Proc. of the 2011 6th International Conference on System of Systems Engineering, Albuquerque, New Mexico, USA - June 27-30, 2011

Implications of Systems of Systems on System Design and Engineering

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***Abstract*— Over the past ten years there has been a steady growth in attention to issues related to systems of systems (SoS) and systems engineering, particularly in Defense in the United States. This attention has focused on how to apply SE principles and practices to SoS, considering the differences between systems and SoS. For many organizations, however, despite recognition of SoS considerations, the focus of investment and development continues to be on individual systems. This paper looks at SoS and SE from the perspective of constituent systems and examines impacts on systems engineering of systems in light of the increased prevalence of SoS. The paper addresses these issues based on the experience and viewpoint of the U.S. Department of Defense and identifies areas for further attention in systems engineering research and practice.**

Keywords- system of systems, system of systems engineering, systems engineering, requirements concepts of operations, adaptability, architecture

I. Background and Introduction

Beginning with the 2000 Quadrennial Defense Review (QDR) [1], the U.S. Department of Defense (DoD) has been reorienting their acquisition decisions based on assessment of current and future user capabilities. The current U.S. DoD requirements definition system, Joint Capabilities Integration and Development System [2] established in 2003, identifies material needs in terms of user capability gaps. Most user capabilities require multiple systems to work together to meet user needs, so there has been increased emphasis on understanding SoS behavior toward user capability objectives, with SoS defined as " a set or arrangement of systems that results when independently useful systems are integrated into larger systems which deliver unique capabilities"[3]. In cases in which the user capability has high priority, the DoD has created organizations and processes focused on achieving the SoS capability. An example of this is Missile Defense Agency. This SoS focus has led to efforts to understand how SE can best be applied to capabilities through engineering of SoS. The DoD published a Guide to Systems Engineering for Systems of Systems [3]. This guide drew on the successful patterns of experience among practitioners to provide an understanding of the nature of SoS in the U.S. DoD, the characteristics of SoS which affect the way SE practices are applied, and guidance on application of SE to SoS.

In DoD, SoS are typically composed of fielded systems which are identified to address new or emerging user needs, often while these systems continue to support original users. SoS evolution is based on changes in these constituent systems, making these systems the essential building blocks of SoS. Figure 1 below shows a view of the core elements of SoS SE [3] showing how changes in the constituent systems are the components of each increment of SoS evolution.

A recent exploratory analysis of the portfolio of SoS in DoD indicates that SoS are pervasive across the DoD. SoS play a role in all of the military Services and address needs across all the U.S. DoD Joint Capability Areas from force application and protection to command and control, battle space awareness and logistics. Even when an SoS is led by one Service, in almost all cases, that SoS includes constituent systems from other Services, and most defense systems are part of one or more SoS, whether they explicitly acknowledge this or not.

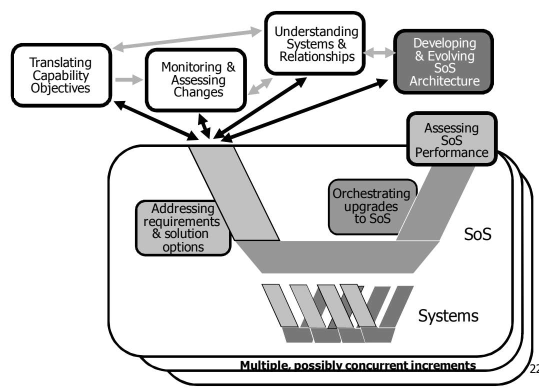

Figure 1: Systems in Context of SoS SE Core Elements [3]

In parallel, SE for SoS has been addressed in SE literature. Beginning with Maier's work on architecting SoS [4] which continues to be foundational after more than a decade, this literature reflects a continued interest in definitions of SoS and SoS characteristics. Key articles include Maier's taxonomy of SoS [4], Sauser and Boardman's "Systems of Systems – The Meaning of It [5] and others [6,7]. Literature has focused on SoS level considerations in policy and on management of SoS [8,9,10], in approaches to analysis and architecting of SoS [11], and in the form and handling of SoS in sectors beyond defense [12].

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This SoS SE literature explores the role systems play in SoS. It recognizes that constituent systems are typically in place when an SoS is created and that these systems were often developed to address needs independent of the SoS, needs which continue even with the advent of a recognized SoS initiative. The literature says little about implications of the trend toward SoS for the engineering of systems. If the trend towards SoS continues, most new systems can expect to be constituents of one or more SoS throughout their service lives. There has been very little attention to how systems engineers should address the engineering of new systems so they are able to support current and future SoS.

This paper examines SoS implications for development of individual systems and the impact of system development approaches on the evolution of SoS with the objective of identifying areas within traditional SE processes which warrant increased attention in order to address the system demands of today and tomorrow.

II. Role of SoS Context in SE Processes

This discussion begins with a review of how systems engineering currently addresses SoS context.

Classic systems engineering processes focus on the system, taking user needs, translating these into system requirements and establishing system boundaries and interfaces based on an understanding of the users' needs. For example, in Blanchard and Fabrycky's "Systems Engineering and Analysis" [14] discussion of "Problem Definition and Need Identification" (p54), they state "[t]he systems engineering process generally commences with the identification of a "want" or "desire" for something and is based on a real (or perceived) deficiency." Their only reference to the broader user context is in their discussion of the definition of system operational requirements, where they say "Once the need and technical approach have been defined, it is necessary to translate this into some form of "operational scenario," or set of operational requirements." (p59) The focus is on understanding the specifics of the system ('mission of the system') to address questions about the system itself, versus the user mission ('the role of the system in that larger mission context') as they address questions including: "What are the anticipated type and quantities of equipment, software, personnel, facilities, etc require, and where are they to be located?" Once these 'system operational requirements' are defined, the focus is entirely on the engineering of the system, independent of consideration of its context of use.

Kossiakoff and Sweet's[15] discussion of complex systems more explicitly addresses the "system environment." For them, "[t]he system environment can be broadly defined as everything outside of the system. The interactions of the system with its environment form the main substance of the system requirements." They emphasize clear definition of the system boundaries and interfaces. In their discussion of needs analysis, the focus is broader, calling for operational analysis to validate the need and define operational requirements. In this context, they introduce the utility of a Concept of Operations, which includes mission descriptions with success criteria, relationships with other systems or entities, information sources and destinations and other relationships or constraints. (p147). However, they caveat this point with the statement that: "Since operational requirements are first formulated as a result of studies and analyses performed outside a formal project structure, they tend to be less complete and rigorously structured than requirements prepared in the subsequent managed phases of the development and are mainly oriented to justifying the initiation of a system development" (p146). Notably, their discussion of the "subsequent managed phases of the development" is focused on the system itself without further consideration of the context of use.

In the U.S. DoD, SE policy and guidance focuses on enabling effective system acquisition by defining specific user needs and ensuring that new systems meet the specific requirements of those needs. Consideration of context traditionally takes the form of specifying system interfaces for information exchange. Only recently has there been attention on the considerations of the longer-term use of the systems and the potential role for systems in multiple current and future missions.

A review of DoD requirements definition [2], acquisition [16] and systems engineering [17] identifies those points in these processes where DoD policy or guidance calls for consideration of the SoS context to be addressed.

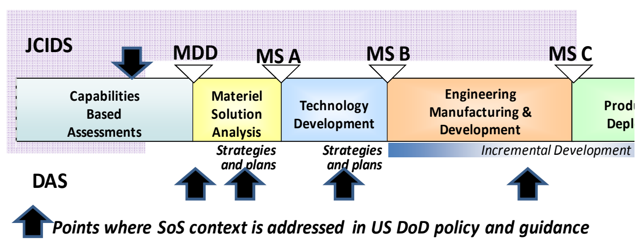

Figure 2: SoS context DoD requirements and acquisition policy and guidance

Context is important to the DoD requirements process. It is core to conducting capability based assessments and setting user capability needs. Capability based assessments examine operational capability needs in a mission or operational context. These are often expressed in terms of mission threads or kill chains, the military equivalent of business architectures. Analysis examines the employment of current or projected material and non-material assets to meet the user capability or mission objectives. Gaps are identified and when analysis shows that non-materiel changes cannot close the gap, a new acquisition may be considered.

For acquisition, context plays a role in the front end of the process and at key points in the acquisition lifecycle. New policy [18] on Development Planning has made consideration of the context (particularly interdependencies) part of the decision to initiate an acquisition (at the Materiel Development Decision (MDD); this policy shift is largely a result of the capability (versus platform) focus of the material investment process. At this initial stage it is important to assess whether filling a gap with a particular new system will affect the target war fighter operational capability. Particularly if there are multiple gaps and/or system dependencies, a new or upgraded system may not be sufficient to improve capabilities in the field. A new sensor, for example, may need a new downlink or expanded communications capacity to affect the results of a mission engagement. By considering these interdependencies, or *SoS context* at the start of a new acquisition, plans can be made to ensure the full complement of solutions and performance attributes are considered in the decision to invest. Failure to adequately evaluate these interdependencies can result in unplanned cost and schedule growth, as well as redesign due to unforeseen constraints. In severe cases, the developer may find the system to meet all performance specifications, but fail to be operationally effective.

Current acquisition policy also emphasizes SoS context in key programmatic and technical plans including the acquisition strategy, systems engineering, and test and evaluation plans. These are prepared for review at major milestones.

U.S. DoD SE guidance emphasizes SoS context as part of program formulation, requirements, and integration. Key SE technical reviews include considerations of interdependencies, interfaces, and information exchange requirements. These areas are important given the long time it takes to develop a complex weapon system or platform and the dynamics of the operational environment. As is shown in Figure 3 below, SE technical reviews pan the acquisition process.

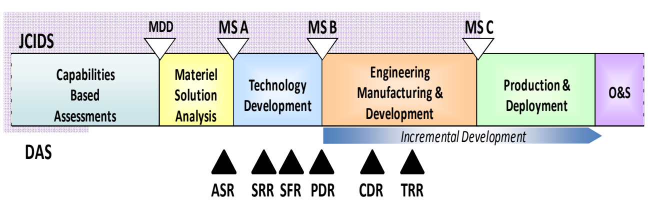

Figure 3: SE technical reviews address SoS context

So, while classic SE processes may not consider the SoS context beyond the initial definition of system requirements, DoD SE policy and guidance have recognized the importance of context early (requirements setting) and throughout the acquisition process in design, engineering, and testing of systems. Questions remain on how SE can support this more deliberate incorporation of context as a consideration in system design and development.

- While policy and guidance can establish formal expectations, the real question is how do you put that policy and guidance into practice?
- What does it mean for SE to consider context throughout the engineering process?
- How do we practically introduce context into the engineering of systems?

III. Some Characteristics of a 'Good' Constituent System

What are the characteristics of systems which make them good constituents of one or more SoS? Based on the work done to support the development of the DoD Systems Engineering Guide for Systems of Systems [4] and follow-up engagement with SoS SE practitioners, there is a set of characteristics of constituent systems that make them useful participants in SoS.

- Understanding the role in the larger capability, and consideration of this role in requirements

Most constituent systems were designed to meet a user need independent of an SoS and the original needs may not be coincident with the SoS needs. When systems owners are open to the expanded role their system can play in an SoS, and extend their system objectives to incorporate the broader set of requirements of the SoS, they proactively identify ways they can support SoS performance and become a cooperative element in the evolution of the SoS. Boardman and Sauser [5] term this 'belonging' and they see it as a key element in characterizing an SoS. Constituent systems with a strong sense of 'belonging' are more likely to identify ways they can support SoS objectives and accommodate need for changes within their larger development processes.

- Designs that facilitate changing or extending functionality and adapting interfaces

The current DoD acquisition system along with the classic SE approach emphasize clear, early specification of requirements and focused development on meeting those requirements. In the commercial environment, development often considers design for adaptation and change to meet new or emerging customers and business opportunities. Systems developed using standard interfaces, open architectures and modular designs all have the inherent ability to respond to changes. As such, they have lower costs for adapting to needs of a changing SoS.

- Short development cycles providing more opportunities to request and make changes within a shorter timeline

Because SoS evolve based on changes in systems, systems with incremental development approaches with frequent increments provide more opportunities for SoS to introduce changes into systems, and facilitate more rapid evolution of the SoS capability.

- Configuration management and requirements processes designed to welcome outside inputs, which implicitly recognize that there are multiple system users and stakeholders

In many ways, SoS can be considered additional users of a system. Systems with configuration management and requirements processes which allow for multiple users to participate provide a more natural way for SoS to work with systems and their stakeholders to articulate their needs from the systems.

- Business model which provides a way to support changes and address issues of maintenance

Finally, it is beneficial if these management processes are accompanied by a business process with contracting and funding mechanisms that facilities full lifecycle cost considerations, valuing flexibility as a design attribute, planned increments to allow opportunity to address changing operational requirements, and/or funding from multiple sources. These mechanisms can be important to the practicalities of SoS evolution.

IV. EXPANDING SE CONSIDERATIONS

Having posited characteristics of systems which facilitate their role as building blocks in dynamic SoS over time, this section identifies areas where SE considerations may need to take an expanded view to support the creation of systems which can readily contribute to new and changing SoS.

Requirements: As the earlier discussions suggest, today, SoS context plays its most significant role during the development of the requirements for a system. As described, it is important to recognize that systems when fielded are part of a larger workflow or mission thread. Requirements development can benefit from a broader understanding of that workflow as currently performed, as well as interdependencies with other systems or elements of the environment. Further, as the data from today's U.S. DoD SoS indicate, systems support multiple capabilities and may be called on to participate in several different SoS with differing needs. SE processes must strongly consider the SoS CONOPs, potential multiple and future use scenarios, and interdependencies to ensure that new systems are better tuned to the needs of the SoS they support. Re-examining these as the new system design matures and development begins could help identify changes that could affect the usefulness of the product early enough to factor into the acquisition. How important these are for any one system will depend on the circumstances surrounding the development. If the new system is not expected to be long-lived, then including requirements to address future uses may not be sensible. However, for systems expected to be employed over a number of years in environments known to be dynamic, it is important for the requirements development be informed and requirements decisions made in light of this information.

Architecture: The context elements discussed above—SoS CONOPs, multiple and future use considerations, and interdependencies—can also provide important inputs to the system design. The SoS architecture embodies this SoS context. As such, architecture can be critical for the systems engineer of a system which will operate in the SoS as a tool to evaluate implications of this context on the system. If a system is conceived as a component in a larger system (SoS), then having a well-defined architecture for the larger system (SoS) is an important prerequisite for the design of a system.

Unfortunately in the U.S. DoD today, architectures have been largely viewed as the domain of information technology, and they are used more for management than for engineering. In an SoS, not only is it important to document interfaces, exchanges and interdependencies, but to visualize and communicate trade space analyses in functional and physical domains as well. To ensure that systems are effective components of systems of systems, then SoS architectures need to become first-rate technical products that can be used as design drivers for new constituent systems and a technical framework for the evolution of legacy constituents.

With this approach, architectures provide context for the systems and to a degree ensure that requirements are better understood, which should lead to better systems engineering sand more successful development of both systems and SoS. Without acknowledging each system's role in the particular mission context and its relationships to other systems, there will continue to be substantial risk that large investments in new systems will not be effective in supporting the capabilities what motivated their development, or there will be added cost to adapt them to meet these needs.

As discussed in the SoS Guide to SE for SoS [3], to be effective these SoS architectures need to be cognizant of the independent demands of the various stakeholders of both the systems and SoS. This means that work is needed in SoS architecture analysis, approaches to architecture representation for SoS, and architecture patterns that support different types of systems of system needs.

System Design and Evolution: As emphasized throughout these past few sections, system designs should properly take into consideration the context in which they will operate in a SoS. In addition, most defense systems today can anticipate that they will evolve over time, often with an explicit incremental development strategy defined from the outset. SoS change over time as well in terms of their objectives and their environment. These changes inevitably impact the constituent systems. With a service life of decades, many major defense systems can expect to operate in a variety of SoS contexts. Because most SoS depend on networks and communications infrastructure, it is inevitable that changes in this dynamic area will affect constituent systems in an SoS.

Increasingly resilience and adaptability are viewed as important characteristics of defense systems. A new DoD science and technology thrust emphasizes the need to address the way we engineer major systems to ensure they are designed to withstand the changes they will face, and to help get needed capability to the user faster by our ability to quickly adapt systems to meet changing needs and conditions. Technology advances in modeling and computing power offer opportunities to enhance the engineering design environment and ultimately systems engineering processes. These advances are already being realized in order to optimize system design to enable multi-role capabilities, adapt to unforeseen needs, and implement cross-constituent system trades during development to balance functionality or correct deficiencies.

Verification: Finally, as systems are engineered with a broader consideration of context for requirements, architecture and design, it is also important to consider context in verification. The challenges of SoS for test and evaluation have been identified [20] but as in the SoS SE literature in general this has focused on issues at the level of the SoS. In most cases changes in systems implemented to meet needs of an SoS are developed and tested as part of the system development with the objective to verify that system has implemented specified changes. Beyond this, system testing provides the opportunity for integration and test of the role of the system in the SoS mission thread or business process. Expansion of system verification to include consideration of SoS interdependencies and assessment of the role of the system in SoS capability objectives is one way that systems engineer of systems can help address the challenges of SoS test and evaluation.

V. Summary

This paper has reviewed the history and literature on SE for SoS from the perspective of the constituent systems that form the building blocks of most SoS.

Attention to SE for SoS has largely focused on the adaptation and development of SE methods and process to address the particular characteristics of SoS. It has paid limited attention to the implications of SoS for the SE of constituent systems. Once requirements are defined and boundaries are established, classic SE processes for systems focus almost entirely on the system itself with attention to system context limited to the initial phase during the definition of requirements and then little to no attention thereafter. U.S. defense requirements and acquisition policy and guidance do focus on system context early in development. Defense acquisition guidance does make provision for recurring review of external dependencies through the acquisition process, in recognition of the typical duration of defense acquisitions and the dynamic nature of military environments.

Based on work done to develop the DoD Guide for SoS SE and follow-up practitioner experiences, the paper describes a set of system attributes which characterize 'good' constituent systems, that is characteristics of systems which enable them to more readily contribute to new, changing or multiple SoS needs. These characteristics include both technical and management aspects of constituent systems. Fundamentally these are systems which embrace their role in the SoS and expand their objectives to include their role in the larger SoS, systems with design which can be easily adapted to changing requirements, and systems which adopt incremental, rapid, development processes and configuration management and funding models which allow for multiple investors.

Finally, the paper identifies some key aspects of system engineering – requirements, architecture, system design and evolution and verification – which warrant review in order that our engineering process and capabilities meet realities of today's SoS opportunities and demands.

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