System of Systems and Complexity

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Lead Author: *Judith Dahmann*

Systems of Systems are generally characterized as complex (Sheard, 2019) (Luzeau et al.,2011) (Simpson, 2009) (DeLaurentis, 2007) (Ireland, 2014) (Magee, 2004), as is noted in the systems of systems (SoS) knowledge area of the SEBoK.

The question for those seeking to perform SoS Engineering (SoSE) then is how to address/use SoS complexity? In an ongoing collaboration between the INCOSE SoS and Complexity Working Groups, recent work on characterizing complexity has been applied to SoS, to assess how and why SoS exhibit complexity, as the basis for identifying approaches from the complexity community to applications of systems principles to systems of systems. This collaboration was spurred by recent work in both communities on concepts to understand how complexity affects systems of systems (Watson, 2020) and guiding principles to complexity thinking can be applied in Systems of Systems Engineering. (INCOSE, 2016)

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Complexity Dimensions Applied to Systems of Systems

How and why are systems of systems (SoS) characterized by different dimensions of complexity? Drawing on the dimensions of complexity (Watson, 2019) it is clear that by their nature SoS are rich in complexity, as described below. For each complexity dimension, the dimension is defined and the characteristics of SoS which make them subject to this dimension are briefly presented. Diversity "encompasses the structural, behavior, and system state varieties that characterize a system and/or its environment." (Watson, 2019) By their nature, SoS are composed of independent systems. (Maier, 1998) (ISO, 2019) SoS can exhibit tremendous diversity across the constituent systems which provide a range of behaviors, functionality, and technical approaches. SoS are comprised of multiple independent systems with their own users, management structures, requirements etc. often developed prior to their membership in an SoS, increasing the likelihood of diversity among the constituents of a SoS.

Connectivity "characterizes connection of the system between its functions and the environment. This connectivity is characterized by the number of nodes, diversity of node types, number of links, and diversity in link characteristics." (Watson, 2019) SoS include connectivity within each constituent system, among SoS constituents and between the SoS and its environment. Discontinuities (breaks in a pattern of connectivity at one or more layers) are often found in SoS. This links directly to dimensions of 'Interactivity' and 'disproportionate effects', since connectivity may lead to complex cascading interactions. Adaptability is defined as the characteristics of complex systems which "proactively and/or reactively change function, relationships, and behavior to balance changes in environment and application to achieve system goals." (Watson, 2019) SoS are composed of operationally independent systems [3]; hence the operators of each of system has their own rules of engagement and may react or adapt to changes in different ways based on their local objectives.

Multi-perspective refers to the fact that "multiple perspectives, some of which are orthogonal, are required to comprehend the complex system." (Watson, 2019) SoS are typically comprised of multiple independent systems which were developed and operated prior to the existence of the SoS; hence they each bring with them their own perspectives, which may or may not be aligned with the SoS. An understanding of the SoS considers all of these different perspectives. This links directly to the dimension of ‘Multi-scale’ since SoS may contain constituent systems of varying scales.

Complex system behavior “cannot be described fully as a response system. Complex system behavior includes nonlinearities. Optimizing system behavior cannot often be done focusing on properties solely within the system.” (Watson, 2019) While the behaviors of the individual systems may be predictable, particularly when the numbers of systems are large and have multiple internal behaviors, SoS behavior can become unpredictable. Each constituent has been designed to be operated independently and safely within its own context. without regard to the potential impact on the behavior of itself, on other systems and on overall SoS behavior.

Dynamics in “complex systems may have equilibrium states or may have no equilibrium state. Complex system dynamics have multiple scales or loops. Complex systems can stay within the dynamical system or generate new system states or state transitions due to internal system changes, external environment changes, or both.” (Watson, 2019) Following the discussion of behavior, these effects can be dynamic and impact other systems or have feedback loops leading to dynamic complexity. Notably, constituent systems may not only be managed independently, but they may also operate independently, increasing prospects of dynamic complexity.

Representations of “complex systems can be difficult to properly construct with any depth. It is often impossible to predict future configurations, structures, or behaviors of a complex system, given finite resources. Causal & influence networks create a challenge in developing 'requisite' conceptual models within these time and information resource constraints.” (Watson, 2019) One feature of SoS is that boundary conditions can be hard to define, which includes not only which constituent systems are members of an SoS, but also which behaviors of a constituent system play a role in the SoS making representation of an SoS a challenge. Evolution is a dimension of complexity as “changes over time in complex system states and structures (physical and behavioral) can result from various causes. Complex system states and structures are likely to change as a result of interactions within the complex system, with the environment, or in application. A complex system can have disequilibrium (i.e., non-steady) states and continue to function." (Watson, 2019) Rarely do we 'develop and field' an SoS, rather SoS are typically composed of existing systems; changes in an SoS result from changes in one or more of the constituent systems (or in the environment), making SoS development an evolutionary process.

System emergence leading to unpredictable behavior is driven by unexpected emergence; "emergent properties of the holistic system unexpected (whether predictable or unpredictable) in the system functionality/response. Unpredictable given finite resources. Behavior not describable as a response system." (Watson, 2019) By definition, SoS are comprised of multiple independent systems. (Maier, 1998) (ISO, 2019). Changes in one system could lead to new behavior in another, leading to unpredictable results. Indeterminate boundaries result from the fact that "complex system boundaries are intricately woven with their environment and other interacting systems. Their boundaries can be non-deterministic. The boundary cannot be distinguished based solely on processes inside the system." (Watson, 2019) One feature of SoS is that boundary conditions can be hard to define, including which constituent systems should be included in representation of an SoS, and which behaviors of a constituent play a role in the SoS.

Guiding Principles to Complexity Thinking Applied in Systems of Systems Engineering

The INCOSE Complexity Primer (INCOSE, 2016) outlines guiding principles to complexity thinking. As SoS exhibit complexity as discussed above, the next question is how these principles might then be applied to SoS.

Think like a gardener, not a watchmaker: "Consider the complexity of the environment and the solution and think about evolving a living solution to the problem rather than constructing a system from scratch." (INCOSE, 2016) SoS are often composed of current and new systems which support desired SoS capabilities and have evolved through interaction. Understanding these 'natural' interaction effects can be important in understanding the responses of constituent systems to various interventions.

Combine courage with humility: “It takes courage to acknowledge complexity, relinquish control, encourage variety, and explore unmapped territory. It takes humility to accept irreducible uncertainty, to be skeptical of existing knowledge, and to be open to learning from failure. A combination of courage and humility enables the complex systems engineer to risk genuine innovation and learn fast from iterative prototyping of solutions in context.” (INCOSE, 2016) This principle aligns with the recognition in SoS, the SoS engineer is moving into new territory where there are large differences between the degree of control, the diversity of system technical and functional capabilities, and multiple overlapping authorities.

Take an adaptive stance: “Systems engineers should mimic how living systems cope with complexity by identifying and creating variation, selecting the best versions, and amplify the fit of the selected versions. This means, for example, to think “influence” and “intervention” rather than “control” and “design.” (INCOSE, 2016) For most SoS, the successful SoS engineer recognizes that influence and intervention are the name of the game, since to a large extent control continues to rest with the constituents, and SoS architecture and design needs to accommodate the state of the constituent systems while addressing SoS capability objectives. Identify and use patterns: “Patterns are exhibited by complex systems, can be observed and understood, and are a key mechanism in the engineering of complex systems. Patterns are the primary means of dealing specifically with emergence and side effects—that is, the means of inducing desired emergence and side effects, and the means of avoiding undesired emergence and side effects.” (INCOSE, 2016) Understanding systems, their behaviors and interactions is a core element of SoSE. By modeling these and treating them as opportunities, patterns can be an effective SoSE approach.

Zoom in and zoom out: Because complex systems cannot be understood at a single scale of analysis, systems engineers must develop the habit of looking at their project at many different scales, by iteratively zooming in and zooming out.” (INCOSE, 2016) Effective SoSE is often called a ‘middle out’ process, where there is a need to understand the top-down drivers for the SoS, but also to respect the bottoms-up needs and capabilities of the constituents. Dynamics between these two perspectives reflects this ‘zoom in and zoom out’ principle in SoSE thinking.

Achieve Balance: "Optimization is often counterproductive within a complex system. Either the whole is sub-optimized when a part is optimized, or an optimized whole becomes rigid, unable to flex with changing conditions. Instead of optimizing, complex systems engineers should seek balance among competing tensions within the project. Systems engineers can leverage integrative thinking to generate improved solutions and avoid binary either/or tradeoffs." (INCOSE, 2016) In SoSE, if you are trying to 'optimize' you probably don't understand the situation. Multiple, often competing, objectives of the SoS and the constituents, requires options which continue to meet the constituent objectives but also address SoS capabilities. This links directly to both the 'Collaborate' and 'See through new eyes' principles.

Learn from problems: "In a changing context, with an evolving system, where elements are densely interconnected, problems and opportunities will continually emerge. Moreover, they will emerge in surprising ways, due to phase transitions, cascading failures, fat tailed distributions, and black swan events." (INCOSE, 2016) SoS development is recognized as evolutionary (Maier, 1998). One life cycle approach, the SoS 'Wave Model' (Dahmann, 2011) explicitly sees each iteration of SoS evolution as starting with assessment of changes since the last wave, recognizing the importance of learning from problems and adapting.

Meta-cognition: "Meta-cognition, or reflecting on how one reflects, helps to identify bias, make useful patterns of thinking more frequent, and improve understanding of a complex situation." (INCOSE, 2016) One of the SoS pain points (Dahmann, 2010) is the need for "SoS Thinking' – a form of meta-cognition.

Focus on desired regions of outcome space rather than specifying detailed outcomes: "Instead of zeroing in on an exact solution, focus on what range of solutions will have the desired effects, and design to keep out of forbidden ranges." (INCOSE, 2016) It is important to define SoS needs in terms of broad capabilities (versus detailed solutions) since there are a larger number of factors to be considered in an SoS. In SoS terminology, the SoS 'requirements space' reflects this perspective.

Understand what motivates autonomous agents: "Changing rewards will shape collective behavior. Implement incentives that will move the system toward a more desired state.” (INCOSE, 2016) A core element of SoSE (DoD, 2008) is to understand constituent systems and their relationships including the objectives and long-term goals for these systems. This provides the basis for assessing of changes systems will welcome, and potential for motivating constituents to provide needed SoS functionality and services aligned with their goals. This links directly to the “Use Free order’ principle emphasizing value of promoting self-organization in complex systems.

Maintain adaptive feedback loops: “Adaptive systems correct for output variations via a feedback mechanism. Over time, feedback loops can either hit the limit of their control space or may be removed in the interest of maintaining stability. To maintain robustness, periodically revisit feedback and ensure that adaptation can still occur.” (INCOSE, 2016) As noted above, under the SoS wave model (Dahmann, 2011) is constructed around this principle as applied to the SoS development and evolution life cycle. Integrate problems: “Focus on the relationships among problems rather than addressing each problem separately. This allows fewer solutions that take care of multiple problems in an integrative fashion.” (INCOSE, 2016) In SoS methods (Cook, 2014) including the SoS Wave Model (Dahmann 2010) and the DoD SoS SE Guide, (DoD, 2008) there is an emphasis on understanding the full SoS context, enabling understanding connections, patterns, and opportunities for this type of integrated view.

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None.
