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Solutions for a New Economy

SoS bring new challenges in managing and evolving systems.

Systems-of-Systems (SoS)

The term system-of-systems (SoS) describes an arrangement of components or constituent systems that themselves are designed to achieve a set of tasks or objectives. These systems collectively collaborate, demonstrating a set of behaviours larger than the sum of the individual parts which can thus, achieve a common goal or mission.

The term system-of-systems is a natural evolution to the systems engineering discipline as systems become more and more dependent and connected. This increase in connectivity and increase in uncertainty in today's operational environments, brings new levels of complexity which needs to be engineered and managed.

The benefits of regarding systems as SoS have been heavily researched since their conception in the 1970s, when the US defence community looked at the idea of an unmanned battlefield populated with intelligent agents. Today, many industries are regarding their products and services as elements of SoS, which need to be smartly engineered and managed throughout their respective lifecycles to effectively coincide with existing legacy systems and operators.

Many challenges present themselves in the field of SoS engineering, some of which will be highlighted within this guide. Some of those challenges include; managing complexity, designing evolutionary systems, understanding uncertainty, and replicating operational systems through valid modelling and simulation.

From a digitalisation standpoint, the notion of SoS in engineering brings many benefits for both the development of products and services, but also from the consumer perspective too.

Novel and effective methods are required to analyse and manage systems of this nature, if their true value is to be recognised within the coming decades.

Loughborough University

Contents

What is a System-of-Systems?

Fundamentally, the term system-of-systems (SoS) defines an assortment of components or constituent systems (CS) that are themselves systems, designed to collaboratively achieve a common goal [1]. These CSs and subsystems are required to perform operations and functions to achieve prescribed goals and requirements. As shown in the below Figure, the CSs share information/data/resources in order to collaborate and achieve a set of prescribed SoS goals and missions.

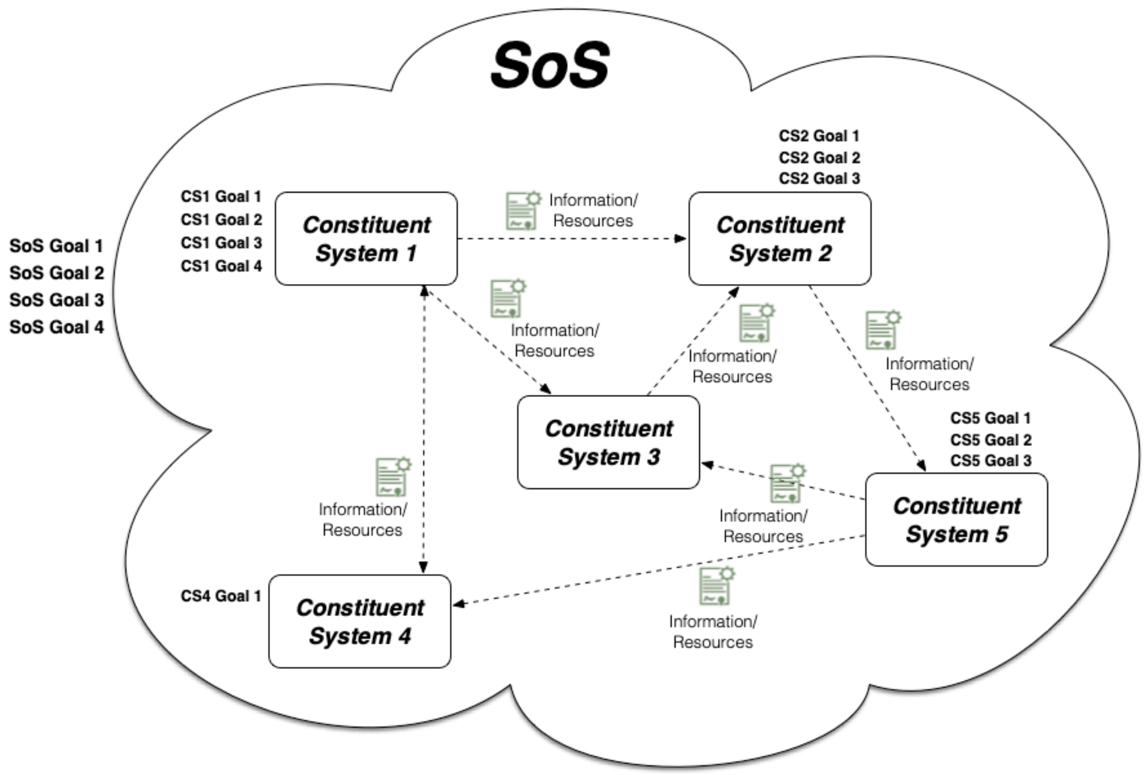

Figure 1: System-of-systems arrangement and collaboration

Over the past few decades there has been a constant growth in the number of 'inter-connected' systems known as systems-of-systems [2]–[4], examples of such systems include transportation systems, emergency response systems, water management and supply systems, air transport systems, power grid technology, manufacturing and production, amongst others.

SoS Definitions

Many definitions for what constitutes to a SoS are available [5]–[8] however a commonly accepted set of characteristics of what a SoS typically demonstrates, from Maier [7], [9] can be more useful in identifying a SoS, many of the existing definitions are pre:

1. **Geographic Distribution**: The constituent systems are distributed geographically in such a way that may affect the interactions between them (both operational and managerial interactions).
2. **Operational Independence**: The elements or constituent systems can usefully operate independently as they have their unique individual purpose.
3. **Managerial Independence**: The constituent systems are separately acquired by different managerial entities.
4. **Evolutionary Development**: A SoS evolves over time. Often, the SoS functions change due to changes in the constituent systems. Such changes, happening asynchronously, result in constant evolution of the SoS.
5. **Emergent Behaviour**: The SoS itself offers additional services above and beyond the capabilities of the constituent systems. However, it can also exhibit unexpected and potentially damaging behaviours.

<u>Additional References</u>

J. O. Clark, 'System of systems engineering and family of systems engineering from a standards,v-model, and dual-v model perspective', *2009 IEEE Int. Syst. Conf. Proc.*, pp. 381–387, 2009.

N. Karcanias and A. G. Hessami, 'System of systems and emergence Part 1: Principles and framework', in *International Conference on Emerging Trends in Engineering and Technology, ICETET*, 2011, pp. 27–32.

a Gorod, B. Sauser, and J. Boardman, 'System-of-Systems Engineering Management: A Review of Modern History and a Path Forward', *Syst. Journal, IEEE*, vol. 2, no. 4, pp. 484–499, 2008.

[4], [6], [10]–[12]

SoS Classifications

The literature shows that SoS can classified into four different types; Directed, Acknowledged, Collaborative and Virtual [13]. These SoS types are distinctly different when looking at each description (Table A); the supporting principle which governs their type is the level of management, and ultimately human control.

Table 1: SoS classification descriptions taken from [5]

Type	Description
Directed	Directed SoS are those in which the integrated system-of-systems is built and managed to fulfil specific purposes. It is centrally managed during long-term operation to continue to fulfil 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 central 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, and development and sustainment approaches. Changes in the systems are based on collaboration between the SoS and the system.
Collaborative	In collaborative SoS the component systems interact more or less voluntarily to fulfil agreed upon central purposes. The Internet is a collaborative system. The Internet Engineering Task Force works out standards but has no power to enforce them. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards.
Virtual	Virtual SoS lack 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 must rely upon relatively invisible mechanisms to maintain it.

Challenges of Managing SoS

Many SoS have legacy systems that are pre-existing and have been developed without any concern with other systems which are now considered within the SoS boundary. Thus, a unique set of requirements have not guided the evolution and coming together of incongruent systems, thus a SoS is a challenge from the integration perspective. Integrating systems is a challenge as interfaces have to be created between CSs which have not been developed for those specific purposes. To add to this challenge, there is no official SoS manager that develops a SoS throughout its multiple lifecycles; this is typically done by a leading organisation within a sector, or a government body.

Complexity, inherent to SoS, results from many heterogeneous systems/parts which are required to connect and co-operate via copious interfaces. CSs typically have different stakeholders who have control of them, and naturally, stakeholders create their own models, (often behavioural models), developed in different tools and modelling languages. This raises the requirement for stakeholders to communicate in an effective manner to ensure SoS are developed in accordance to the common goal, and to steer the SoS to reach its agreed, desired capabilities.

Example SoS Project - Designing for Adaptability and Evolution in Systems of Systems (DANSE)

DANSE developed new approaches to the design and management of the operation of SoS based on advanced methodologies based on a new evolutionary:

- Adaptive and iterative SoS life-cycle model;
- Semantically sound architectural models;
- Innovative architectures that provide the infrastructure to allow the dynamic affiliation of components so that the behaviour of the ensemble is not disturbed;
- Novel supporting model-based tools for analysis, simulation, and optimization;
- Organized in an integrated environment.

DANSE focussed on the development of a new methodology to support evolving, adaptive and iterative SoS life-cycle models based on a formal semantics for SoS inter-operations and supported by novel tools for analysis, simulation, and optimisation.

More information found at:

https://www.lboro.ac.uk/research/avrrc/research/currentprojects/modellingandsimulation/designing-for-adaptability-and-evolution-in-system-of-systems-engineering-danse.html

EU, 'Designing for Adaptability and Evolution in Systems of Systems Engineering (DANSE)', 2011. [Online]. Available: http://www.danse-ip.eu/home/. [Accessed: 15-Oct-2016].

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[1] W. C. Baldwin and B. Sauser., ‘Modeling the Characteristics of System of Systems’, *SoSE*, pp. 1–6, 2009.

[2] J. Dahmann and K. Baldwin, ‘Implications of systems of systems on system design and engineering’, *2011 6th Int. Conf. Syst. Syst. Eng.*, pp. 131–136, Jun. 2011.

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[12] J. Dahmann, J. A. Lane, G. Rebovich, and R. Lowry, ‘Systems of Systems Test and Evaluation Challenges’, 2010.

[13] J. Dahmann and G. Rebovich, ‘An implementers’ view of systems engineering for systems of systems’, *Syst. Conf. …*, pp. 1–6, 2011.

Useful information sources

- **This Guide has been funded under the RAEng Regional Engagement Award.**

Videos:

No Magic – Systems of Systems Engineering Webinar
https://www.youtube.com/watch?v=MqjWbnArX40&t=307s

Websites:

MITRE Corporation
https://www.mitre.org/publications/systems-engineering-guide/enterprise-engineering/systems-of-systems

INCOSE Systems of Systems Working Group
https://www.incose.org/incose-member-resources/working-groups/analytic/system-of-systems

Designing for Adaptability and evolutioN in System of systems Engineering DANSE
https://www.lboro.ac.uk/research/avrrc/research/currentprojects/modellingandsimulation/designing-for-adaptability-and-evolution-in-system-of-systems-engineering-danse.html

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