Systems of Systems Characterization and Types

Dr. Judith S. Dahmann
The MITRE Corporation
7525 Colshire Drive
McLean, VA 22301
USA

jdahmann@mitre.org

ABSTRACT

This paper provides an overview of 'Systems of Systems' (SoS) beginning with the definition of SoS and SoS systems engineering. It describes the characteristics of SoS and SoS types. It compares systems with SoS and discussed the implications for Systems Engineering. Finally the paper concludes with a discussion of the challenges SoS pose for systems engineering with a description of recognized SoS 'pain points'.

1.0 INTRODUCTION

Systems of Systems (SoS) abound in today's world. As shown in Figure 1, many common societal capabilities, including water and energy resources, air transportation and defence all are composed of SoS. Systems engineering of Systems of Systems (SoS) has been a topic of increasing interest in defence globally for the past decade. Most military missions depend on sets of systems to work together effectively as a SoS to provide the needed user capability whether those missions are implemented by a single nation or by a coalition. While most nations acquire individual systems, to be effective they need to be engineered to work as part of the larger SoS they will support once deployed. In many cases systems were not originally designed for a particular SoS, may support multiple SoS for multiple missions, and are owned and operated by independent organization with their own goals and objectives. Therefore SoS pose certain challenges to systems engineering. In this paper, the defining characteristics of SoS will be discussed, along with their implications for systems engineering.

Figure 1: Examples of Systems of Systems[1].

[1] From Dahmann, J. "*Systems Engineering View of Systems of Systems*" Presented at 4th International Conference on Complex Systems Design & Management, December 4 – 6 in Paris France, 2013.

2.0 DEFINING SoS

2.1 Definitions

There are many definitions of SoS and systems engineering for SoS. For the purposes of this lecture, we will use the definitions from the US Defense Acquisition Guidebook (DAG)[2]:

> **System of Systems** is a “set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities”.
>
> **Systems of Systems Engineering** is “the process of planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a system-of-systems capability that is greater than the sum of the capabilities of the constituent parts”.

As can be seen from Table 1, the US definition of SOS is similar to the definitions in other sources including the Systems Engineering Body of Knowledge where SoS is defined as:

> A SoS is an integration of a finite number of constituent systems which are independent and operatable, and which are networked together for a period of time to achieve a certain higher goal.[3]

Table 1: Definitions of Systems of Systems.

Source	Definition
SE Body of Knowledge	A SoS is an integration of a finite number of constituent systems which are independent and operatable, and which are networked together for a period of time to achieve a certain higher goal. (Jamshidi 2009)
INCOSE SE Handbook	[A] system-of-interest whose elements are managerially and/or operationally independent systems. These interoperating and/or integrated collections of systems produce results unachievable by the individual systems alone.
Draft ISO 15288 SoS Annex	A system of systems (SoS) is a system-of-interest (SOI) whose elements are themselves systems. A SoS brings together a set of systems for a task that none of the systems can accomplish on its own. Each constituent system keeps its own management, goals, and resources while coordinating within the SoS and adapting to meet SoS goals.
US DoD SoS SE Guide	A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities.

These definitions share several of the characteristics typically associated with SoS as discussed in the next section.

2.2 SoS Characteristics

Perhaps the best known source on SoS in the paper “Architecting Systems of Systems” by Maier (1998)[4]. Recognizing that SoS are systems in their own right, Maier postulated five key characteristics of SoS.

[2] US Defense Acquisition Guidebook Chapter 4 Systems Engineering, Table 4.1.3.T2. Four Types of Systems of Systems https://acc.dau.mil/CommunityBrowser.aspx?id=638297&lang=en-US, Accessed 11/26/2014.

[3] Jamshidi, M., Ed. (2009). System of systems engineering - innovations for the 21st century, pg. 2, J. Wiley & Sons.

[4] Maier, M.W. (1998). “Architecting principles for systems-of-systems.” Systems Engineering 1(4): 284.

Operational Independence of Constituent Systems

In a SoS, constituent systems operate independently of the SoS and other systems. Most often these systems existed prior to the formation of the SoS and in many cases in defence these systems are deployed and in use when called upon to support a new capability.

Managerial Independence of Constituent Systems

The systems in a SoS are managed independently and their owner/managers may be evolving the systems to meet their own needs.

Geographical Distribution

In many cases, constituent systems in a SoS are geographically distributed, although many view this as a less significant or secondary characteristic of SoS.

Evolutionary Development Processes

SoS development is based on developments in the constituent systems. These developments may take place asynchronously based on the independent development processes of the constituent systems. This means that the SoS will evolve incrementally rather the be 'delivered' as normally envisioned in a single system development or acquisition.

Emergent Behaviour

Emergence is described as:

> "Emergent system behaviour can be viewed as a consequence of the interactions and relationships between system elements rather than the behaviour of individual elements. It emerges from a combination of the behaviour and properties of the system elements and the systems structure or allowable interactions between the elements, and may be triggered or influenced by a stimulus from the systems environment."[5]

In many ways emergence is the objective of a SoS where multiple systems are brought together to generate capability which results from the interaction of the constituent systems. However, unanticipated, and undesirable emergent behaviour is a risk of SoS as will be discussed in Section 5 on SoS challenges.

2.3 Scale and Scope of SoS

SoS can range in complexity and scope. On one end of the spectrum is a SoS focused almost entirely on technical integration as shown in Figure 2 with an example from an European Commission (EC) research project COMPASS[6] which used as a case study in SoS the integration of the components of a consumer audio-visual 'system'. Here the focus was on maintaining the quality of the user experience across various combinations of constituent system combinations with a clear focus on the technical integration of the constituent systems.

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[5] From SEBOK Fundamentals Knowledge Area: Emergence; http://www.sebokwiki.org/wiki/Emergence, Accessed 11/23/2014).

[6] Comprehensive Modelling for Advanced Systems of Systems, http://www.compass-research.eu/, Accessed 11/26/2011.

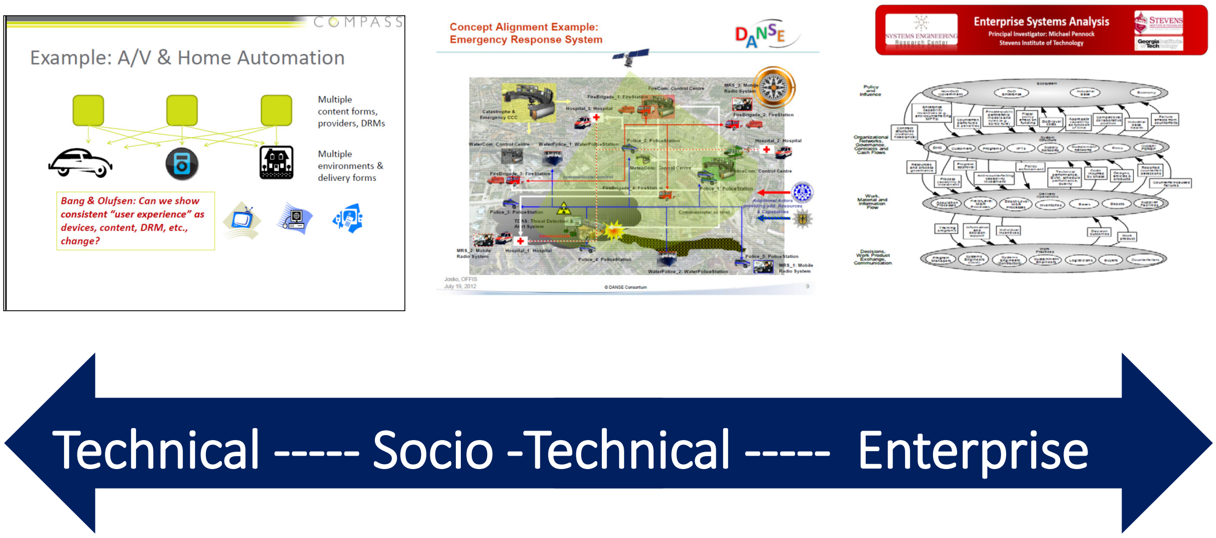

Figure 2: Scale and Scope of Systems of Systems.

Other examples of systems of systems move into the sociotechnical domain where not only are the systems integral to the SoS capability but also the organizations and their processes. This is shown in the figure by the example of a disaster response SoS, another SoS case example developed by the DANSE[7] project, another EC SoS research activity. In disaster response, the coordinated activities of the various responder organizations are as important to the success of the SoS as is the integration of the supporting technical systems.

Finally, SoS can be broader in their scale and scope and address enterprise level concerns. In the figure this is shown by work on fighting the problem of counterfeiting as an enterprise comprised of a wide variety of systems, organizations, policies, and competing efforts.

2.4 SoS Domains in Defence

Finally, looking at the application of SoS to defence systems, Figure 3 illustrated the various domains where SoS occur in military applications.

[7] Designing for Adaptability and evolutioN in System of systems Engineering (DANSE), www.danse-ip.eu/, Accessed 11/26/2011.

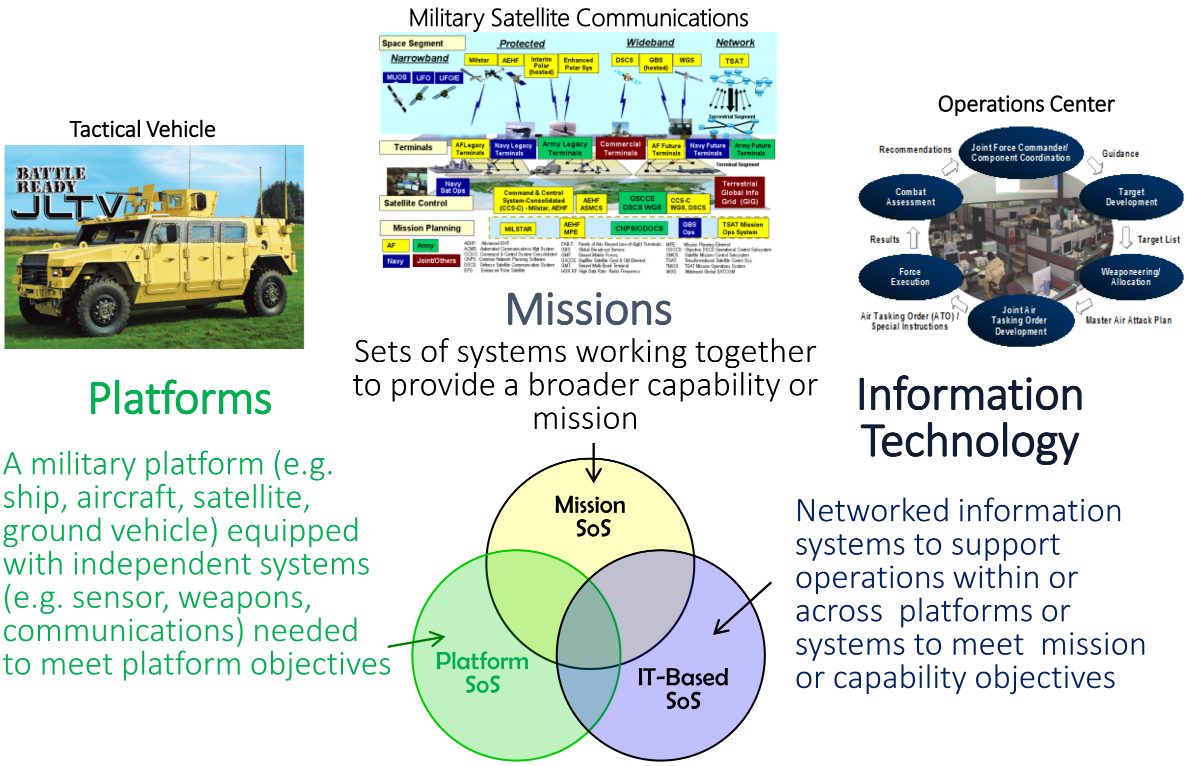

Figure 3: Systems of Systems Domains in Defence.

Missions

- Sets of systems working together to provide a broader capability to support a military mission

Typically, SoS are considered as multiple systems working together to support a war fighter mission such as air defence or undersea warfare. These 'mission' SoS are often described in terms of mission 'threads' or series of actions to be performed by different actors using different systems to implement end-to-end operations.

Platforms

- A military platform (e.g. ship, aircraft, satellite, ground vehicle) equipped with independent systems (i.e. sensors, weapons, communications) need to meet platform systems objectives

In defence, another common domain for SoS are 'platform-based' SoS. Military warfighting physical platforms are typically developed independently from the systems which will be hosted on the platform to equip it to meet its warfighting objectives. These systems are usually developed independently and asynchronously and require the platforms and hosted systems to be integrated into a SoS to support user needs.

Information Technology (IT)

- Networked information systems within or across platforms or systems to meet mission or capability objectives

Finally, with the increased use of information technology in military systems, there is increased emphasis on "IT-based" SoS, where the automated IT systems for command and control, targeting, logistics management and many other functions can be integrated into larger enterprise SoS to meet a broader set of user capabilities through information exchanges.

As the figure shows, these three domains are not independent. Mission SoS depend on command and control IT-based SoS to support the communications and information exchange critical to mission operations. Missions also incorporate platforms as constituent systems contributing to the SoS conduct of end to end mission operations. And platforms increasingly depend on on-board IT-based SoS to support the effective integrated platform operations. All domains share common SoS characteristics while each domain has some particular characteristics and challenges.

3.0 SOS TYPES

3.1 Overview

Many SoS exist but may not be recognized as SoS. As a result, they develop and evolve without benefit of SE. When SoS are recognized and treated as a SoS, they can be categorized as one of four SoS types, based the authority relationships between the SoS and the constituent systems. This is not the only way to characterize SoS types but given the importance of the independence of the constituent systems in a SoS on SE, these types have been found to be useful in describing SoS. In reality, most SoS are a combination of these types. Understanding the types provides a useful framework for understanding SoS.

Table 2 from the US Defense Acquisition Guidebook displays these types which were originally based on work done by Maier[8] and expanded as part of the development of guidance for SoS systems engineering in the US DoD[9]. In the following section each of these types will be discussed.

Table 2: Systems of Systems Types[10].

Type	Definition
Directed	Directed SoS are those in which the SoS is engineered and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the centrally managed purpose.
Acknowledged	Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, development, and sustainment approaches. Changes in the systems are based on cooperative agreements between the SoS and the system.
Collaborative	In collaborative SoS, the component systems interact more or less voluntarily to fulfill agreed-upon central purposes.
Virtual	Virtual SoS lacks a central management authority and a centrally agreed-upon purpose for the system of systems. Large-scale behavior emerges—and may be desirable—but this type of SoS relies upon relatively invisible, self-organizing mechanisms to maintain it.

8 Maier, M. W. (1998). "Architecting principles for systems-of-systems." Systems Engineering 1(4): 284.

9 Dahmann, J. and K. Baldwin (2008). Understanding the Current State of US Defense Systems of Systems and the Implications for Systems Engineering. 2nd Annual IEEE Systems Conference Montreal.

10 US Defense Acquisition Guidebook, 2014; https://acc.dau.mil/dag4, Accessed 11/23/2014.

3.2 Directed SoS

Directed SoS are integrated SoS built and managed to fulfil specific purposes. Directed SoS are centrally managed and evolved. While the constituent systems in a direct SoS systems maintain the ability to operate independently, their normal mode of operations is subordinated to the central purpose of the SoS. The constituent system–SoS relationships in directed SoS are depicted in Figure 4 from "The Systems of Systems Engineering Strategic Research Agenda" of the Trans-Atlantic Research and Education Agenda in Systems of Systems (T-AREA-SoS) project of the European Commission.

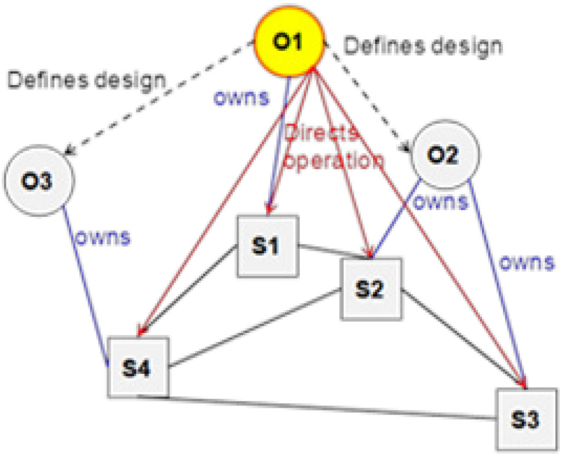

Figure 4: SoS and Constituent System Relationships in a Directed SoS[11].

As the figure shows:

> "In a Directed SoS: operators O2 and O3 accept direction from O1 in terms of the specification and operation of the systems they own (O2 owns systems S2 and S3; O3 owns S4) This type of SoS is highly controlled by the central managing entity (O1)."[12]

3.3 Virtual SoS

At the other end of the SoS spectrum are Virtual SoS. In this type of SoS there is no a central management authority and no commonly agreed purpose for the SoS. Virtual SoS exhibit emergent behaviours that rely upon relativity invisible mechanisms to maintain the SoS. The best example of a Virtual SoS is the Internet.

Again drawing upon T-AREA SoS, Figure 5 shows the relationships between systems and the SoS in Virtual SoS:

> "In a Virtual SoS: Owners (O1, O2, O3) access other systems through their own systems in order to realize individually sought benefits, though high level emergent behaviour may still occur. There is no overall goal, no central management and interoperation is achieved by recognized protocols, or standards, not through individual agreements between pairs of systems.[13]"

[11] Henshaw, M. "*The Systems of Systems Strategic Research Agenda*", TAREA-PU-WP5-R-LU, Issue 2, Release 15 August 2013.

[12] Ibid.

[13] Ibid.

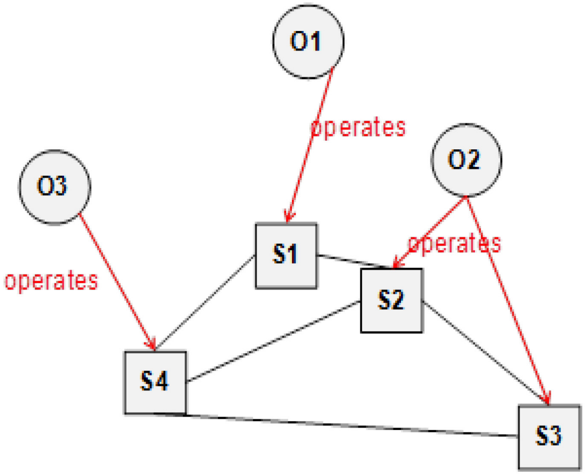

Figure 5: SoS and Constituent System Relationships in a Virtual SoS[14].

3.4 Collaborative SoS

In Collaborative SoS, the constituent systems interact voluntarily to fulfil agreed purposes and the systems themselves collectively decide how to interoperate, by enforcing and maintaining standards. There is no central authority, rather a Collaborative SoS is based on the agreements among the systems alone.

Figure 6 shows the relationships between the systems and the SoS in Collaborative SoS:

> "In a Collaborative SoS: there is mutual agreement to collaborate; usually covered by agreements of some form, but there is no overall managing entity; systems owners (O1, O2, O3) operate their own systems and collaborate with others to realize some shared benefit."[15]

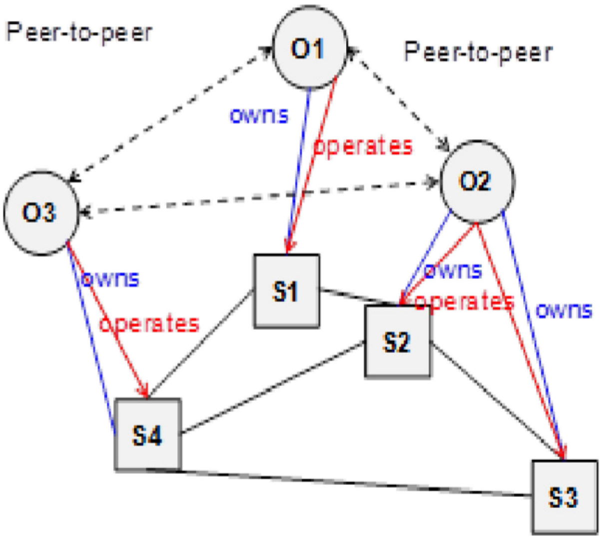

Figure 6: SoS and Constituent System Relationships in a Collaborative SoS[16].

[14] Ibid.

[15] Ibid.

[16] Ibid.

3.5 Acknowledged SoS

Finally, 'Acknowledged SoS' essentially fall between directed and collaborative, with recognized objectives, a designated manager, and resources for the SoS. In parallel the constituent systems retain their independent ownership, management and resources. This acknowledged case tends to be the most common in defence, with top-level mission objectives balanced with the objectives of the owners of the systems which support the SoS.

Typically, Acknowledged SoS are not new developments. They usually arise to address a new capability need by leveraging available systems. As a result they tend to take the form of an overlay to an ensemble of existing systems with the objective of improving the way the systems work together to meet a new user need. Under these circumstances, the SoS manager, when designated, typically does not control the constituent systems in the SoS and consequently is in a position of influencing rather than directing constituents to meet SoS need.

Figure 7 shows the relationships between the SoS and constituent systems in the Acknowledged SoS, again drawing from T-Area-SoS:

> "In an Acknowledged SoS: O1 directs choice of systems and operation; O2 and O3 have a contractual relationship (e.g. Service Level Agreement) with O1. In this case, the central managing entity (O1) has less control over the systems owned by O2 and O3 (S2, S3, S4) and must rely more on influence."[17]

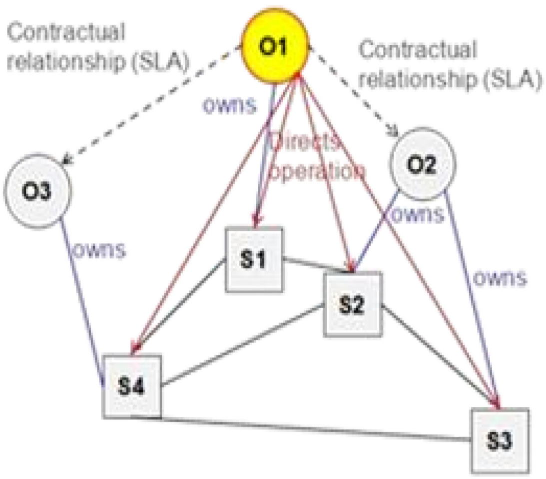

Figure 7: SoS and Constituent System Relationships in an Acknowledged SoS[18].

3.6 Summary

In sum, SoS can be categorized into four types based on the authority relationships between the SoS and the systems. These types - Directed, Acknowledged, Collaborative, and Virtual - are one way to conceptualize SoS. In an actual SoS very often the SoS is comprised of elements which exhibit characteristics of the different types across the SoS. In some cases the SoS owner may also have authority over some of the constituent systems, while others maintain their independence. Also, particularly in non-defence applications, the communications infrastructure supporting the information exchange may itself be a SoS, possibly a Virtual SoS (e.g. the internet).

[17] Ibid.

[18] Ibid.

4.0 DIFFERENCES BETWEEN SYSTEMS AND SoS AS THEY APPLY TO SYSTEMS ENGINEERING

4.1 Overview

The characteristics of a SoS as described in Section 2 and the authority relationships between the systems and the SoS as depicted in the SoS types describe in Section 3, all affect the way systems engineering can be applied to SoS.

Table 3, from the SEBOK, compares the differences between systems and SoS in the application of systems engineering in four areas: management and oversight, operational focus, implementation and engineering and design considerations. Each area is discussion in the following sections.

Table 3: Differences Between Systems and Systems of Systems as They Apply to Systems Engineering[19].

	Systems Engineering	Systems of Systems Engineering
Management and Oversight		
System	Physical engineering	Socio-technical management and engineering
Stakeholder Involvement	Clear set of stakeholders	Multiple levels of stakeholders with mixed and possibly competing interests
Governance	Aligned management and funding	Added levels of complexity due to management and funding for both SoS and systems; SoS does not have control over all constituent systems
Operational Focus (Goals)		
Operational Focus	Designed and developed to meet common objectives	Called upon to meet new SoS objectives using systems whose objectives may or may not align with the SoS objectives
Implementation		
Acquisition/Development	Aligned to established acquisition and development processes	Cross multiple system lifecycles across asynchronous acquisition and development efforts, involving legacy systems, developmental systems, and technology insertion
Process	Well-established	Learning and Adaptation
Test and Evaluation	Test and evaluation of the system is possible	Testing is more challenging due to systems' asynchronous life cycles and given the complexity of all the parts
Engineering and Design Considerations		
Boundaries and Interfaces	Focuses on boundaries and interfaces	Focus on identifying systems contributing to SoS objectives and enabling flow of data, control and functionality across the SoS while balancing needs of the systems OR focus on interactions between systems. Difficult to define system-of-interest
Performance and Behavior	Performance of the system to meet performance objectives	Performance across the SoS that satisfies SoS use capability needs while balancing needs of the systems
Metrics	Well defined (e.g. INCOSE handbook)	Difficult to define, agree, and quantify

4.2 Management and Oversight

The first area addresses the differences in management and oversight of systems and SoS. As the table shows, there are several core differences. Most SoS are comprised of systems which have their own users, funding, management structures and development plans. This means that SoS development must accommodate the constraints of these independent systems in managing changes to meet SoS objectives. The resulting political and cost considerations all impact technical engineering activities.

[19] From SEBOK Fundamentals Knowledge Area: SoS; http://www.sebokwiki.org/wiki/Systems_of_Systems_(SoS) (11/23/2014); SEBOK original adapted from adapted from Dahmann and Baldwin (2008) and Neaga et al. (2009).

Dahmann, J. and K. Baldwin. 2008. "Understanding the Current State of US Defense Systems of Systems and the Implications for Systems Engineering." Paper presented at IEEE Systems Conference, 7-10 April, Montreal, Canada.

Neaga, E.I., M.J.D. Henshaw, and Y. Yue. 2009. "The influence of the concept of capability-based management on the development of the systems engineering discipline." *Proceedings of the 7th Annual Conference on Systems Engineering Research,* 20th - 23rd April 2009, Loughborough University, UK.

Physical vs. Socio-Technical Considerations

In a typical system development, the engineering focus in on the physical system design and implementation. However, as discussed above in SoS scale and scope, the SoS systems engineer is often integrating not only the technical systems but also the organizational operations across the SoS to support a new end-to-end capability which may go well beyond the initial needs driving the development and engineering of the constituent systems.

Stakeholder Complexity

Ideally in a system development there is a clear set of user and stakeholders driving the system requirements. In a SoS however, there are multiple levels of users and stakeholders. Stakeholders for the constituent systems have their own perspectives and needs which may not align with those of the SoS.

Alignment with Funding and Management

Finally, in a system development, typically there is a program manager and organic systems engineering with aligned funding and management responsibility for the system. In a SoS, each constituent system has its own manager, systems engineer and resources, and in all but the directed case these are managerially independent of the SoS.

As discussed in the US DoD Guide to SoS SE:

> "SoS governance is complex. It includes the set of institutions, structures of authority, and the collaboration needed to allocate resources and coordinate or control activity. Effective SoS governance is critical to the integration of efforts across multiple independent programs and systems in a SoS. While the SoS will have a manager and resources devoted to the SoS objectives, the systems in the SoS typically also have their own PMs, sponsors, funding, systems engineers, and independent development programs. Some systems may be legacy systems with no active development underway. In addition, some systems will participate in multiple SoS. Consequently, the governance of the SoS SE process will necessarily take on a collaborative nature."[20]

4.3 Operational Focus and Goals

In system development the objective of the system will drive the systems requirements. In SoS, the objectives of the SoS may not align with those of the constituent systems. These systems very often continue to support their original mission functions as well as new SoS mission functions. These multiple mission objectives can lead to issues of competing management and technical authority.

As described in the US DoD SoS SE guide:

> "For a single system within an operational environment, the mission objectives are established based on a structured requirements or capability development process along with defined concepts of operation and priorities for development …. There is a strong emphasis on maintaining a specific, well-defined operational focus and deferring changes until completion of an increment of delivery. SE inherits these qualities in an individual system development. On the other hand, SoS SE is conducted to create operational capability beyond that which the systems can provide independently. This may make new demands on the systems for functionality or information sharing which had not been considered in their individual designs. In some cases these new demands may not be commensurate with the original objectives of the individual systems." [21]

[20] DoD. 2008. *Systems Engineering Guide for Systems of Systems.* Arlington, VA: U.S. Department of Defense, Director, Systems and Software Engineering Deputy Under Secretary of Defense (Acquisition and Technology) Office of the Under Secretary of Defense (Acquisition, Technology and Logistics). Accessed 23 November 2014. Available at: http://www.acq.osd.mil/se/docs/SE-Guide-for-SoS.pdf. p12.

[21] Ibid. p 12-13.

4.4 Implementation

In defence, systems engineering is typically implemented as part of an established systems acquisition process with clear decision points and a well establish set of engineering activities and reviews aligned with those decision points. In contrast, in a SoS, systems engineering addresses the set of systems which contribute to SoS capability objectives, including legacy systems, new systems or systems still in development. The challenge is to evolve the SoS capabilities by leveraging the asynchronous developments of the constituent systems.

Again an extract from the US DoD SoS SE Guide provides a good description of this:

> "Typically, SoS involve multiple systems that may be at different stages of development, including sustainment. SoS may comprise legacy systems, developmental systems in acquisition programs, technology insertion, life extension programs, and systems related to other initiatives. The SoS manager and systems engineer need to accept the challenge to expand or redefine existing SE processes to accommodate the unique considerations of individual systems to address the overall SoS needs. It is the role of the SoS systems engineer to instil technical discipline in this process. The development or evolution of SoS capability generally will not be driven solely by a single organization but will most likely involve multiple …. Program Managers .. and operational and support communities. This complicates the task of the SoS systems engineer who must navigate the evolving plans and development priorities of the SoS constituent systems, along with their asynchronous development schedules, to plan and orchestrate evolution of the SoS toward SoS objectives. Beyond these development challenges, depending on the complexity and distribution of the constituent systems, it may be infeasible or very difficult to completely test and evaluate SoS capabilities."[22]

4.5 Engineering and Design Considerations

Engineering of individual systems focus on establishing system boundaries, defining interfaces, developing approaches to ensure system performance and behaviour., using establish metrics to assess system development progress and performance.

In a SoS, things are often more complex. Again the discussion in the DoD SoS SE guide describes this well:

> In a SoS, it is important to identify the critical set of systems that affect the SoS capability objectives and understand their interrelationships. It can be difficult to establish the boundaries of a SoS since the constituent systems of the SoS typically will have different owners and supporting organizational structures beyond the SoS management.
>
> Further, a SoS can place demands on constituent systems that are not supported by those systems' designs. Combinations of systems operating together within the SoS contribute to the overall capabilities. Combining systems may lead to emergent behaviors more than is usually seen in single systems. As with emergent behaviors of single systems, these behaviors may either improve performance or degrade it.
>
> In addition, beyond the ability of the systems to support the functionality and performance called for by the SoS, there can be differences among the systems in characteristics that contribute to SoS "suitability" such as reliability, supportability, maintainability, assurance, and safety.… The challenge of design in a SoS is to leverage the functional and performance capabilities of the constituent systems to achieve the desired SoS capability as well as the crosscutting characteristics of the SoS to ensure the meets the broader user needs. [23]

[22] Ibid. p13.

[23] Ibid. p14.

5.0 PERSISTENT SoS CHALLENGES

Given the characteristics of SoS, the types of SoS and the differences in systems engineering of systems and SoS, what then are the challenges systems engineers face when it comes to applying SE to SoS? Drawing on work done under the auspices of the Internal Council on Systems Engineering (INCOSE) SoS working group (SoSWG), this section describes what have been termed ‘SoS Pain Points’, areas where systems engineers face challenge when applying SE to SoS.[24]

One of the initial activities of the INCOSE SoS was to understand the issues of importance or ‘pain points’ in SoS as the basis for planning working group initiatives. A ‘SoS Pain Point’ survey was constructed asking respondents to identify their priority SoS areas of concern. The results of the survey were reviewed and sorted into major challenge areas. The key areas and issues were summarized in a white paper which was presented to the SoSWG in June 2012 for review and comment. Based on initial feedback, short descriptions of the key pain points were drafted and posted for additional feedback. The pain points were subsequently updated and circulated for discussion at the INCOSE International Symposium in June 2013 and the final results were presented in a paper to the INCOSE International Symposium in July 2014.

The results identified seven areas of particular concern to systems engineers when applying SE to SoS. These are summarized in the upcoming update to the INCOSE Handbook[25]:

SoS Authorities. In a SoS each constituent system has its own local ‘owner’ with its stakeholders, users, business processes and development approach. As a result, the type of organizational structure assumed for most traditional systems engineering under a single authority responsible for the entire system is absent from most SoS. In a SoS, SE relies on cross-cutting analysis and on composition and integration of constituent systems which, in turn, depend on an agreed common purpose and motivation for these systems to work together towards collective objectives which may or may not coincide with those of the individual constituent systems.

Leadership. Recognizing that the lack of common authorities and funding pose challenges for SoS, a related issue is the challenge of leadership in the multiple organizational environment of a SoS. This question of leadership is experienced where a lack of structured control normally present in SE of systems requires alternatives to provide coherence and direction, such as influence and incentives.

Constituent Systems’ Perspectives. Systems of systems are typically comprised, at least in part, of in-service systems, which were often developed for other purposes and are now being leveraged to meet a new or different application with new objectives. This is the basis for a major issue facing SoS SE; that is, how to technically address issues which arise from the fact that the systems identified for the SoS may be limited in the degree to which they can support the SoS. These limitations may affect the initial efforts at incorporating a system into a SoS, and systems ‘commitments to other users may mean that they may not be compatible with the SoS over time. Further, because the systems were developed and operate in different situations, there is a risk that there could be a mismatch in understanding the services or data provided by one system to the SoS if the particular system’s context differs from that of the SoS.

Capabilities and Requirements. Traditionally (and ideally) the SE process begins with a clear, complete set of user requirements and provides a disciplined approach to develop a system to meet these requirements. Typically, SoS are comprised of multiple independent systems with their own requirements, working towards broader capability objectives. In the best case the SoS capability needs are met by the constituent systems as they meet their own local requirements. However in many cases the SoS needs may not be consistent with the requirements for the constituent systems. In these cases, the SoS SE needs to identify alternative approaches to meeting those needs through

[24] The materials in this section are drawn from Dahmann, J. “System of Systems Pain Points,” INCOSE IS 2014.

[25] INCOSE SE Handbook, Systems of Systems. (Update forthcoming 2015).

changes to the constituent systems or additions of other systems to the SoS. In effect this is asking the systems to take on new requirements with the SoS acting as the 'user'.

Autonomy, Interdependencies and Emergence. The independence of constituent systems in a SoS is the source of a number of technical issues facing SE of SoS. The fact that a constituent system may continue to change independently of the SoS, along with interdependencies between that constituent system and other constituent systems, add to the complexity of the SoS and further challenges SE at the SoS level. In particular these dynamics can lead to unanticipated effects at the SoS level leading to unexpected or unpredictable behaviour in a SoS even if the behaviour of constituent systems is well understood.

Testing, Validation, and Learning. The fact that SoS are typically composed of constituent systems which are independent of the SoS poses challenges in conducting end-to-end SoS testing as is typically done with systems. Firstly, unless there is a clear understanding of the SoS-level expectations and measures of these expectations, it can be very difficult to assess level of performance as the basis for determining areas which need attention, or to assure users of the capabilities and limitations of the SoS. Even when there is a clear understanding of SoS objectives and metrics, testing in a traditional sense can be difficult. Depending on the SoS context, there may not be funding or authority for SoS testing. Often the development cycles of the constituent systems are tied to the needs of their owners and original ongoing user base. With multiple constituent systems subject to asynchronous development cycles, finding ways to conduct traditional end-to-end testing across the SoS can be difficult if not impossible. In addition, many SoS are large and diverse making traditional full end-to-end testing with every change in a constituent system prohibitively costly. Often the only way to get a good measure of SoS performance is from data collected from actual operations or through estimates based on modeling, simulation and analysis. Nonetheless the SoS SE team needs to enable continuity of operation and performance of the SoS despite these challenges.

SoS Principles. SoS is a relatively new area, with the result that there has been limited attention given to ways to extend systems thinking to the issues particular to SoS. Work is needed to identify and articulate the cross cutting principles that apply to SoS in general, and to developing working examples of the application of these principles. There is a major learning curve for the average systems engineer moving to a SoS environment, and a problem with SoS knowledge transfer within or across organizations.

6.0 SUMMARY AND CONCLUSIONS

In conclusion, this paper provides fundamental information on systems of systems and systems engineering. The paper reviews the current definitions of SoS and SoS SE and the key characteristics of SoS. It addresses the scope and scale of SoS and the domains for defence SoS. It describes the major types of SoS and the compares systems and SoS from the perspective of systems engineering. Finally, the paper describes the persistent SoS issues based on work conducted by the INCOSE SoS Working Group and reflected in the upcoming revised INCOSE SE handbook.