

System-of-Systems Cost Estimation: Analysis of Lead System Integrator Engineering Activities

Jo Ann Lane, University of Southern California, USA; E-mail: jolane@usc.edu
Dr. Barry Boehm, University of Southern California, USA; E-mail: boehm@cse.usc.edu

Abstract

As organizations strive to expand system capabilities through the development of system-of-systems (SoS) architectures, they want to know "how much effort" and "how long" to implement the SoS. In order to answer these questions, it is important to first understand the types of activities performed in SoS architecture development and integration and how these vary across different SoS implementations. This paper provides results of research conducted to determine types of SoS Lead System Integrator (LSI) activities and how these differ from the more traditional system engineering activities described in Electronic Industries Alliance (EIA) 632 ("Processes for Engineering a System"). This research further analyzed effort and schedule issues on "very large" SoS programs to more clearly identify and profile the types of activities performed by the typical LSI and to determine organizational characteristics that significantly impact overall success and productivity of the LSI effort. The results of this effort have been captured in a reduced-parameter version of the Constructive SoS Integration Cost Model (COSOSIMO) that estimates LSI SoS Engineering (SoSE) effort.

Keywords: *System of Systems, System of Systems Engineering, Lead System Integrator, Cost Model.*

1. Introduction

As organizations strive to expand system capabilities through the development of system-of-systems (SoS) architectures, they want to know "how much effort" and "how long" to implement the SoS. Efforts are currently underway at the University of Southern California (USC) Center for Software Engineering (CSE) to develop a cost model to estimate the effort associated with SoS Lead System Integrator (LSI) activities. The research described in this paper is in support of the development of this cost model, the Constructive SoS Integration Cost Model (COSOSIMO). Research conducted to date in this area has focused more on technical characteristics of the SoS. However, feedback from USC CSE industry affiliates indicates that the extreme complexity typically associated with SoS architectures and political issues between participating organizations have a major impact on the LSI effort. This is also supported by surveys of system acquisition managers (Blanchette, 2005) and studies of failed programs (Pressman and Wildavsky, 1973). The focus of this current research is to further investigate effort and schedule issues on "very large" SoS programs and to determine key activities in the development of SoSs and organizational characteristics that significantly impact overall success and productivity of the program.

2. Background

We are seeing a growing trend in industry and DoD to "quickly" incorporate new technologies and expand the capabilities of legacy systems by integrating them with other legacy

systems, Commercial-Off-the-Shelf (COTS) products, and new systems. With this development approach, we see new activities being performed to define the new architecture, identify sources to either supply or develop the required components, and then to integrate and test these high level components. Along with this “system-of-systems” development approach, we have seen a new role in the development process evolve to perform these activities: that of the LSI. A recent Air Force study (United States Air Force Scientific Advisory Board, 2005) clearly states that the SoS Engineering (SoSE) effort and focus related to LSI activities is considerably different from the more traditional system development projects. According to this report, key areas where LSI activities are more complex or different than traditional systems engineering are the system architecting, especially in the areas of system interoperability and system “ilities”; acquisition and management; and anticipation of needs.

Key to developing a cost model such as COSOSIMO is understanding what a “system-of-systems” is. Early literature research (Jamshidi, 2005) shows that the term “system-of-systems” can mean many things across different organizations. For the purposes of the COSOSIMO cost model development, the research team has focused on the SoS definitions provided in (Maier, 1999) and (Sage and Cuppan, 2001): an evolutionary net-centric architecture that allows geographically distributed component systems to exchange information and perform tasks within the framework that they are not capable of performing on their own outside of the framework. This is often referred to as “emergent behaviors”. Key issues in developing an SoS are the security of information shared between the various component systems, how to get the right information to the right destinations efficiently without overwhelming users with unnecessary or obsolete information, and how to maintain dynamic networks so that component system “nodes” can enter and leave the SoS.

Today, there are fairly mature tools to support the estimation of the effort and schedule associated with the lower-level SoS component systems (Boehm et al, 2005). However, none of these models supports the estimation of LSI SoSE activities. COSOSIMO, shown in Figure 1, is a parametric model currently under development to compute just this effort. The goal is to support activities for estimating the LSI effort in a way that allows users to develop initial estimates and then conduct tradeoffs based on architecture and development process alternatives.

Recent LSI research conducted by reviewing LSI statements of work identifies the following typical LSI activities:

- Concurrent engineering of requirements, architecture, and plans
- Identification and evaluation of technologies to be integrated
- Source selection of vendors and suppliers
- Management and coordination of supplier activities
- Validation and feasibility assessment of SoS architecture
- Continual integration and test of SoS-level capabilities
- SoS-level implementation planning, preparation, and execution

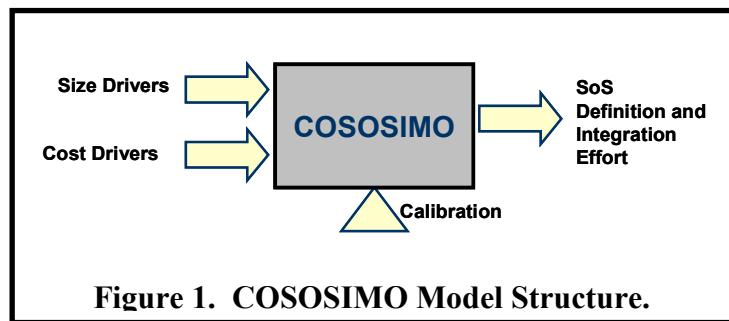


Figure 1. COSOSIMO Model Structure.

- On-going change management at the SoS level and across the SoS-related integrated product teams to support the evolution of requirements, interfaces and technology.

3. LSI Effort Estimation Approach

As mentioned above, key to an LSI effort estimation model is having a clear understanding of the SoSE activities performed by the organization as well as which activities require the most effort. In addition, it is important to understand how these SoSE activities differ from the more traditional systems engineering activities. Analysis presented in (Lane 2005) describes how the typical LSI SoSE activities differ from the more traditional system engineering activities identified in EIA 632 (Electronic Industries Alliance, 1999) and the Software Engineering Institute (SEI) Capability Maturity Model Integration (CMMI) (Software Engineering Institute, 2001). Subsequently, Delphi surveys conducted with USC CSE industry affiliates have identified key size drivers and cost drivers for LSI effort and are shown in Table 1.

Table 1. COSOSIMO Cost Model Parameters.

Size Drivers	Cost Drivers	
<ul style="list-style-type: none"> • # SoS-related requirements • # SoS interface protocols • # independent component system organizations • # SoS scenarios • # unique component systems 	<ul style="list-style-type: none"> • Requirements Understanding • Architecture Maturity • Level of Service Requirements • Stakeholder team cohesion • SoS team capability • Maturity of LSI processes 	<ul style="list-style-type: none"> • Tool support • Cost/schedule compatibility • SoS Risk Resolution • Component system maturity and stability • Component system readiness

Because there are concerns about the availability of effort data from a sufficient number of SoS programs to support model calibration and validation, current efforts are focussing on defining a “reduced parameter set” cost model or ways to estimate parts of the LSI effort using fewer, but more specific,

parameters. The following paragraphs present the results of this recent research.

Further observations of LSI organizations indicate that the LSI activities can be grouped into three areas: 1) planning, requirements management, and architecting, 2) source selection and supplier oversight, and 3) SoS integration and testing. There are typically different parts of the LSI organization that are responsible for these three areas. Figure 2 illustrates, conceptually, how effort for these three areas is distributed across the SoS development life cycle phases of inception, elaboration, construction, and transition for a given increment or evolution of SoS development.

Planning, requirements, and architecting begin early in life cycle. As the requirements are refined and the SoS architecture is defined and matured, source selection activities can begin to identify component

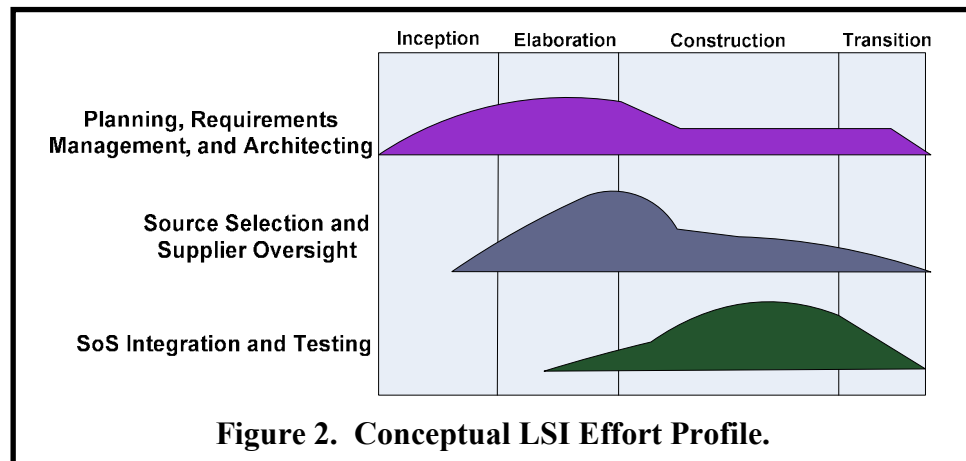


Figure 2. Conceptual LSI Effort Profile.

system vendors and to issue contracts to incorporate the necessary SoS-enabling capabilities. With a mature SoS architecture and the identification of a set of component systems for the current increment, the integration team can begin the integration and test planning activities. Once an area ramps up, it continues through the transition phase at some nominal level to ensure as smooth a transition as possible and to capture lessons learned to support activities and plans for the next increment. (Boehm and Lane, 2006) describes how some of these activities directly support the current plan-driven SoS development effort while others are more agile, forward looking, trying to anticipate and resolve problems before they become huge impacts. The goal is to stabilize development for the current increment while deferring as much change as possible to future increments. For example, the planning/requirements/architecture group continues to manage the requirements change traffic that seems to be so common in these large systems, only applying those changes to the current increment that are absolutely necessary, and deferring the rest to future increments. The architecture team also monitors current increment activities in order to make necessary adjustments to the architecture to handle cross-cutting technology issues that arise during the component system supplier construction activities. Likewise, the supplier oversight group continues to monitor the suppliers for risks, cost, and, schedule issues that arise out of SoS conflicts with the component system stakeholder needs and desires. As the effort ramps down in the transition phase, efforts are typically ramping up for the next increment or evolution.

By decomposing the COSOSIMO cost model into three components that correspond to the three primary areas of LSI SoSE effort, the parameter set for each COSOSIMO component can be reduced from the full set and the applicable cost drivers made more specific to the target area. Table 2 shows the resulting set of size and cost drivers for each of the three primary areas.

Table 2. COSOSIMO Parameters by SoSE Area.

COSOSIMO Component	Associated Size Drivers	Associated Cost Drivers	
Planning, Requirements Management, and Architecting	<ul style="list-style-type: none"> • # SoS-related requirements • # SoS interface protocols 	<ul style="list-style-type: none"> • Requirements understanding • Level of service requirements • Stakeholder team cohesion • SoS planning/reqs/ architecting capability • Maturity of LSI planning/ reqs/ architecting processes 	<ul style="list-style-type: none"> • Planning/reqs/architecting tool support • Cost/schedule compatibility with planning/reqs/ architecting processes • SoS planning/reqs/ architecting risk resolution
Source Selection and Supplier Oversight	<ul style="list-style-type: none"> • # independent component system organizations 	<ul style="list-style-type: none"> • Requirements understanding • Architecture maturity • Level of service requirements • SoS source selection/ oversight capability • Maturity of LSI source selection/oversight processes 	<ul style="list-style-type: none"> • Supplier selection/oversight tool support • Cost/schedule compatibility with source selection/ oversight activities • SoS source selection risk resolution
SoS Integration	<ul style="list-style-type: none"> • # SoS interface protocols • # SoS scenarios • # unique component systems 	<ul style="list-style-type: none"> • Requirements understanding • Architecture maturity • Level of service requirements • SoS integration capability • Maturity of LSI integration processes • Integration tool support 	<ul style="list-style-type: none"> • Cost/schedule compatibility with integration activities • SoS integration risk resolution • Component system maturity and stability • Component system readiness

This approach allows the model developers to calibrate and validate the model components with fewer parameters and data sets. It also allows the collection of data sets from organizations that are only responsible for a part of the LSI SoSE activities. Finally, this approach to LSI SoSE effort estimation allows the cost model to provide estimates for the three areas, as well as a total estimate—a key request from USC CSE industry affiliates supporting this research effort.

4. Conclusions

LSI organizations are realizing that if more traditional processes are used to architect and integrate SoSs, it will take too long and too much effort to find optimal solutions and build them. Preliminary analysis of LSI activities shows that while many of the LSI activities are similar to those described in EIA 632 and the SEI's CMMI, LSIs are identifying ways to combine agile processes with traditional processes to increase concurrency, reduce risk, and further compress overall schedules. In addition, effort profiles for the key LSI activities (the up-front effort associated with SoS abstraction, architecting, source selection, systems acquisition, and supplier and vendor oversight during development, as well as the effort associated with the later activities of integration, test, and change management) show that the percentage of time spent on key activities differs considerably from the more traditional system engineering efforts. By capturing the effects of these differences in organizational structure and system engineering processes in a reduced parameter version of COSOSIMO, management will have a tool that will better predict LSI SoSE effort and to conduct “what if” comparisons of different development strategies.

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