

Synthesizing SoS Concepts for Use in Cost Estimation

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Abstract - *Today's need for more complex, capable systems in a short timeframe is leading many organizations towards the integration of existing systems into network-centric, knowledge-based system-of-systems (SoS). Software and system cost model tools to date have focused on the software and system development activities of a single system. When viewing the new SoS architectures, one finds that the effort associated with the design and integration of these SoSs is not handled well, if at all, in current cost models. This paper includes (1) a comparison of various SoS definitions and concepts with respect to cost models, (2) a classification of these definitions in terms of product, process, and personnel focus, and (3) the definition of a set of discriminators for defining model boundaries and potential drivers for an SoS cost estimation model. Eleven SoS definitions are synthesized to provide reasonable coverage for different properties of SoS and illustrated in two examples.*

Keywords: System of Systems definitions, cost estimation, cost modeling, FCS, GEOSS.

1 Current system and software cost estimation models

A growing trend is emerging 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, new activities are being performed to define the new architecture, identify sources to either supply or develop the required components, and eventually integrate and test these high level components. Along with this “system-of-systems” (SoS) development approach, a new role in the development process has evolved to perform these activities: that of the Lead System Integrator (LSI).

Today, there are increasingly sophisticated, albeit subjective tools to support the estimation of the effort and schedule associated with the development of the lower-level SoS component systems using three categories of parameters: product characteristics, process characteristics, and personnel characteristics. [1]

- At the single system level, there is COSYSMO to estimate the system engineering effort and PRICE H and SEER-H to estimate hardware development costs.
- For software development activities, there are the COCOMO II, Cost Xpert, Costar, PRICE S, and SEER-SEM cost models.
- For the implementation and integration of COTS, there is COCOTS to estimate the effort associated with the assessment, tailoring, and glue-code implementation of COTS software products.

Despite the availability of the aforementioned models, none of these models includes SoS-related activities such as the definition of the SoS architecture, the solicitation and procurement process for the SoS components, and the integration of the SoS components into the SoS framework. Many organizations often estimate these costs using a percentage of the lower level system component development costs. While this may be sufficient in some cases, it is not helpful in determining the individual drivers that affect LSI cost and schedule. A better understanding of these drivers can help the acquirers and developers (a) reduce the risk of underestimating or overestimating the resources needed to support their investment in large technology-intensive systems, and (b) explore alternatives and support trade-off activities.

2 What is a SoS?

A review of recent publications [2] and feedback received from industry via workshops [3] show that the term “system-of-systems” means many things to many different people and organizations. In the business domain, an SoS is the enterprise-wide integration and sharing of core business information across functional and geographical areas. In the military domain, an SoS is a dynamic communications infrastructure to support operations in a constantly changing, sometimes adversarial, environment. For some, an SoS may be a multi-system architecture that is planned up-front by an LSI. For others, an SoS is an architecture that evolves over time, often driven by organization needs, new technologies appearing on the horizon, and available budget and schedule. The

evolutionary SoS architecture is more of a network architecture that grows with needs and available resources.

In any case, users and nodes in the SoS network may be either fixed or mobile. Communications may be either point-to-point or broadcast. Networks may tie together other networks as well as nodes and users. SoS component systems typically come and go over time. These component systems can operate both within the SoS framework and independent of this framework. In a general sense, it is challenging to define clear boundaries of an SoS because of its dynamic nature. Equally challenging is the process of deciding what systems appropriately deserve the SoS label because, depending on an individual's system-of-interest, one person's subsystem may be another's system.

This paper begins by dissecting the most relevant concepts available and continues by defining a set of useful discriminators for determining the applicability of these concepts to the area of cost estimation. This approach gets one step closer to understanding the types of SoS characteristics that can be used to define a relevant set of parameters that estimate the effort associated with the LSI role.

2.1 Current SoS-related concepts

In preparation for this year's IEEE Systems, Man, and Cybernetics conference, Professor Mo Jamshidi compiled a group of SoS definitions from a diverse group of authors. [2] Each definition focused on distinct types, characteristics, and applications of SoSs. The list below includes Jamshidi's compilation as well as other concepts appropriate to the context of SoS cost modeling. At first glance it is apparent that these definitions have very little in common, possibly due to the diversity of interests and applications addressed. However, they help define the scope of SoS that is relevant for cost estimation purposes. The definitions are presented in chronological order to show how the SoS-related concepts have evolved over time.

Eisner: Systems of systems are large geographically distributed assemblages developed using centrally directed development efforts in which the component systems and their integration are deliberately, and centrally, planned for a particular purpose. [4]

Shenhar: An array system (system of systems) is a large widespread collection or network of systems functioning together to achieve a common purpose. [5]

Manthorpe: In relation to joint warfighting, system of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR) Systems. [6]

Kotov: Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems. [7]

Lukasik: SoS Engineering involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure. [8]

Maier: A system-of-systems is a set of collaboratively integrated systems that possess two additional properties: operational independence of the components and managerial independence of the components. [9]

Pei: System of Systems Integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios. [10]

Carlock and Fenton: Enterprise Systems of Systems Engineering is focused on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis. [11]

Sage and Cuppan: Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development. [12]

Gupta: The key success factor for good LSIs is not their internal capabilities to design, develop, and implement major defense systems, but their ability to be visionaries and leaders who can coordinate, motivate, and work closely with a set of co-contractors to achieve the ultimate objective in an optimal manner. The LSI must seek to perform its mission not by performing the bulk of the work in-house, but by seeking to leverage the work that is being done by others in a highly coordinated manner. [13]

Bergey, O'Brien, and Smith: An LSI is an agent with the authority to acquire and integrate assets from a variety of potential system suppliers on behalf of an organization that is acquiring a complex software-intensive system. The LSI has the authority to contract with and manage other suppliers on behalf of the acquirer. A primary task of the LSI is to determine early in the integration cycle whether required software assets can be mined from existing assets, can be purchased as COTS components, or need to be developed from scratch. [14]

2.2 Classification of SoS definitions

On closer inspection of these definitions, it is apparent that they each have a different application domain such as military, private enterprise, or education. They also focus on different characteristics of the SoS. These characteristics have been classified into the following three

foci: operational/product, implementation/process, and personnel. Most of the definitions that were analyzed focus on either the product or process characteristics of SoS. In fact, most definitions address both. However, only two of the eleven definitions address the personnel characteristics of the SoS, a crucial function typically played by the Lead Systems Integrator. Table 1 provides a summary of the different foci and the definitions that apply.

Table 1. Focus of Selected SoS-Related Definitions

Definition	Focus		
	Product	Process	Personnel
Eisner	X	X	
Shenhar	X		
Manthorpe	X		
Kotov	X		
Lukasik	X	X	
Maier	X	X	
Pei	X	X	
Carlock and Fenton		X	
Sage and Cuppan	X	X	
Gupta			X
Bergey, O'Brien, and Smith		X	X

Rather than comparing these definitions and attempting to develop a “best” definition for SoS, a more appropriate approach is to analyze them to determine a common set of SoS characteristics that can be synthesized with our SoS cost model goals and later be used to define an appropriate set of model size drivers and scale factors. A set of discriminators has been developed to help distinguish features and clarify the distinction between definitions that apply or don’t apply to cost modeling. These discriminators are then applied to two current government SoS programs.

3 Model development process

One of the best-known quality gurus, W. Edwards Deming, popularized the teaching “If you can’t measure it, you can’t manage it.” In order for this teaching to be effective, Deming must have assumed that there was a good definition for whatever was being measured. In the case of cost estimation, there needs to be: (1) clear definitions of what is being estimated, (2) clearly defined cost model parameters, and (3) established counting rules

for size factors. Consider the following example: when attempting to estimate the cost of LSI effort in the context of SoS it is essential to (1) clarify what is meant by SoS, (2) define parameters relevant to SoS and LSI activities, and (3) develop counting rules for the relevant size factors that influence cost in this setting. Defining what is being estimated has led us to an equivalent corollary to Deming’s teaching: “If you can’t describe it, you can’t estimate it.” This statement is an antecedent to Deming’s teaching and creates the following logical sequence: describe → estimate → measure → manage. The current focus is to describe SoSs in order to facilitate the estimation and eventually management of SoS development activities.

In an effort to determine criteria relevant to the development of a SoS cost model, it is important to understand the process of developing a cost estimation model. The University of Southern California (USC) Center for Software Engineering (CSE) has developed and used a seven-step process for creating cost models, as illustrated in Figure 1. [15]

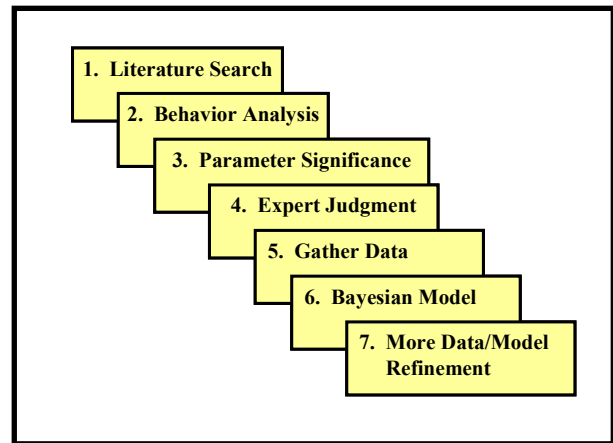


Figure 1. USC CSE Cost Estimation Development Methodology

Prior to step 1 in this methodology, it is essential to identify a market for a cost estimation model. This is typically a group of stakeholders that will support the model development effort with funding, expertise, and data. Without these three forms of support it is very difficult to develop an industry validated cost model in a research setting. The full life cycle of a cost estimation model might be viewed as a cyclical process as shown in Figure 2.

Once a market for the model has been identified and the stakeholder needs are understood, a spiral process begins that involves the development, use, and refinement of model artifacts. The role of industry practitioners is crucial in this process since they provide the real-life examples of SoS.

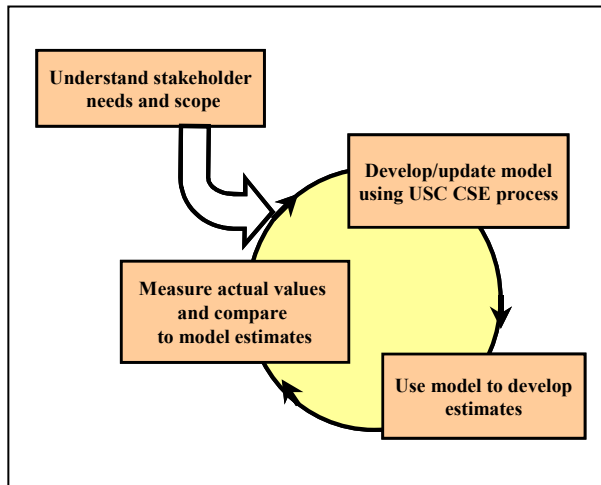


Figure 2. Cost Estimation Model Life Cycle

4 Discriminators for evaluating definitions

During the process of analyzing the different SoS definitions, a set of discriminators were developed to help filter existing definitions. An acceptable definition must obtain at least one of the discriminators. No single definition may meet all three discriminators, but portions of each definition can be borrowed to help guide users to the next step of creating meaningful metrics. The main feature of interest is the descriptiveness of each definition and whether it has a product, process, or personnel focus.

Discriminator #1—The SoS Stakeholders: For an SoS cost estimation model to be useful, it is important that there exist strategically-oriented organizations that have a need for this type of information. These organizations include *clients that will pay for the system* and signoff on major milestones as well as *user communities* that will be responsible for SoS operation and sustainment.

Discriminator #2—The LSI and SoS Architecture: The program must identify a single (or an obvious set of) Lead Systems Integrator(s) that is responsible for the definition of the SoS architecture and the total component integration and test activities at the SoS level. It is important that this organization have *complete technical oversight* over the entire SoS and SoS component suppliers. This ensures that an organization be responsible for defining an overall architectural vision for the SoS while maintaining the architectural concepts throughout the development, integration, and test phases. This is in contrast to SoSs that are more evolutionary in nature and based on much shorter-term strategies that can change frequently due to business needs and performance.

Discriminator #3—System Component Independence: Each of the system components envisioned within the SoS must be independent with respect to development, maintenance, and operation. This allows estimators to use

existing system and software cost estimation models to estimate the implementation of SoS-enabling functionality and minimize the potential overlap between the SoS cost estimation model and the system and software cost estimation models.

5 Synthesizing definitions

Now that the different definitions of SoS have been described and the discriminators for evaluating them have been presented, the next step is to synthesize these definitions and identify what each of them provides in the domain of cost estimation. As previously stated, the more discriminators met, the more useful the definition is for purposes of cost estimation. The results of the evaluation of these definitions are presented in Table 2.

Table 2. Results of Definition Synthesis

Definition	Discriminator		
	1	2	3
Eisner	X	X	
Shenhar	X		X
Manthorpe			X
Kotov			X
Lukasik			X
Maier		X	X
Pei	X	X	X
Carlock and Fenton	X		
Sage and Cuppan		X	X
Gupta	X	X	
Bergey, O'Brien, and Smith		X	X

It is clear from the information in Table 2 that many of the selected SoS-related definitions meet at least two of the cost model discriminators and that together, the selected definitions provide reasonable coverage of the product, process, and personnel characteristics of interest in cost modeling. To test these discriminators, two systems generally thought to be system-of-systems are analyzed in terms of consistency and relevancy with respect to the selected criteria: the US Army's Future Combat System and the Group on Earth Observation's Global Earth Observation System of Systems.

Future Combat System (FCS): As stated in an October 2004 white paper [16], "FCS is a joint networked system of systems...connected via an advanced network architecture that will enable levels of joint connectivity, situational awareness and understanding, and synchronized operations heretofore unachievable. FCS will operate as a SoS that will network existing systems, systems already under development, and systems to be developed to meet the requirements of the Army's Future Force Unit of

Action.” An architecture view of FCS is shown in Figure 3.

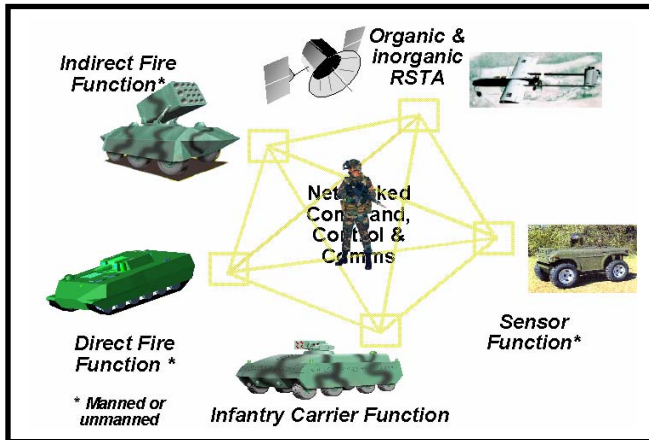


Figure 3. FCS SoS Architecture View [17].

A summary of the three discriminators for the FCS is provided in Table 3. All three discriminators are easily identifiable and well suited for an SoS cost model to estimate LSI effort, making the FCS an exemplar for SoS cost modeling tools.

Table 3. FCS Discriminators

Discriminator	Fulfilled by
1: SoS stakeholder	US Army
2: LSI & SoS Architecture	LSI: Boeing & SAIC Architecture: See Figure 3
3: Component Independence	See Figure 3

Global Earth Observation System of Systems (GEOSS): As stated on the Environmental Protection Agency’s (EPA) GEOSS website [18], the “earth observation systems consist of measurements of air, water, and land made on the ground, from the air, or from space. Historically observed in isolation, the current effort is to look at these elements together and to study their interactions.” Over 100 datasets, models, decision support tools, and programs are identified as part of GEOSS. [18] One of these earth observation elements is the Tropical Ocean Global Atmosphere (TOGA) project. It includes a comprehensive array of moored buoys, drifting buoys, tide gauges, and volunteer observation ships along the Pacific Ocean as shown in Figure 4.

Contrary to FCS, the three discriminators are not yet clearly defined or easily determined, possibly as a result of the collaborative, loosely-coupled, emergent nature of GEOSS.

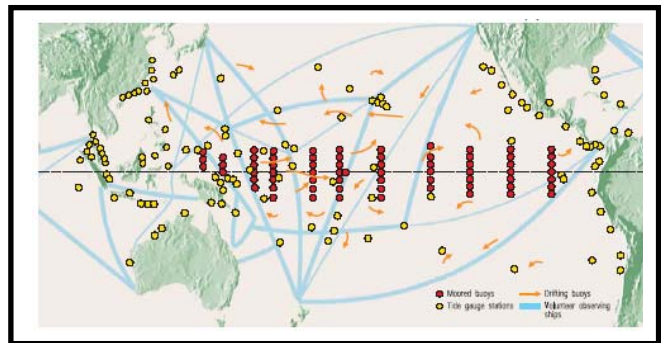


Figure 4. GEOSS TOGA Operational View [18].

For instance, the complicated structure of the Group on Earth Observations (GEO) involves over 80 countries and participating organizations. The structure of GEO does not allow for a single organization to act as a majority stakeholder. The primary focus of the GEO appears to be worldwide collaboration and sharing of data and information from a variety of systems, with no significant plans to tightly integrate the systems or data. While there is distinct component independence, there is no primary set of stakeholders or LSI organizations. Rather, it is designed to be an evolutionary SoS that is supported by member organizations. The member organizations can be viewed as both the stakeholders and the LSIs. While GEOSS is a valid SoS by many of the SoS definitions identified earlier, the discriminators indicate that GEOSS is not a good candidate for cost modeling at this time. A summary of the three discriminators for GEOSS is provided in Table 4.

Table 4. GEOSS Discriminators

Discriminator	Fulfilled by
1: SoS stakeholder	52 member countries and 29 participating organizations
2: LSI & SoS Architecture	LSI: Political officials acting as members of the GEO Architecture: not yet defined
3: Component Independence	Existing/new systems, datasets, models, decision support tools and programs

The FCS and GEOSS provide two examples of SoS developments that behave differently when compared in terms of our three discriminators. Going back to the earlier corollary “if you can’t describe it, you can’t estimate it”, one sees with the three discriminators that the FCS LSI effort is a good candidate for cost estimation, while GEOSS SoS design and integration is too undefined to support cost estimation. The GEO organization may find an SoS cost model beneficial in the future if the SoS evolves to include tighter integrations of subsystems, tools, and databases.

6 Conclusions

A crucial first step in developing relevant models involves the identification of what is being modeled. This paper synthesized existing SoS definitions and developed concepts to evaluate different properties of SoS. It also showed that the product, process, and personnel characteristics needed for cost model development are adequately covered by eleven existing definitions. Moreover, these characteristics have enabled the development of three discriminators for evaluating the relevance of SoS definitions in the area of cost modeling. These discriminators were useful for evaluating two distinct SoSs: FCS and GEOSS. The FCS discriminators are well-defined and well-suited for cost modeling, making it a good candidate for cost model development. GEOSS, however, is not a good candidate for cost model development because of its loosely-defined stakeholders, disparate LSI, and unpredictable architecture.

The synergy of the eleven definitions, their coverage of three relevant characteristics, and the development of the three discriminators will aid the SoS cost model developers in the next steps as they proceed to develop and refine relevant cost and size drivers in the SoS context. The cost and size drivers are based on the SoS architecture characteristics (product), processes used for design and integration/test (process), and LSI experience and capabilities (personnel). The three discriminators will also help in identifying more SoSs, other than FCS, that can be used to test these drivers and calibrate a cost model.

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