System Engineering Artifacts for SoS

Dr. Judith Dahmann and George Rebovich
MITRE
McLean, VA USA
{jdahmann, grebovic} at mitre.org

Dr. Jo Ann Lane
Department of Industrial and Systems Engineering
University of Southern California
Los Angeles, CA USA
jolane at usc.edu

Ralph Lowry
Modern Technology Solutions, Inc.
Alexandria, VA USA
ralph.lowry at mtsi-va.com

***Abstract*— This paper describes system of systems (SoS) systems engineering (SE) artifacts, compares and contrasts them with similar ones developed and used for individual systems, and explains how they are used to guide SoS engineering processes. The paper concludes with next steps for using SoS artifacts to continue maturing the understanding of SoS SE in an international cooperative effort with the United Kingdom, Australia, and Canada.**

Keywords-component; system of systems, system of systems engineering, engineering artifacts

I. BACKGROUND AND MOTIVATION

The system of systems (SoS) systems engineering (SE) community is evolving SE processes to better apply SE to broadly defined SoS capabilities which span multiple systems. The knowledge from these efforts includes a greater awareness of SoS characteristics which create SE challenges, a recognition that some activities are unique to SoS SE, and ways to better employ fundamental SE processes in an SoS environment. Building on this knowledge, a United States (US) team is identifying key SoS SE artifacts (work products) and applying them to SE of SoS. The focus is on the critical information included in the artifacts rather than the documents. The objective is to develop a common set of concrete approaches to applying SE to SoS by understanding SE artifacts developed and used in SoS SE today.

II. SYSTEMS ENGINEERING FOR SYSTEMS OF SYSTEMS

With the increased emphasis on capabilities and networking, the US Department of Defense (DoD) is recognizing the criticality of effective end to end performance of SoSs to meet user needs. While acquisition processes continue to focus on systems, system requirements are increasingly based on assessment of gaps in user capabilities that require integration across systems. Thus, the role of systems engineering is expanding to the engineering of SoS that provide user capabilities. This dynamic is occurring in other nations as well and in areas beyond defense to include civilian and commercial enterprises.

Applying SE to SoS requires an understanding of the characteristics of SoS and their impact on basic SE processes which have traditionally been applied to the development of new, individual systems. An SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [1]. A primary interest in SoS SE concerns 'acknowledged' SoS [2]. This type of SoS leverages existing system capabilities to address new needs while recognizing the programmatic and operational autonomy of the systems. Acknowledged SoS have top level objectives and governance and have SE teams working at the SoS level. These operate in concert with SE teams for the constituent systems. Acknowledged SoS are common in the DoD. Examples include the Single Integrated Air Picture, Ballistic Missile Defense System and Naval Integrated Fire Control Counter Air [3]. This paper is based on interviews with practitioners working in this environment conducted as part of the development of the DoD guide for SE of SoS [3] and the artifacts described here apply to acknowledged SoS. Future work will investigate their applicability other types of SoS.

The analysis of SoS SE efforts in DoD today has identified a set of core elements of SE in an SoS environment. SoS systems engineers focus attention on the core elements as they evolve an ensemble of multiple existing and new systems to meet user capability objectives:

> *"In SoS SE, systems engineers are key players in the core elements of: (1) translating SoS capability objectives into SoS requirements, (2) assessing the extent to which these capability objectives are being addressed, and (3) monitoring and assessing the impact of external changes on the SoS. Central to SoS SE is: (4) understanding the systems that contribute to the SoS and their relationships, (5) developing an architecture for the SoS that acts as a persistent framework for (6) addressing SoS requirements and solution options. Finally, the SoS systems engineer (7) orchestrates enhancements to the SoS, while monitoring and integrating changes made in the systems to improve the performance of the SoS."* [3]

These core elements and their relationships characterize the top level SoS SE coordinating and integrating role which is implemented cyclically via a 'battle rhythm' driven by the nature of the SoS. Particularly in acknowledged SoS, evolution of the SoS is based on the changes made in the systems which contribute to the SoS objectives. Often, these systems are evolving concurrently to address the needs of their own users by following their own SE processes.

III. Identifying SoS SE Artifacts

Tangible examples of the products essential to SoS SE help to understand SoS SE practices and communicate them to others. The US is working with the Australia Defense Materiel Organization on an initiative to develop a shared view of SoS SE and the critical supporting artifacts. This work is an ongoing activity under The Technical Cooperation Program (TTCP) Technical Panel 4: Systems Engineering and Modernization [4].

In the DoD and elsewhere there has been increased attention to supporting development and acquisition decisions with evidence or knowledge [5] and recent attention has focused on the need to address technical as well as programmatic considerations in these decisions [6]. In 2008 changes in the DoD acquisition process shifted key program decisions to the point where there has been sufficient technical work to support an informed decision [7, 8]. New approaches to systems engineering have likewise emphasized evidence based decision-making [9]. In the DoD acquisition context, these decision points are aligned with acquisition milestones.

While they may not be managed under acquisition processes, SoS typically identify key decision points and support these by different forms of evidence or knowledge. In at least one case, the Ballistic Missile Defense System, these are called 'knowledge points'[10]. This paper addresses the SoS SE process and examines the key work products or artifacts which provide the basis for these decisions. These artifacts can be viewed as 'boundary objects' [11, 12, 13] which bridge, in some cases, between elements of the SoS SE process and, in others, among the multiple organizations that work together in an SoS.

Based on the US DoD work with SoS SE practitioners in acknowledged SoS, an initial set of SoS SE artifacts has been identified. These artifacts have been used in one or more SoS SE efforts in the US. The understanding of the artifacts, their form, and use is based on the current experiences drawn from interviews with SE practitioners. These artifacts provide a focus for continued collaboration across SoS SE communities. The SoS artifacts include:

- Capability Objectives
- Concept of Operations (CONOPS)
- Information About Systems That Impact SoS Capability Objectives
- Requirements Space
- Performance Measures and Methods
- Performance Data
- SE Planning Elements
- Risks & Mitigations
- Master Plan
- Agreements
- Architecture
- Technical Baselines
- Technical Plan(s)
- Integrated Master Schedule (IMS)

Just as SE artifacts are enablers of effective SE at the system level, they can be viewed as enablers of SE for SoS. The role each plays in SoS SE should be clearly understood and reflected in the content and form of the artifact. Figure 1 shows the core elements of SoS SE [3] and the way these SoS SE artifacts align with the elements.

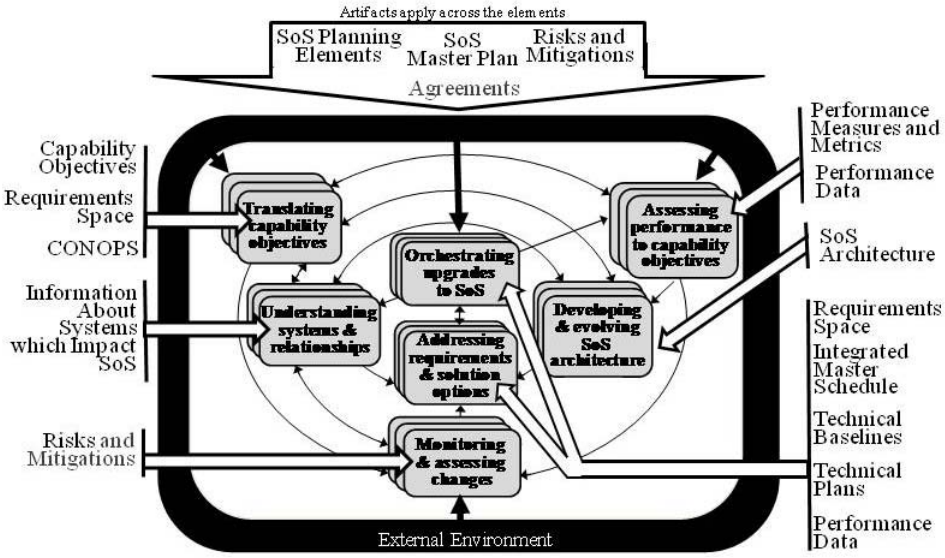

Figure 1. Core Elements of SoS SE and Associated Artifacts

This mapping shows which core elements develop or update each artifact. The next section describes each artifact in more detail, along with a brief description of how they are employed in the SoS SE process.

IV. Characterizing Artifacts

This section describes each of the SoS SE artifacts. The descriptions also include a discussion of how each artifact is used in the SoS SE process.

SoS Capability Objectives are a statement of top level objectives for the SoS. They describe the capabilities needed by the user, ideally based on some definitive or authoritative materials (e.g., policy memo, directive). They are used by SoS management, stakeholders, and SE teams as the foundation for SoS requirements, metrics, etc. The capability objectives provide a basis for translating operational needs into high level requirements, assessing performance to capability objectives, and developing an architecture and solution options.

The **SoS CONOPS** describes how the functionality of the systems in the SoS will be employed in an operational setting. The CONOPS is developed by the operational users and with active participation from the SoS systems engineers to describe the way users plan to operate and use systems to achieve the objectives, as influenced by the various environments and conditions anticipated. It is developed in parallel with the capability objectives. As the capability objectives evolve, the CONOPS should evolve in detail, as well. SoS management and SE teams use the CONOPS to define the SoS requirements space, to identify aspects of systems which could impact SoS design, and to select performance metrics and test environments.

Systems Information is collected and organized by the SoS SE team and is used as the basis for trades as the SoS evolves. This is information about systems that impacts SoS capability objectives and includes both programmatic and technical aspects of the constituent systems relevant to the SoS. The content is produced by multiple stakeholders of both the SoS and constituent systems, including operational/using commands, acquisition agencies and program offices, operations and maintenance organizations, and systems engineers. This information assists the SoS SE to understand the components of the SoS, including technical, organizational, fiscal, and planning perspectives. The information provides the basis for developing and evolving the SoS architecture, monitoring and assessing changes to both the SoS and individual systems, and developing SoS capability solution options.

The **SoS Requirements Space** bounds the first order SoS user needs (including operational tasks and missions) and defines functions required to provide the capability with consideration of the variability in the user environment that impacts the ways these functions will be executed. This is a 'requirements space' versus 'requirements', because in an SoS, 'requirements' are taken on by the systems to meet the SoS objectives as part of identifying requirements and solutions options. The requirements space includes both the SoS Capability Backlog and Problem Reports. It is developed by the SoS SE team, with strong lines into the SoS and system operational communities in liaison with constituent system SE teams. It is used by the SoS and system SE teams to: determine information needed to understand systems and relationships, compare performance to capability objectives, develop an SoS architecture, identify areas to be addressed in an increment(s), identify solution options, develop a plan for SoS increment(s), and develop a plan to test and evaluate the changes.

SoS Performance Measures and Methods provide the basis for assessing overall performance of the SoS and planning for 'continuous SoS improvement'. These performance measures and methods are traceable to the capability objectives established for the SoS. They are created by SoS and system SE teams and the test and evaluation (T&E) community to assess status and progress in meeting SoS capability objectives and are used to structure events to generate the data needed.

SoS Performance Data, along with data on unanticipated factors observed during performance analysis, are gathered from different environments by SoS SE and T&E teams and operators to assess progress toward achieving SoS capability objectives. These data are used by SoS management and SE teams to assess impact of changes and to identify areas needing more attention (new gaps/requirements). The data also provide feedback on architecture implementation variability; factors impacting capability; and additional capability needs based on operational user experience. The aggregate feedback serves as a basis for addressing requirements and orchestrating SoS upgrades.

SoS SE Planning Elements provide the structure and process for SE for the SoS much as a System Engineering Plan (SEP) does for an acquisition program. Key elements include (1) battle rhythm or pacing of SoS upgrades, (2) organization structures and decision processes, and (3) technical reviews. These elements are developed and evolved by the SoS SE team in conjunction with SE teams from key systems. The elements provide the basic SE rules of engagement for the SoS and are used by the full range of participants in SoS to understand the overall SoS SE process.

SoS Risks and Mitigations are addressed throughout the process. The SoS SE team works in collaboration with system SE teams to capture potential risks associated with SoS capabilities and mitigations for them. The status of risks and their mitigation are updated on a periodic or event-driven basis and tracked by the SoS SE team, system SE teams, and SoS stakeholders to understand potential risks, issues, and obstacles to achieving desired capabilities and to guide selections of alternative solutions. SoS risks often emanate from areas outside the SoS where changes may impact SoS objectives, particularly changes made in the constituent systems to meet system user needs. Monitoring and addressing this type of risk is an important role for the SoS SE.

SoS Master Plan is an integrated plan that provides a top level view across multiple incremental upgrades to implement the SoS evolution strategy, the SoS analog to a systems acquisition strategy. This plan is developed and evolved by the SoS SE team in collaboration with system SE teams. The SoS

SE team, system SE team, and SoS stakeholders use it to understand current status and plans of the SoS. Since this master plan looks across iterations of the SoS, it provides a mechanism for supporting trade-off decisions and adjusting priorities over time.

Agreements formalize roles and responsibilities of SoS participants at a broad level (e.g. Charter) as well as specific commitments of participants in a development increment. Because SoS cut across organizational boundaries, agreements are critical to SoS SE success. SoS and system management and SE teams (and contracting officers and commercial contractor representatives, as needed) define agreements among participants regarding organizational relationships, roles, and responsibilities, and to manage interactions of participants and other stakeholders.

SoS Architecture is the persistent technical framework for addressing the evolution of the SoS to meet user needs, and for addressing possible changes in systems functionality, performance, or interfaces. The architecture defines the way the systems work together and addresses the implementation of individual systems only when the functionality is key to crosscutting issues of the SoS (including shared data specifications or data model). It includes systems, key SoS functions supported by the systems, and relationships and dependencies as well as end-to-end functionality, data flow, and communications protocols. The SoS SE team defines the desired approach to organize existing and newly developed systems. SoS and system SE teams use the architectures as a framework for developing SoS solutions. It provides a shared representation of the SoS technical framework used to inform and document decisions and guide evolution of the SoS.

SoS Technical Baselines are developed for each increment of SoS development. These SoS baselines include a requirements baseline, an allocated baseline, and a product baseline for the SoS and reference the detailed system baselines maintained by the systems themselves. These are used to understand the current "as is" state of the SoS (product), monitor the SoS enhancements being currently developed for the next increment (allocated), and plan changes for future increments (functional/requirements).

Technical Plans are developed for each development increment and include plans for SoS implementation, integration, and test. SoS technical plans follow the principles for technical planning for systems, paying attention to defining critical event-driven reviews and risks throughout the process. SoS and systems managers and SE teams as well as T&E community use these plans to guide activities and document agreements on changes to be made in an SoS increment(s), to track implementation progress, and identify changes/issues in implementation.

Integrated Master Schedules (IMS) are also created for each SoS development increment. They include the key points in the technical plans which need to be addressed in orchestrating SoS development. The IMS focuses on key SoS SE activities and integration points and links to the detailed development schedules maintained by the systems for the update. In the IMS, the SoS SE team, in collaboration with system SEs, identifies key activities in SoS SE as well as common points (synchronization points, critical events) across elements of the SoS for an increment(s). SoS and system management and SE teams use the IMS to monitor key points across elements of the SoS for an increment(s).

As noted above, in SoS, constituent systems implement SE for their systems and create artifacts to support their processes. In general, SoS artifacts address comparable issues but with a broader focus across the SoS. In most cases, systems owners and engineering retain responsibility for their systems even as part of the SoS. There is no intention to replicate information available for the systems in SoS artifacts but rather to point to that information retained by systems as it impacts the SoS. Table 1 highlights differences in characteristics of SoS and system artifacts.

TABLE I. COMPARING SOS AND SYSTEM SE ARTIFACTS

Artifact	SoS	System
Capability Objectives	Focused on capabilities at the SoS-level. Solution(s) typically require multiple constituent systems, not all of which may be known in advance. Scope typically initially defined in the charter for the SoS.	Addresses a gap in a user capability as defined by formal process (Joint Capabilities Development System (JCIDS) or Component equivalent process); may provide functionality that supports SoS capability objectives.
CONOPS	Multiple system focus. Often developed after constituent systems have been fielded; Evolves over time, sometimes substantially.	Single system focus. Defined when systems acquisition begins.
Systems Information	Focus is on system-level information that impacts SoS-level capability objectives. Extends beyond technical issues to include operational, fiscal, organizational, and planning issues.	Focus is on interfaces and inputs/outputs with external systems and how they support or inhibit single system performance. Focus is usually on technical issues.
Requirements	Requirements 'space' versus set of specific requirements. Defined at a level of detail that enables trades among potential and actual constituent systems and interfacing external systems.	Defined by needs of the operational users of the system and by the threat. Usually articulated as detailed operational requirements or specified technical requirements.
Performance measures and methods	Focus is on performance of SoS solution. As independent as possible of the specific systems to allow for assessment of alternative implementation approaches.	Focus is on performance of the specific system and connections with external interfaces.
Performance Data	Often collected in operational environment. Used to support continuous improvement of the SoS.	Predominantly collected in traditional acquisition lifecycle T&E, including simulation/modeling. Used to support fielding decisions.
SE Planning Elements	Focus is on determining rhythm, organizational structure, technical reviews, and decision processes across SoS evolution. Ability and willingness of constituent systems to support SoS plans is an important consideration.	Focus is on an individual system typically part of the acquisition process; takes the form of an SE Plan.

Artifact	SoS	System
Risks and Mitigations	Focus is on desired capabilities and undesirable emergent behaviors of the SoS. Includes single system risks or dependencies essential to SoS capabilities and plans.	Focus is on system issues and potential problems. Includes external dependencies that pose special risks.
Master Plan	Focus is on SoS-level view across multiple increments and touch points for constituent systems. Reflects the SoS evolution strategy. Focus is often on continuous improvement versus achievement of a defined end state.	Focus is typically on individual system and approach to achieve defined end-state. Reflects the system acquisition strategy.
Agreements	Focus is on managing relationships among multiple organizations. Agreements support SoS evolution including specific commitments to execute SoS increment development.	Focus is on defining specific system dependencies (e.g. commitments to provide components to a system through Government Furnished Equipment (GFE) or Commercial Of-the Shelf (COTS) components).
Architecture	A shared framework primarily aimed at informing analysis and decisions for developing or evolving SoS capabilities. A context for understanding the relationships among constituent systems and developing implementation options for meeting capability requirements. Includes key constituent systems information, connectors and protocols used to communicate and/or synchronize processing across the constituents, key data elements/structures that cross interfaces, and key data conversions to facilitate data sharing and communications between constituents.	A framework for analyzing and making decisions on system development and interfaces with external systems. For the single system, includes information about system's top level components, connectors between the components, protocols used to communicate between the components and synchronize processing across the components and key data elements/structures that cross interfaces between the components and any interfacing external systems.
Technical Baselines	Focus is on SoS-level description plus identification of constituent system baselines that are part of the SoS baseline.	System detailed artifacts/components that comprise the system baseline.
Technical plan(s)	Focus is on planning the implementation of changes to constituent systems to execute an SoS increment.	Focuses on implementation of changes to the system, including those required for the system to interface with external elements.
Integrated Master Schedule	Set of SoS SE activities and milestones plus key single system activities and milestones that are driving SoS critical path. Focus is on key synchronization points among SoS constituents and pointers to development schedules of constituent systems for the current SoS increment.	Detailed list of development activities, milestones, and associated schedule for the system.

V. Summary and Conclusions

The analysis of the initial set of artifacts provides the basis on which the SoS SE team can identify critical knowledge elements and knowledge points in executing SE for SoS. The next steps in this effort include developing an SoS SE 'practitioner view' to further detail the role of information provided by the artifacts and how this information is used to support technical decisions. These will be reviewed against current SoS SE initiatives to further understand, from a practitioner perspective, the content and role of the knowledge provided by these artifacts in implementing SE for SoS. This work will be done as part of an international partnership to leverage a broad set of diverse SoS experiences to support furthering understanding of systems engineering of SoS.

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