System of Systems

Working on the Horizon

Public sector leaders operate many systems designed to achieve outcomes and deliver services. Increasingly, such efforts are combinations of many independent systems that must work together as a "system of systems". This paper provides a formal model for understanding the principal characteristics of a system of systems, and its key management activities.

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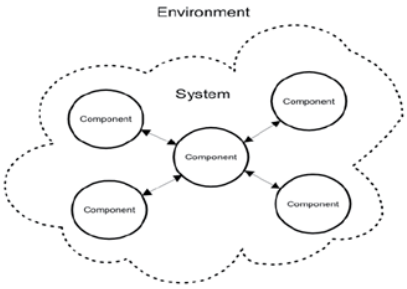
What is a System of Systems?

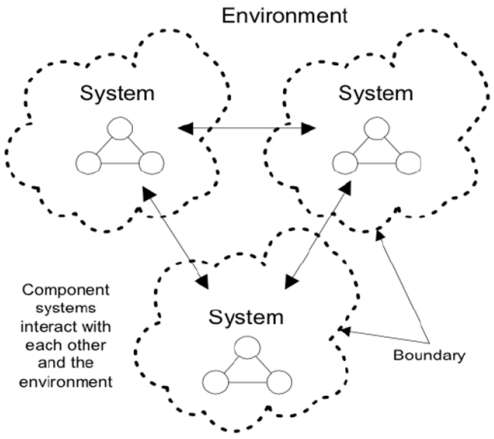
Start by considering a single system. A system is a group of interacting, interrelated, or inter-dependent things that form a whole. We can describe a system through:

- The parts or components within the system which form its structure. These components could be organizational units or information systems, and each has its own features or capabilities.
- The processes or interconnected relationships between the components, through which work is done.
- The choices we make about what is within the system boundary and what remains outside (environment).
- The characteristics of the system as a whole, namely the features or capabilities which are achieved by taking a systems approach – the whole is more than the sum of the parts.



Now, when we think about a system achieving an outcome, we make some assumptions about our ability to engineer and manage the system, and our authority to do so. As we move towards more complicated systems, questions about structure and scope arise. What components are actually inside our system? What authority do we have to get these components to work together in the ways that we envision? How are certain components shared with other systems? How can we be accountable for something so complex that we do not fully control?

Increasingly, we end up trying to assemble components into our system over which we have little or no authority, which exist for other purposes often indifferent to our purpose, and have no easy way of interconnecting with each other. *It is at this point that we need to shift from the idea that we can assemble and manage a system, towards the idea that we need to deal with a system of systems.* [2]



A system of systems (SoS) is a collection of independent systems, each with its own purpose, functioning together to meet a common purpose. It is an emergent class of systems which are built from components which are systems in their own right.

For example, if we are trying to take a systematic approach to managing an integrated policy, such as a provincial land use framework, we need to get various independent planning, regulating, decision-making and reporting systems to work together towards a common goal. These systems may be distributed among various government departments, local and regional governments, independent agencies, NGO's and industry groups.

For another example, when we are trying to build a new or enhanced service delivery capacity, such as citizen-centered services, we need to get various independent information, decision-making and service

delivery channels to work together. These may be distributed among various government departments or divisions, independent agencies, other governments and the private sector.

Other examples include: a common application process for a group of post-secondary institutions can be implemented as a system of systems rather than as a discrete process; a federated identity management system; and many horizontal policy initiatives.[3]

In all of these examples, getting the various systems to participate together is necessary but not sufficient. In addition to participation, we need agreement to common purpose, standardized interfaces, new forms of governance and accountability – to name a few.

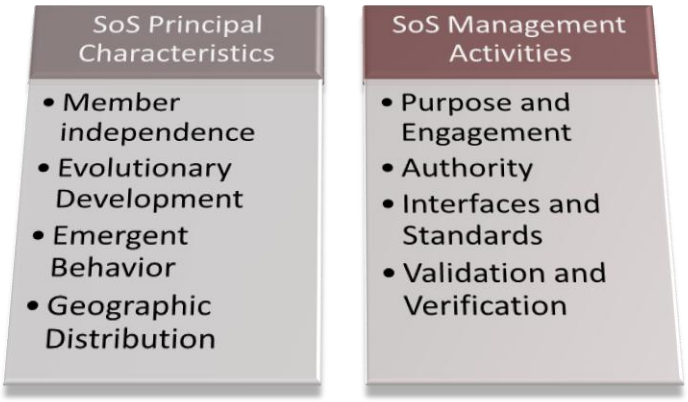
System of systems engineering is about leveraging the capabilities of individual, participating systems into overall SoS solutions, while leaving the individual systems intact to perform their functions for other intentions. For example, a registry agency may play an important role in an overall identity management SoS, but at the same time it has statutory obligations and other roles which must be maintained. Also, a registry system may need to participate in multiple systems of systems – identity management, justice, policing, health, and so on.

As we modify our SoS over time, we should not need to significantly increase its complexity or make major changes to the architecture. It should scale and adapt. Properly designed, the SoS approach allows us to add, remove or replace constituent systems without increasing the overall complexity of the SoS and, equally important, without necessitating that constituent systems be re-engineered as they enter or leave. This can lead to big improvements over traditional organizational redesign and re-investment approaches.[4]

In the next section, we present a formal model for understanding and managing a system of systems.

System of Systems Model

Here is a formal model for understanding the most important characteristics of a system of systems, and the key actions we need to be responsible for as a SoS manager. [5]



Together, an understanding of these characteristics and activities answers the question: what's different and what must we do differently to succeed?

Equally, it is useful to apply this model from the opposite perspective: are we designing our independent system so that it can easily participate in larger systems of systems, or are we creating a system which will be isolated?

(Additional information about how SoS is differentiated from single systems is provided in the Appendix.)

The essence of the SoS approach is simply that we do not have the resources or time to build single-purpose systems for everything we need to do, or expect that all future requirements can be accommodated by single systems which cannot interoperate without significant upheaval or additional cost.

Principal Characteristics

The difference between SoS and other system/organizational forms is explained through four principal characteristics.

Member Independence. Each of our member systems has operational and managerial independence and must be treated accordingly. Each has unique mandate and governance. Each must continue to operate independently and usefully in its own right; their individual sustainability and value should not be jeopardized by their active participation in our SoS. The SoS approach is highly applicable in jurisdictions which have a culture of strong autonomy among many distributed participants.

For example, our provincial program may contract with a number of local agencies to deliver a specific service. These local agencies are independent non-profits or part of a local government. Each is accountable to someone else. Each will continue to operate at the end of our contract. As the SoS manager, we need to negotiate a suitable agreement with each individual system which meets our requirements, but also recognizes its other accountabilities.

Evolutionary Development. A SoS does not suddenly appear fully formed. Indeed, a system of systems is never fully formed or complete. It develops over time, and it does so unevenly. We need to accommodate the variability in capability and maturity which will exist across participants.

As SoS manager, we must be familiar with both the journey and its milestones. Systems of systems are dynamic. One approach to managing the evolutionary development is through step-wise "versioning", that is to say: version n of our SoS will accomplish this set of things, while we prepare for the next set of things through version n+1. Another consideration is that rapid experimentation as the SoS evolves is more useful than trying to create a master plan.

Emergent Behavior. A successful SoS performs functions and carries out purposes that do not necessarily reside in or are localized to any member system in particular. This is the joy of "the whole being greater than the sum of the parts". It is also perhaps the sorrow, as we neither manage directly nor predict exactly these emergent behaviors!

System managers must concentrate on the functions and capabilities of the SoS as a whole. We must learn ways to manage system-level behaviors indirectly through governance rather than operational control. New features and capabilities will emerge unpredictably, some favorable and others not. This calls for an ongoing process of choice and adaptation.

Geographic Distribution. Our system of systems will have a geographic distribution or diversity which needs to be considered. Some of our participants may have different geographic scope or emphasis, including local, regional and broader scope. We need to accommodate continuous and episodic information exchanges in all geographic settings.

In the field of public safety and emergency management, the SoS approach is the foundation for connecting independent local agencies across multiple disciplines and scale up for a regional response.[6]

SoS Management Activities

There are four primary management activities which we find most important for success.

Purpose and Engagement. Our role as system manager is to establish and maintain agreement to our common purpose as part of a shared vision among participants, recognizing that each will also have other purposes and priorities they need to balance. This requires a robust and ongoing engagement process with system participants, including multi-layered governance and coordination, and formal agreements.

The engagement process will also need to accommodate disagreements and dynamic relationships among and within participating systems. Interactions between member systems can enable or impede overall development, management and operations.

Management Type. There are four fundamental types of SoS management– virtual, collaborative, acknowledged and directed. (These are described in the Appendix.) The choice of a management type depends in large measure on the nature of central authority, or its absence. Participating systems and the overall system manager must understand what management type(s) they are using, and use them consistently.

It is possible that management type may vary according to activities. For example, a provincial government may provide central management authority for policy, both in terms of managing a policy

process and providing directive management to the system through policy instruments, such as legislation or regulation. In other cases, strategic government policy may be directional but not directive. For example, a government may provide soft mandates through strategic policy or financial incentives. It is then up to participating systems to more or less voluntarily collaborate or accept the direction. In this case, the management authority derives from mutual agreements to central purpose. Finally, management may be virtual in some aspects of implementation, similar to the World Wide Web, where control arises through standard behavior and exchange between participants.

Interfaces and Standards. Communication between systems within our SoS will take place primarily through interfaces which have two characteristics. First, they must be standardized so that the individual systems know how to communicate with each other. Second, they must be layered, with each layer dealing with a logical context (e.g. governance, operations, physical resources, request to use a facility, agreement about a joint activity, communications, etc.)

Just as each of our member systems will have its own standard operating procedures and worldview, we must have, in parallel, a SoS worldview and standard operating procedures. One of our most significant activities as system manager is the make sure that interfaces are created, agreed to and maintained.

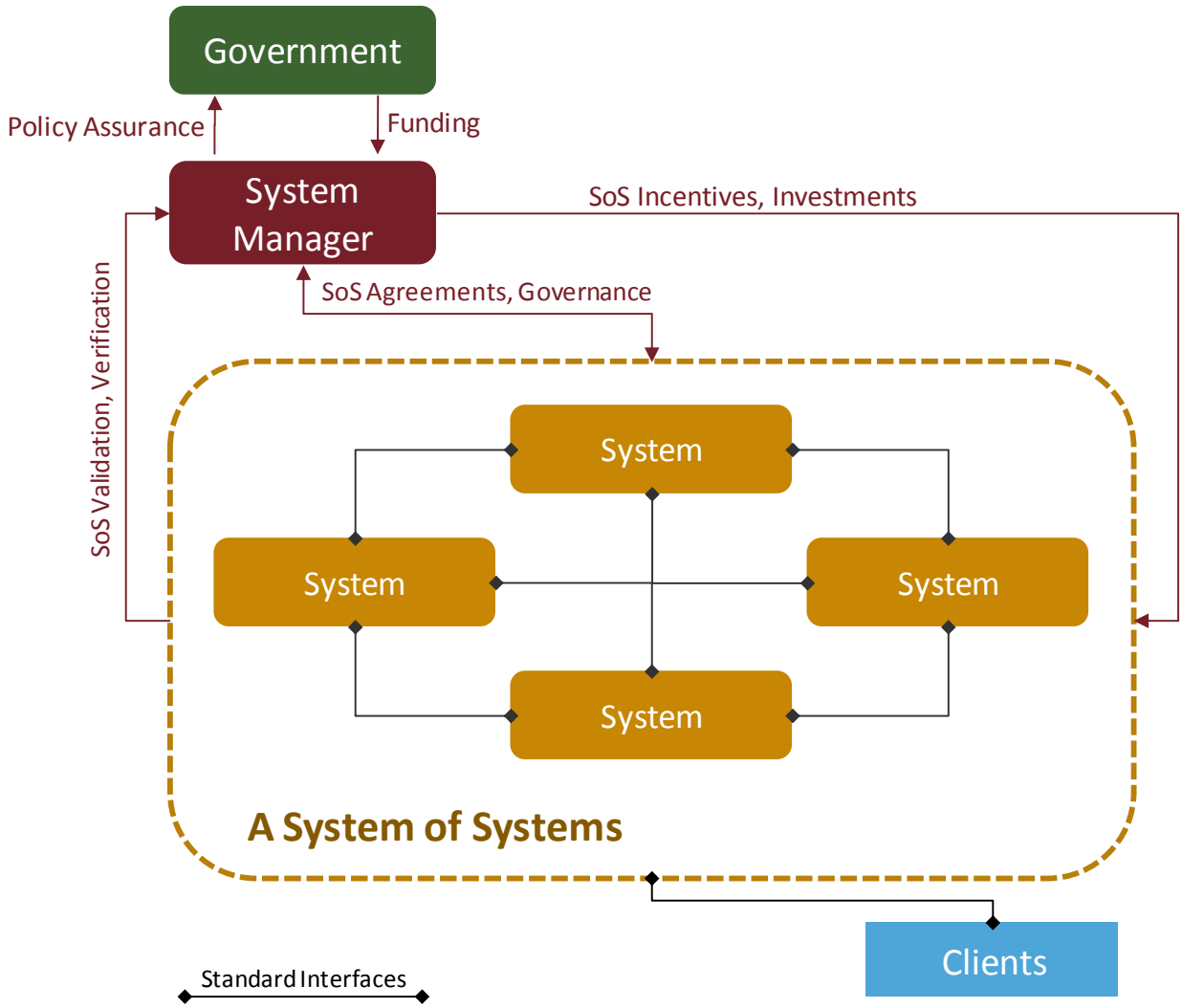
Verification and Validation. It is likely that our SoS will have some formal, mandated requirements that are established by policy, perhaps even statutory. Participating systems may be responsible for contributing functionality towards or even also meeting these requirements, and doing so within a SoS which is loosely coupled and without extensive central monitoring or meddling.

We will need a process for verifying that our formal requirements are met. This will be some combination of monitoring our overall SoS outcomes, as well as validating that our component systems are providing the agreed-to inputs, outputs or outcomes to each other as part of an interdependent network of systems, to us, and to our clients in the environment. SoS may be distributed across a province in many organizations, and face-to-face interaction thereby limited. Traditional management approaches such as span of control or unity of command will not be applicable and alternatives must be sought.

Conclusion

The system of systems approach is a useful way to extend our thinking about how we get independent systems to work together, and how we perform our role as system manager. Indeed, the SoS model is more reflective of how the world really works using modern organizational forms.

In most cases, we believe that the components needed to assemble a successful system of systems already exist. Or, as is sometimes the case, there is a *de facto* system of systems which is already in place but under-performing. What is missing, or perhaps not sufficient, is the overall strategy for putting it together and "controlling without control". We suggest that this model provides a useful checklist for evaluating a SoS – a coherent approach for identifying and crossing the gaps to superior performance.



Appendix

About SoS Management Types

There are four SoS system management types. [7]

- 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.
- Collaborative. In collaborative SoS the component systems interact more or less voluntarily to fulfill 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.
- 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 manager.
- Directed. Directed SoS are those in which the integrated system of systems is built 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 central managed purpose.[8]

It is unlikely that a system of systems will have a central authority directing all member activities, or a unified hierarchy through which to direct and control. If this were the case, it would be an organization rather than a network.

The hybrid nature of the management of a SoS will require strong governance participation and processes, so that roles and decision-making can be clarified and a common understanding of the SoS built and maintained.

Difference between a Single System and a System of Systems

What is different and worthy of attention.[9]

Aspect	Single System	SoS (Acknowledged Type)
Purpose	Optimized to meet specific performance and/or requirements	Optimized for both individual system performance and SoS performance, i.e. broad capability and interoperability
Architecture	Defined early in the life cycle and remains stable	Dynamically reconfigured as needs change
Behaviors	Single behavior set only for validated requirements	Flexibility and adaptability to accept legacy, emerging and ad-hoc systems behaviors
Stakeholder Involvement	Clearer set of stakeholders	Stakeholders at both system level and SoS levels (including the system owners), with competing interests and priorities; in some cases, the system stakeholder has no vested interest in the SoS.
Governance	Aligned mandate and funding	Added levels of complexity due to management and funding for both the SoS and individual systems; SoS manager does not have authority over all the systems.
Operational Focus	Designed and developed to meet operational objectives	Called upon to meet a set of operational objectives using systems whose objectives may or may not align with the SoS objectives.
Evaluation	Evaluation of the system is generally possible	Testing is more challenging due to the difficulty of synchronizing across multiple system life cycles; given the complexity of all the moving parts and potential for unintended consequences.
Boundaries and Interfaces	Focuses on boundaries and interfaces for the single system	Focus on identifying the systems that contribute to the SoS objectives and enabling the flow of data, control and functionality across the SoS while balancing needs of the systems.
Performance	Performance of the system to meet specified objectives	Performance across the SoS that satisfies SoS user capability needs while balancing needs of the individual systems.

[1] By "systems" we are not talking narrowly about information systems. Technology, software and computer networks have an important part to play in modern human systems but are not the focal point of systems science.
[2] Mika Myller, On the System of Systems Approach to the Development of Everyday Life Applications, University of Helsinki, September 2005.
[3] An alternative to a taking a system of systems might be to implement a shared service, where a new common system is created centrally and adopted as a replacement to existing, independent systems. The main challenge

with this approach in many cases is that the common shared service will not have the depth of capabilities and specializations as the independent systems it intends to replace.

[4] Selberg and Austin, Towards an Evolutionary Systems of Systems Architecture, Institute for Systems Research, 2008

[5] Based on Selberg and Austin, Towards an Evolutionary System of Systems Architecture, Institute for Systems Research, 2008

[6] The System of Systems Approach for Interoperable Communications, U.S. Department of Homeland Security.

[7] Architecting Principles for System of Systems, at http://www.infoed.com/Open/PAPERS/systems.htm

[8] Dahmann et al, Systems of Systems and Net-Centric Enterprise Systems, The MITRE Corporation

[9] Table adapted from Dahmann et al, Systems of Systems and Net-Centric Enterprise Systems, The MITRE Corporation, and material from System of Systems Engineering Center of Excellence