural change might be before it occurs. For example, suppose we are interested in estimating the SE effort required to incorporate an additional subsystem (**U**) into the architecture without knowing its purpose or function. In light of COSYSMO's CER, this ultimately forces us to estimate the number of interfaces (by complexity level) **U** will generate. More granularly, we need to answer the following three *growth modeling questions:*

- **a.** How many subsystems should **U** connect to (degree)?,
- **b.** Given **U** connects to *d* subsystems, which *d* subsystems should it connect to (adjacency)?, and
- **c.** Given **U** connects to a specific set of *d* subsystems, what should the complexity of these interfaces be (weights)?

Of course, the answer to these questions cannot be known with certainty, as subsystem **U**'s purpose is unknown. To illustrate this visually, consider Figure 5, which represents six distinct possibilities for subsystem **U**'s connections.

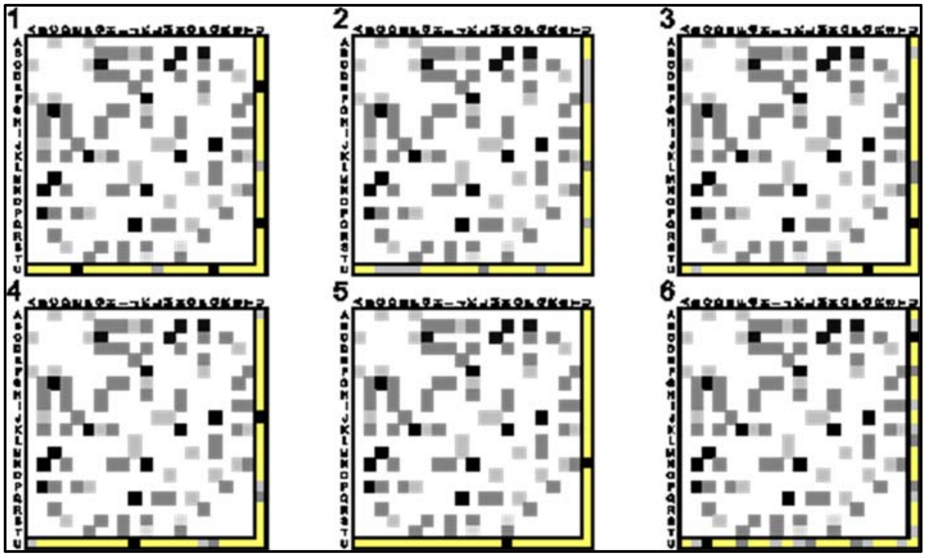

Figure 5. Potential Realizations of Subsystem U's Connections

As seen in Figure 5, subsystem **U** can connect to the existing architecture in a variety of ways. For example, in Panel 3 of Figure 5, **U** connects to **B, L, M**, and **Q** with complexities easy, nominal, nominal, and difficult respectively. On the other hand, in Panel 6, it connects to nine subsystems, where its connection to **I** is rated as easy.

This raises the question: Which of these realizations is more likely? Of course, with no information on the function or purpose of **U**, we could claim neither. However, if we make the reasonable assumption that the network's structure prior to **U**'s addition provides a reasonable facsimile of its structure following **U**'s addition, then Panel 3 seems to be the obvious choice. After all, while 40% of the existing subsystems have four or fewer interfaces, none have more than eight. Additionally, although each of **I**'s existing interfaces are rated as nominal, its interface to **U** in Panel 6 is categorized as easy.

Beyond the obvious inconsistencies in Panel 6 of Figure 5, the manner in which systems engineers architect complex systems should also be taken into account. As the authors of the 2008 NRC report note with respect to system architecture development,

> [a] well-known approach to addressing a complex problem is to break it into parts that can be addressed separately. Architecture here refers to the partitioning of the system into separately definable and procurable parts, the structuring of interfaces between the system and the outside world, and the structuring of interfaces (physical, functional, and data) among the segments. Through careful partitioning, architecture can minimize complexity and thereby development risk. (p. 78)

While the deliberate or subconscious partitioning of the hypothetical system is not apparent in Figure 4, we can use the well-known Girvan-Newman algorithm from network science to identify the system's "architectural communities"—groups of subsystems where the number of interfaces is dense within and sparse between groups. Running this procedure on our hypothetical system identifies three communities, namely: community 1 = {**Q, O, E, L, M, J**}, community 2 = {**N, G, H, D, I, K, T, B, S**}, and community 3 = {**F, P, A, R, C**}.[6] Furthermore, when the subsystems are permuted by their community membership (Figure 6), the partition's veracity is quite apparent.

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[6] See Dabkowski et al. (2014) for details on the Girvan-Newman algorithm.

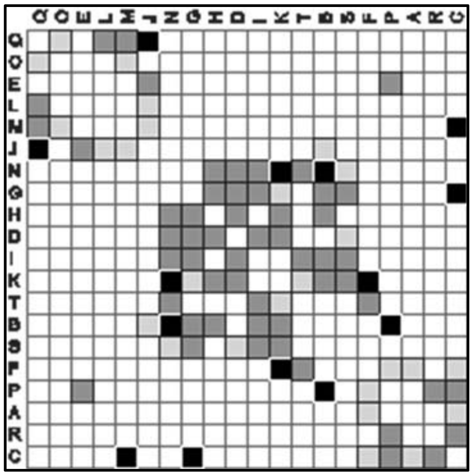


Figure 6. Permuted SV3 for the Hypothetical System

Given this partition, we return to Panel 6 of Figure 5 and note that **U**’s connections with {**Q, L**}, {**I, K, T, B**}, and {**F, P, C**} span the three communities, minimally adding five intercommunity interfaces to the existing architecture (if **U** is assigned to community 2). With just seven intercommunity interfaces prior to the addition of subsystem **U**, this seems extremely unlikely. To the contrary, in Panel 3 of Figure 5, **U**’s connections to **Q, L**, and **M** are consistent with its assignment to community 1, and its connection to B reinforces the only intercommunity interface between communities 1 and 2 in the existing architecture (interface **J-B**). Unlike Panel 6 of Figure 5, this seems plausible.

In light of this, community membership matters, and partitioning the architecture prior to assessing **U**’s degree, adjacency, and weights is implied. Accordingly, we elected to apply the Girvan-Newman algorithm as a preprocessing step, and we subsequently treat intracommunity and intercommunity growth separately. Nonetheless, regardless of the type of growth, we can address our previously identified growth modeling questions as follows:

- **a.** Degree: To model a “rich-by-birth” effect, view the degree of **U** (D_{U}) as a random variable with a probability mass function (pmf) equal to the observed degree distribution of the existing system;
- **b.** Adjacency: To incorporate a “rich-get-richer” effect, utilize the Barabási–Albert preferential attachment (PA) model from network science, where highly connected subsystems are more likely to interface with **U**; and
- **c.** Weights: To mimic the observed complexity in the existing architecture, cast the complexity of the interface between **U** and subsystem i ($w_{i\mathrm{U}}$) as a conditional random variable, where the pmf for $W_{i\mathrm{U}}$ equates to the observed interface complexity distribution of subsystem i.

Taken together, our mechanism for generating unforeseen architectural growth is as follows:

Preprocessing

1. Initialize the system as the current system,
2. Use Girvan-Newman to identify architectural communities,
3. Randomly assign **U** to community j,

Intracommunity Growth

4. Generate a realization for $D_{\mathrm{U,intra}}$, given **U** is assigned to community j (d_{intra}),
5. Connect **U** to d_{intra}subsystems inside community j using the PA model,
6. For each interface established in (5), assign complexity ($W_{i\mathbf{U,intra}}$),

Intercommunity Growth

7. Generate a realization for $D_{,\mathrm{inter}}$ given **U** is assigned to community j (d_{inter}),
8. Connect **U** to d_{inter} communities using the PA model, and
9. For each interface established in (8), assign complexity ($W_{i\mathbf{U},\mathrm{inter}}$).

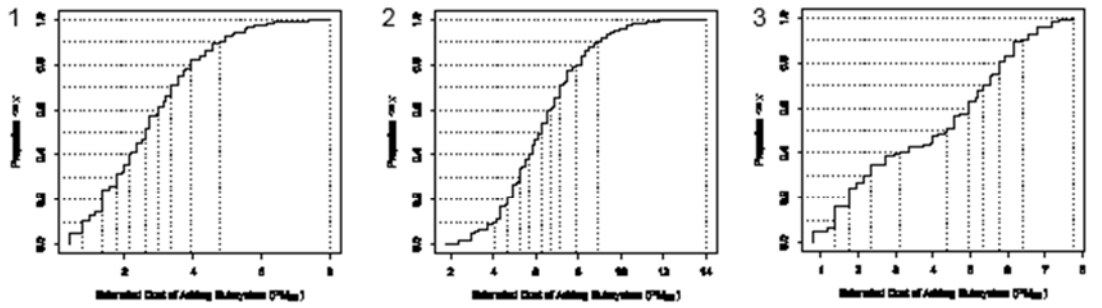
Estimating the Cost of Architectural Growth

The algorithm described in steps (1) through (9) generates a single realization of the architectural growth inspired by the addition of subsystem **U**. Of course, we ultimately want to estimate the cost of these architectural changes; therefore, we add steps (10) and (11), to wit:

Cost Estimation

10. Estimate the cost for the augmented system using COSYSMO (PMNS*), and
11. Calculate the additional cost of adding subsystem **U** (PMNS* − PMNS).

Furthermore, as each realization of cost is drawn from an unknown, underlying probability distribution, we add a final, looping step ((12) Store results and return to (3)), and we repeat the procedure a large number of times. Implemented in the statistical software R, the results of 10,000 iterations are given in Figure 7.



- 95% CI is (2.68, 2.78) in $\mathrm{PM}_{\mathrm{NS}}$
- "Best guess" is $54,740
- Cost should not exceed $160,020

- 95% CI is (6.25, 6.39) in $\mathrm{PM}_{\mathrm{NS}}$
- "Best guess" is $126,520
- Cost should not exceed $280,240

- 95% CI is (3.86, 4.00) in $\mathrm{PM}_{\mathrm{NS}}$
- "Best guess" is $78,720
- Cost should not exceed $155,120

Figure 7. Empirical Cumulative Distribution Functions and Statistics for the Cost of Adding Subsystem U to Communities 1, 2, and 3

As seen in Figure 7, if subsystem **U** is added to architectural community 1, a plausible range of values for the expected, marginal SE effort is 2.68 to 2.78 $\mathrm{PM}_{\mathrm{NS}}$ (the 95% confidence interval on the mean), while the expected (or mean) SE cost is $54,740. Moreover, as the expected value of the squared difference between a random variable's mean and itself is minimal, this value can be interpreted as a "best guess." Alternatively, if a decision maker requires an upper bound for the SE cost necessary to add subsystem **U** to community 1, $160,020 (the largest observed simulated value) is a reasonable estimate. Similar interpretations apply to Panels 2 and 3 of Figure 7, where the greater complexity of communities 2 and 3 generates higher costs.

Limitations

While still in its infancy, the above methodology has been well received by both industry and academia, as it provides a new tool for Pre-MS A cost estimation, prior to settling on a design. Nonetheless, as with any model, it is not a panacea, and it has numerous limitations. For example, in the hypothetical system portrayed in Figure 4, we have assumed the existing architecture's interface complexities are known a priori and with certainty. Unfortunately, both are questionable. Specifically, in its current form, DoDAF does not require the complexity of a system's interfaces to be assessed, and, even if such an assessment occurred, uniformly treating existing interface complexities as deterministic seems artificial. That said, neither of these issues are insurmountable, as interface complexity can minimally be assessed through expert opinion, and multiple expert opinions can be stochastically modeled via opinion pools.

Additionally, by employing COSYSMO, the above methodology only estimates the SE effort (and cost) required to connect a new subsystem; it does not estimate total cost. While this seemingly limits the model's utility, industry has found SE effort to be a valuable proxy for total system cost (Honour, 2004). Exploiting this relationship, Lockheed Martin's Proxy Estimation Costing for Systems (PECS) method uses COSYSMO to generate an initial estimate of SE effort, converts it to program effort, and subsequently integrates additional cost parameters to estimate total system cost (Cole, 2012). A similar approach, after appropriate modification, would almost certainly work here.

Lastly, in its current form, the above methodology is entirely stochastic, and this may inadvertently cause unrealistic connections. For instance, consider the SV2 and SV3 for the OOI Portland site given in Figures 2 and 3, respectively. By inspection, every subsystem in this architecture is minimally connected to one of three subsystems, namely: Core Switch #1, Control/Operations Switch, and Infrastructure Management Switch. They are hubs. With this in mind, if we add a new subsystem to the existing architecture, it is reasonable (and perhaps mandatory) to assume the new subsystem will minimally connect to one of these three hubs. While the PA model in our current methodology makes this likely, it is not guaranteed. As such, identifying design imperatives upfront and incorporating these rules into the algorithm can improve its realism and accuracy.

Future Work

As previously mentioned, the current methodology utilizes just 1 of the 25 DoDAF models required in the CDD. Thus, we are currently exploring the relationship between the remaining 24 and COSYSMO, with the ultimate goal of mapping relevant artifacts to COSYSMO's CER parameters. Similarly, beyond the draft CDD, there are many other acquisition documents available Pre-MS A in either approved (i.e., Initial Capabilities Document (ICD), Market Research, etc.) or draft form (i.e., Analysis of Alternatives, Consideration of Technology Issues, Cooperative Opportunities, etc.; Under Secretary of Defense [AT&L], 2013b). Accordingly, we will be examining these documents for information that provides additional, useful input for Pre-MS A cost estimation. Finally, as with Dabkowski et al. (2014), validating the current methodology (especially the architectural growth mechanism) remains a priority. As such, we are using the Army's recently launched Army Capability Architecture Development and Integration Environment (ArCADIE) database to analyze the SV2's of unclassified programs.

Conclusion

Given recent budgetary stress and increased program scrutiny, the need for better cost estimation, earlier in the systems life cycle, is paramount. Unfortunately, due to complications stemming from a lack of system specification, Pre-MS A cost estimation remains challenging. That said, the recently signed interim DoD Instruction 5000.02 now requires a DoD component-approved CDD prior to MS A (Under Secretary of Defense [AT&L], 2013b, p. 46), and this document must contain 25 of the 31 DoDAF models ever required by JCIDS (CJCS, 2012a, p. B-F-6). Among these models is the SV2, which visually captures how the subsystems of a larger system (or program) connect. Compactly represented as the SV3, this artifact provides an abstract representation of internal and external system complexity, a factor identified as a primary cause of cost overruns (National Research Council, 2008, pp. 82–85).

Accordingly, in this paper we posited and demonstrated a novel algorithm for estimating the cost of architectural growth (and more generally change) early in the system life cycle when uncertainty is high. Specifically, drawing on the disparate disciplines of systems engineering, parametric cost estimation, and network science, we treated the SV3 as an adjacency matrix and modeled the architectural change stemming from the addition of a subsystem. Following this growth, we estimated the marginal increase in SE effort via an explicit connection between the open academic cost model COSYSMO and the SV3. Although our approach has limitations, its principal shortcomings are largely addressable by known methods. Nonetheless, this work serves as a proof of concept, and substantial calibration and validation effort is required prior to implementation.

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