Estimating the Cost of Systems Engineering for Space Systems

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Systems engineering continues to play a critical role in the design and operation of space systems. Despite the role of systems engineering in ensuring mission success, engineers have not been able to estimate the costs of the systems engineering process to the same level of precision that they have achieved in estimating the costs of the items that the process produces, namely, hardware and software. Traditionally, industry and government have bundled the costs of systems engineering with the other costs for program management, test, and integration, but this approach causes two problems. First, it does not justify in a sufficiently quantifiable way how the organization should assign systems engineering costs to space systems. Without such justification, many programs do not adequately staff their systems engineering teams. Second, this approach does not consider in the technical drivers and programmatic factors that affect the cost of systems engineering, but instead relies on estimation techniques that lack the necessary repeatability, fidelity, and objectivity. But now, thanks to the recently developed parametric cost model COSYSMO, engineers can now justify systems engineering costs with quantifiable systems engineering cost estimating relationships.

This paper provides a detailed analysis of a systems engineering cost model, the Constructive Systems Engineering Cost Model (COSYSMO), and explains how its activities and lifecycle phases can be adjusted to apply to space systems. We will also provide a technique for partial estimation of systems engineering costs, which can help an engineer to estimate the costs of space systems engineering activities based on the characteristics of today's acquisition contracts.

The Constructive Systems Engineering Cost Model

The COSYSMO model can help analysts think through the economic implications of systems engineering on projects. Similar to its predecessor, the Constructive Cost Model II (COCOMO) (Boehm et al. 2000), it was developed at the University of Southern California as a research project with the help of The Aerospace Corporation, BAE Systems, Boeing, General Dynamics, L-3 Communications, Lockheed Martin, Northrop Grumman, Raytheon, and SAIC. Following a parametric modeling approach, COSYSMO estimates the quantity of systems engineering labor (in terms of person-months) required for conceptualizing, designing, testing, and deploying large-scale software and hardware projects. COSYSMO gives the user the ability to develop proposal estimates, investment decisions, budget planning, project tracking, tradeoffs, risk management, strategy planning, and process improvement measurements.

Assumptions of the Model

COSYSMO is based on a systems engineering work breakdown structure (WBS) that uses a standard set of thirty-three systems engineering activities, which is assumed to adequately represent the systems engineering activities for the program of interest. The WBS is derived from the American National Standards Institute/Electronic Industries Association (ANSI/EIA) standard *Processes for Engineering a System* (ANSI and EIA 1999). Before the space community can adopt COSYSMO, it must consider the differences between the WBS provided in the ANSI/EIA standard and a typical systems engineering WBS for space systems, such as the Unmanned Space-Vehicle Cost Model (USCM).

COSYSMO is also based on systems engineering lifecycle, derived from the International Organization for Standardization and the International Electrotechnical Commission's standard *15288: Systems Engineering: System Life Cycle Processes* (ISO and IEC 2002). The *ISO/IEC 15288* standard is assumed to adequately capture where the systems engineering activities occur during the lifecycle of the program of interest. This paper compares the lifecycle phases in *ISO/IEC 15288* to the mandated acquisition lifecycle defined by the U.S. Department of Defense policy that guides acquisition of space systems (U.S. Department of Defense, 2004). The findings from this study will likely reveal what adjustments would be necessary to successfully incorporate COSYSMO into the space domain.

COSYSMO Work Breakdown Structure (*ANSI/EIA 632*)

The *ANSI/EIA 632* standard was developed between 1994 and 1998 by a working group of industry associations, INCOSE, and the U.S. Department of Defense with the intent to provide a standard for use by commercial enterprises, as well as government agencies and their contractors. It was designed to have a broader scope than previous systems engineering standards and to provide less detail. The activities in the model are set in the context of: (1) acquisition and supply, (2) technical management, (3) system

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design, (4) product realization, and (5) technical evaluation. The standard identifies five fundamental systems engineering processes (listed in table 2), thirteen systems engineering process categories (presented in table 1), and thirty-three systems engineering activities. These processes and activities help to answer the *what* of systems engineering and to characterize the COSYSMO model. The *ANSI/EIA 632* standard provides a generic industry list that may not be applicable to all domains, but is useful in describing the scope of systems engineering.

Space Systems Work Breakdown Structure

USCM is a parametric model that provides linear and nonlinear cost estimating relationships to estimate the costs of satellite development and production (Tieu et al. 2000). The cost estimating relationships describe the costs for the bus and for the communication payload, as well as the associated costs for systems engineering/program management and for integration/assembly/test. The model includes all types of satellite buses, but focuses only on communication satellite payloads. The majority of the costs included in this model are end-of-program actual costs.

To better understand the relationship between *ANSI/EIA 632* and USCM, we mapped the *ANSI/EIA 632* process categories to the USCM WBS items. Mapping these two documents at the level of the process categories and the WBS items was a logical decision, as both represented approximately the same level of detail with respect to system activities. The thirteen *ANSI/EIA 632* process categories were compared to the USCM WBS program management (1.4.1), systems engineering (1.4.2), and assembly, integration, and system test (1.1) categories (Tecolote Research, Inc., 2002). The result of this mapping is provided in table 1.

This mapping is based on a subjective assessment of the overlap between the process categories in *ANSI/EIA 632* and a broad interpretation of WBS items 1.4.1, 1.4.2, and 1.1 in USCM. At first glance, it is evident that the added detail in the WBS from *ANSI/EIA 632* may provide an advantage, but in practice,

Table 1. Mapping of two work breakdown structures

ANSI/EIA 632 Process Categories	Unmanned Space-Vehicle Cost Model WBS Items
Acquisition and supply	
Supply process	1.4.1 Program management
Acquisition process	1.4.1 Program management
Technical management	
Planning process	1.4.1 Program management
Assessment process	1.4.1 Program management
Control process	1.4.1 Program management
System design	
Requirements definition process	1.4.2 Systems engineering
Solution definition process	1.4.2 Systems engineering
Product realization	
Implementation process	1.4.2 Systems engineering
Transition to use process	1.4.2 Systems engineering
Technical evaluation	
Systems analysis process	1.4.2 Systems engineering
Requirements validation process	1.4.2 Systems engineering
System verification process	1.1 Integration, assembly, and system test
End products validation process	1.1 Integration, assembly, and system test

Table 2. Systems engineering effort distribution across ANSI/EIA 632 fundamental processes (Valerdi and Wheaton 2005)

ANSI/EIA 632 Fundamental Process	Typical Effort
Acquisition and supply	7%
Technical management	17%
System design	30%
Product realization	15%
Technical evaluation	31%

cost accounting data is not always collected at this level of detail. The WBS in USCM is likely a reflection of the cost accounting practices of the space systems industry over the last forty years; it intends to be detailed enough to be applied to all space systems, but generic enough to be applicable across the diverse types of space systems.

Partial Estimation of Systems Engineering Effort by Activity

Nevertheless, it is beneficial to understand the cost of systems engineering at a finer level of granularity: this task is at the core of COSYSMO. With this added detail we can estimate the amount of systems engineering effort by activity and improve the management and execution of the discipline in the space domain. As described earlier, one of the assumptions of the COSYSMO model is that a standard set of systems engineering activities are being performed throughout certain phases in the lifecycle. In a previous study (Valerdi and Wheaton 2005), the standard thirty-three systems engineering activities were mapped across the expected distribution of systems engineering effort across the lifecycle. This mapping resulted in an association between each activity and a percentage of total effort. In table 2, those percentages have been aggregated from the level of the 33 activities to the level of the 5 fundamental processes. Although not universal, this represents the typical distribution of effort that is characteristic of systems engineering projects in the COSYSMO data repository.

By utilizing this effort distribution table along with COSYSMO, a user can better allocate the estimated systems engineering resources. To illustrate,

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assume that P_1, P_2, P_3, P_4, and P_5 represent the fundamental processes as shown in table 2, and that x is the single point estimate provided by COSYSMO.

The sum of the five fundamental processes equals the total systems engineering estimate:

$$\sum_{i=1}^{5} P_i = 100\%$$

Therefore, the COSYSMO estimate (x) can be allocated to each of the five processes.

$x * 0.07$ = effort required for P_1
$x * 0.17$ = effort required for P_2
$x * 0.30$ = effort required for P_3
$x * 0.15$ = effort required for P_4
$x * 0.31$ = effort required for P_5

TOTAL = x

The breakdown of effort by systems engineering process is helpful not only for planning purposes but also when an organization is only interested in estimating part of the systems engineering activities. For example, if the systems engineering organization is only responsible for system design (P_3), product realization (P_4), and technical evaluation (P_5), then the typical effort can be calculated as a function of the adjusted effort factor as follows:

$P_3 + P_4 + P_5$ = adjusted effort factor
$0.30 + 0.15 + 0.31$ = adjusted effort factor
0.76 = adjusted effort factor

The initial estimate provided by COSYSMO, x, is then adjusted by a factor of 0.76 to reflect the absence of "acquisition & supply" (P_1) and "technical management" (P_2) activities. This case is typical when organizations are contracted to perform a supporting systems engineering function in space systems. However, caution should be taken when using these numbers, because they represent an average observed across a range of programs included in COSYSMO. These proportions are likely to change under different circumstances such as a different customer, technical complexity, or business process. Organizations are encouraged to derive their own systems engineering effort profile from their historical data following this WBS or one that applies to their way of doing business.

COSYSMO Lifecycle Phases (*ISO/IEC 15288*)

In the same way that the standard systems engineering activities play a significant role in defining the scope of the activities covered by COSYSMO, the lifecycle phases guide the scope of the estimate. In 2002, an international effort to define systems engineering lifecycle phases yielded the standard *ISO/IEC 15288: Systems Engineering: System Life Cycle Processes* (ISO and IEC 2002). The standard establishes a high-level, common framework for describing the lifecycle of systems based on well-defined processes and terminology.

Despite an infinite variety in models of system lifecycles, *ISO/IEC 15288* provides an essential set of characteristic lifecycle phases for use in the systems engineering domain. The first four lifecycle phases, shown in figure 1, are within the scope of COSYSMO. The final two were included in the data collection effort but did not yield enough data to be useful in the model calibration.

Each stage has a distinct purpose and contribution to the whole lifecycle and represents the major lifecycle periods associated with a system. The stages also describe the major milestones for progress and achievement of the system through its lifecycle and help describe *when* systems engineering activities occur. Since *ISO/IEC 15288* may not be applicable to all space systems, we compare this standard to one more commonly used in the acquisition of space systems by the U.S. Department of Defense.

Space System Lifecycle Phases (*NSS 03-01*)

National Security Space Acquisition Policy 03-01 (U.S. Department of Defense, 2004) presents the guidelines and processes required for the acquisition of space systems. This document is tailored for space applications, parallels the defense department's *Directive 5000.1*, and replaces the processes and procedures described in *Instruction 5000.2* (U.S. Department of Defense 2002). Whereas other acquisition policies from the defense department are focused on the making decisions on the production of large quantities of systems, the NSS acquisition policy provides specific guidance for a small number of high-tech programs, thus addressing the situation most commonly encountered with space systems. Therefore, the acquisition of space systems follows the acquisition lifecycle shown in figure 2.

To illustrate how this acquisition lifecycle is related to the older, "legacy" lifecycle, table 4 maps the Department of Defense *Instruction 5000.2 to NSS 03-01* (Blackman 2003). The third column shows the lifecycle phases from *ISO/IEC 15288*.

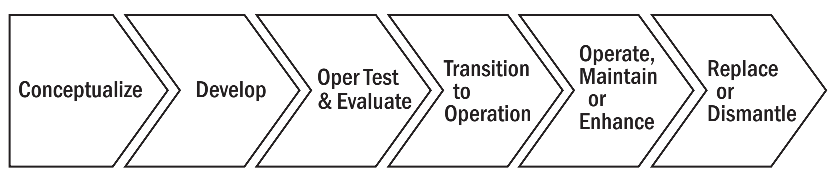

Figure 1. COSYSMO lifecycle phases

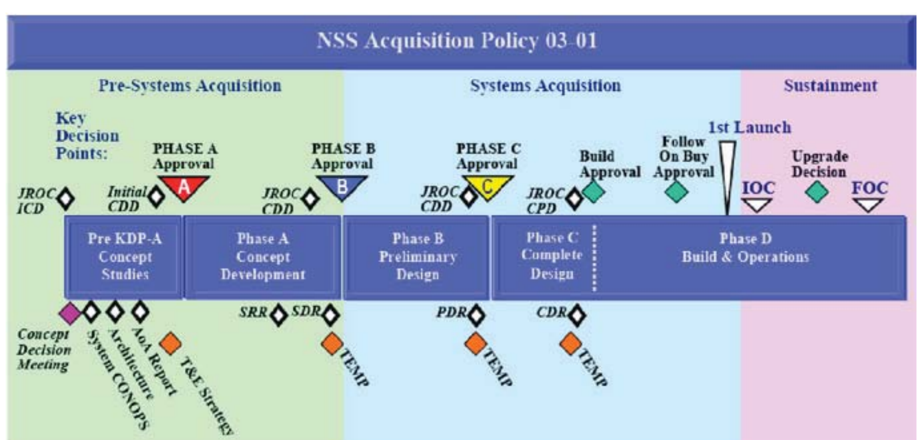

Figure 2. NSS 03-01 *acquisition phases (NSS 2004)*

Two major observations result from the mapping for the lifecycle phases. *NSS 03-01* and *ISO/IEC 15288* begin and end at similar stages and are therefore relatively compatible. But upon closer inspection, it is evident that the mapping is not balanced between the two lifecycles, especially in the "system development" and "transition to operation" phases. This imbalance is not a problem, since the entry and exit points are similar. But care must be taken when estimates are decomposed by lifecycle phase, as defense contractors often are hired only to participate in certain portions of the system's lifecycle.

Partial Estimation of Systems Engineering Effort by Phase

Similar to the way that systems engineering costs can be estimated by activity, space systems engineering costs can be estimated by program phase based on data obtained from the COSYSMO repository. The estimate provided by COSYSMO can be distributed by lifecycle phase for better planning and management of systems engineering activities throughout the lifecycle. COSYSMO assumes that a standard set of systems engineering activities is being performed throughout certain phases in the lifecycle. This typical distribution of effort for systems engineering projects is provided in table 5.

To illustrate its application for adjusting a systems engineering estimate, consider the following example. With A_1, A_2, A_3, and A_4 representing the distribution across lifecycle phases, the sum of the four lifecycle phases equals the total systems engineering estimate:

$$\sum_{i=1}^{4} A_i = 100\%$$

Therefore, the COSYSMO estimate (x) can be allocated across each of the four lifecycle phases.

$x * 0.23$ = effort needed in A_1
$x * 0.35$ = effort needed in A_2
$x * 0.28$ = effort needed in A_3
$x * 0.14$ = effort needed in A_4
TOTAL = x

The breakdown of effort by systems engineering lifecycle phase is helpful not only for resource management purposes but also when an organization is only interested in estimating part of the systems engineering lifecycle. For example, if the systems engineering organization is only responsible for the conceptualization (A_1) and development (A_2) of the system, then the typical effort can be calculated as a function of the adjusted effort factor:

$A_1 + A_2$ = adjusted effort factor
$0.23 + 0.35$ = adjusted effort factor
0.58 = adjusted effort factor

The initial estimate provided by COSYSMO, x, should be adjusted by a factor of 0.58 to reflect the absence of the "operational test and evaluation" (A_3) and "transition to operation" (A_4) lifecycle phases assumed in the estimate.

Implications

In addition to making COSYSMO more relevant to space systems, this work has two important implications. The first is that it enables comparison to a normative effort profile. This helps determine the progress of a program from the perspective of managing earned value. Such resource tracking can serve as a leading indicator for program performance based on a relative determination of whether a program is behind schedule. For example, COSYSMO's effort profile indicates that 35% of the total systems engineering effort should be expended during the development phase of a

Table 4. Comparison of the names of phases in the acquisition lifecycle (adapted from Blackman 2003)

DoD 5000.2	*NSS 03-01*	*ISO/IEC 15288*
Pre-acquisition activities requirements document, concept of operation, analysis of alternatives	Pre key decision point activities requirements document, concept of operation, analysis of alternatives report	Conceptualize
Milestone A Technology development	Key decision point-A Study phase, ends with system requirements review	Develop
	Key decision point-B (program initiation). Design phase (system design review, preliminary design review, and critical design review)	
Milestone B (program initiation); System development and demonstration (starts system integration subphase)		
Mid-phase design readiness review (starts system demonstration subphase)	Key decision point-C Build phase (critical design review, build, test launch, support)	Operational test and evaluation
Milestone C (low-rate initial production decision); Production and deployment phase	"Follow-on buy" or low-rate initial production decision as appropriate	Transition to operation
Milestone decision authority review; Full rate production decision	Major upgrade decision or full rate production decision as appropriate	
		Operate, maintain, enhance
		Disposal

Table 5. The distribution of systems engineering effort across the phases of ISO/IEC 15288 (Valerdi and Wheaton 2005)

Conceptualize	Develop	Operational Test and Evaluation	Transition to Operation
23%	35%	28%	14%

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program. If a program or effort estimate drastically deviates from this, it would warrant further investigation.

The second implication is that the additional level of granularity in the effort estimate can aid in the piecemeal estimation of systems engineering effort. Following the previous example, the systems engineering effort can be adjusted to include only the lifecycle phases being performed. If an organization is only concerned with the "up-front" systems engineering needed for a program, the total systems engineering effort can be proportionately adjusted by the appropriate effort factor.

Ultimately, these methods should be validated by each organization, since the percentages provided could vary depending on organizations and domains. Since this paper has focused on the analysis of systems engineering costs for space systems, we expect that this approach will be useful to organizations operating in the space and related technical domains, who wish to improve their ability to estimate the cost of systems engineering.

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