System of Systems Engineering Management Framework

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Abstract: As systems become more complex, managing the development of these systems becomes more challenging. Additionally the integration of multiple independent systems increases the management challenge. System of Systems (SoS) has unique attributes which bring about unique management challenges. Architecture frameworks exist to organize and manage information about an architecture, and can be used to manage SoS architecture. One proposed approach was a framework that spans from component to enterprise, where enterprise is an SoS. A potential problem for this approach is that the lower half of the framework (from system down), is constructed using a reductionist approach while the upper part of the framework is constructed using a composition approach—that is, it is constructed by combining systems to make the broader enterprise system or SoS. So, does it stand to reason that the management approach for systems development should be the same as for SoS development? This article addresses some of the reasons why they should be managed differently, as well as offers a methodology for implementing the widely accepted Zachman Framework to facilitate the managing of SoS architectures.

Keywords:

EMJ Focus Areas: Systems Engineering

System of systems (SoS) comprises numerous constituent interdependent systems. These systems are autonomous and heterogeneous forming partnerships whereby their interoperability relationship produces capabilities or unintended consequences that do not originate from any one individual constituent system. They exhibit the SoS characteristics of autonomy, belonging, connectivity, diversity, and emergence (Boardman and Sauser, 2006). The interoperability relationships of the constituent systems create new behaviors of the holistic system. The picture that emerges is one of a holistic perspective versus a constituent perspective. The organization's systems engineering must form an enterprise architecture that supports the engineering of the SoS. The nature of an SoS has many disparate stakeholders representing their disparate systems as well as the capabilities to be derived for the SoS. The enterprise architecture must operate in support of the constituent systems as well as the formation of the SoS.

Many enterprise architecture frameworks have been reviewed to support an SoS environment because they help organize architecture descriptions and information as perceived by their users. We have chosen to extend and modify the Zachman Framework (ZF) (Zachman, 1987) because it provides various artifacts needed to describe an information system as viewed by different stakeholder's perspectives of the system. Through the modification and extension of the Zachman Framework, an SoS engineering methodology emerges that enables the management of constituent systems and the SoS that is functionally dependent upon the SoS attributes.

Systems and System of Systems

There are numerous definitions of a system. INCOSE defines a system as an integrated set of elements that accomplishes a defined objective. These elements include products (hardware, software, and firmware), processes, people, information, techniques, facilities, services, and other support elements (INCOSE, 2006). Buede defines a system as "a set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks" (Buede, 2000). For the purposes of this article, we will consider a system as something that has the ability to perform a set of tasks to satisfy a mission or objective. For example, an automobile can move a person from one location to another and is a system. The motor with the automobile cannot perform a goal by itself. Removed from the automobile and placed on the ground, it does nothing until it is combined with other parts of a system, e.g. a fuel delivery element, can it work in concert with those other parts to perform the goal of moving an individual to another location. This is not to minimize the complexity or importance of the motor. It is simply a subsystem of a broader system. The same holds true for the fuel delivery subsystem. It is an important part of the automobile, but is a subsystem in the automobile.

There are numerous definitions of SoS. INCOSE defines an SoS as "a system-of-interest whose system elements are themselves systems; typically these entail large scale inter-disciplinary problems with multiple, heterogeneous, distributed systems" (INCOSE, 2006). The various definitions of systems do not provide a detailed enough taxonomy to provide differentiation resulting in a dual perspective of a *system-of-interest is my element versus your system*. This perception extends to *your system is my SoS,* resulting in sufficient discussion on differentiating elements and systems (Simon, 1962; Koestler, 1967; Boardman, 1995; Simon, 1996).

Koestler (1967) managed this perceptual challenge with the introduction of *holons*—nodes on a hierarchic tree that behave partly as systems, or as elements, depending on how the observer perceives them. In this model there are intermediary forms of a series of levels in an ascending order of complexity. These levels are considered sub-systems that have characteristics of the system

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as well as its elements. This leads to the Janus Principle, which is the dichotomy of the systems and elements of autonomy and dependence (Koestler, 1967). Within the concept of hierarchic order, members of the hierarchy have two faces looking in two directions: one looking up the hierarchy, and the other looking down the hierarchy. The *member as a system* is looking downward in descending order to less complex levels while the *member as an element* is looking upward in ascending order to more complex levels and is the dependent part of the hierarchy.

The system's spectrum displays a traditional, ordinary system as a whole and its assemblies to a large SoS comprised of constituent systems. The attributes range from one of central control for a monolithic system, to a mixture of attributes for a decentralized system, to a set of attributes for an SoS. A primary assumption of an SoS is that they are open systems and are best understood in the context of their environments. It is also proposed that SoS have unique attributes unlike traditional, ordinary systems (Maier, 1996; Sage and Cuppan, 2001; Keating, Rogers, et al., 2003; DeLaurentis and Crossley, 2005; Saunders, Croom et al., 2005; Boardman and Sauser, 2006). A set of attributes used for reference are shown in Exhibit 1 as they relate to a system and an SoS (Boardman and Sauser, 2006). An SoS is comprised of autonomous constituent systems fulfilling an objective as independent systems but are interdependent to fulfill holistic objectives of an SoS. The constituent systems must perform an interoperation to fulfill an SoS capability in a collective manner whereby the capability does not exist on any of the constituent systems.

SoS behavior and capabilities are that of the whole and not properties of the constituent systems (elements) or that can be deduced by properties of the elements. The emergent behavior is a product of the interactions, not the sum of the actions of the constituent elements. Behavior arises from the organization of the elements without having to identify the properties of the individual elements. For example, a computer is an organization of elementary, functional components. Only the function performed by those components is relevant to the behavior of the whole system (Simon, 1996).

Architecture and Architecture Frameworks

While architecture is an overused and misunderstood word in the engineering lexicon, it is necessary to describe the structure of a system. Every system has an architecture, whether it is explicitly or implicitly designed and documented. There are many definitions for architecture. INCOSE defines system architecture as "The arrangement of elements and subsystems and the allocation of functions to them to meet system requirements" (INCOSE, 2006).

IEEE 1471 defines architecture as the "fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution" (Institute of Electrical and Electronics Engineers, 2000). While the words between the two definitions are somewhat different, let us agree that the organizing concept behind architecture is an organizing of a system, into constituent parts as specified through requirements, to satisfy a desired goal.

One challenge when discussing architecture is to understand what part of the architecture is under discussion. Frameworks help in the organizing architectural information, as the elements and subsystems, seen by different consumers of that information while providing a technique for thinking about architecture and organizing architecture descriptions. The ZF, shown in Exhibit 2, provides a sample of what type of information might be found in each of the intersections between the perspectives (rows) and the aspects (columns).

Exhibit 1. Differentiating a System from a System of Systems (Boardman and Sauser, 2006)

Attribute	System	System of Systems
Autonomy	Autonomy is ceded by parts in order to grant autonomy to the system.	Autonomy is exercised by constituent systems in order to fulfill the purpose of the SoS.
Belonging	Parts are akin to family members - they did not choose themselves but came from parents. Belonging of parts is in their nature.	Constituent systems choose to belong on a cost/benefits basis; also in order to cause greater fulfillment of their own purposes, and because of belief in the SoS supra purpose.
Connectivity	Prescient design, along with parts, with high connectivity hidden in elements, and minimum connectivity among major subsystems.	Dynamically supplied by constituent systems with every possibility of myriad connections between constituent systems, possibly via a net-centric architecture, to enhance SoS capability.
Diversity	Managed, i.e. reduced or minimized by modular hierarchy; parts' diversity encapsulated to create a known discrete module whose nature is to project simplicity into the next level of the hierarchy.	Increased diversity in SoS capability achieved by released autonomy, committed belonging, and open connectivity.
Emergence	Foreseen, both good and bad behavior, and designed in or tested out as appropriate.	Enhanced by deliberately not being foreseen, though its crucial importance is, and by creating an emergence capability climate, that will support early detection and elimination of bad behaviors.

Exhibit 2. Zachman Framework™ for Enterprise Architecture (Zachman, 1987)

	What Data	How Function	Where Network	Who People	When Time	Why Motivation
Scope [Contextual] Planner	List of important things to the Business	List of processes the Business performs	List of locations in which the Business operates	List of organizations important to the Business	List of events/ cycles significant to the business	List of Business goals/ strategies
Business Model [Conceptual] Owner	Semantic model	Business process model	Business logistics system	Work flow model	Master schedule	Business plan
System Model [Logical] Designer	Logical data model	Application architecture	Distributed system architecture	Human interface architecture	Processing structure	Business rule model
Technology Model [Physical] Builder	Physical data model	System design	Technology architecture	Presentation architecture	Control structure	Rule design
Detailed Presentation [Out-Of-Context] Subcontractor	Data definition	Computer Program	Network architecture	Security architecture	Timing definition	Rule specification
Functioning Enterprise	e.g.: Data	e.g.: Function	e.g.: Network	e.g.: Organization	e.g.: Schedule	e.g.: Strategy

The ZF identifies the various artifacts needed to describe an information system, as viewed by different stakeholder's perspectives of the system. "The framework is a classification schema for descriptive representations of an enterprise. By observing design artifacts of physical objects like airplanes, buildings, ships, and computers, John Zachman derived the framework" (O'Rourke, Fishman et al., 2003). The artifacts captured in the ZF can be viewed either by the perspective of the person viewing the artifact or the aspect of the content or subject focus. Over time, Zachman has added additional information to his framework. Exhibit 3 represents the current state of the ZF.

Initially intended for use by Information Technology organizations, the ZF has since been applied to facilitate understanding of information architectures in multiple domains. The ZF provides a contextual basis for discussions among stakeholders with disparate levels of understanding regarding the enterprise under discussion in a holistic manner (Morganwalp and Sage, 2004). Based on the organizing benefits of frameworks, and their use to manage aspects of complex enterprise architecture, it follows to investigate a framework approach in discussing and managing SoS. The rest of the article will propose such a framework.

Systems of Systems Engineering Management

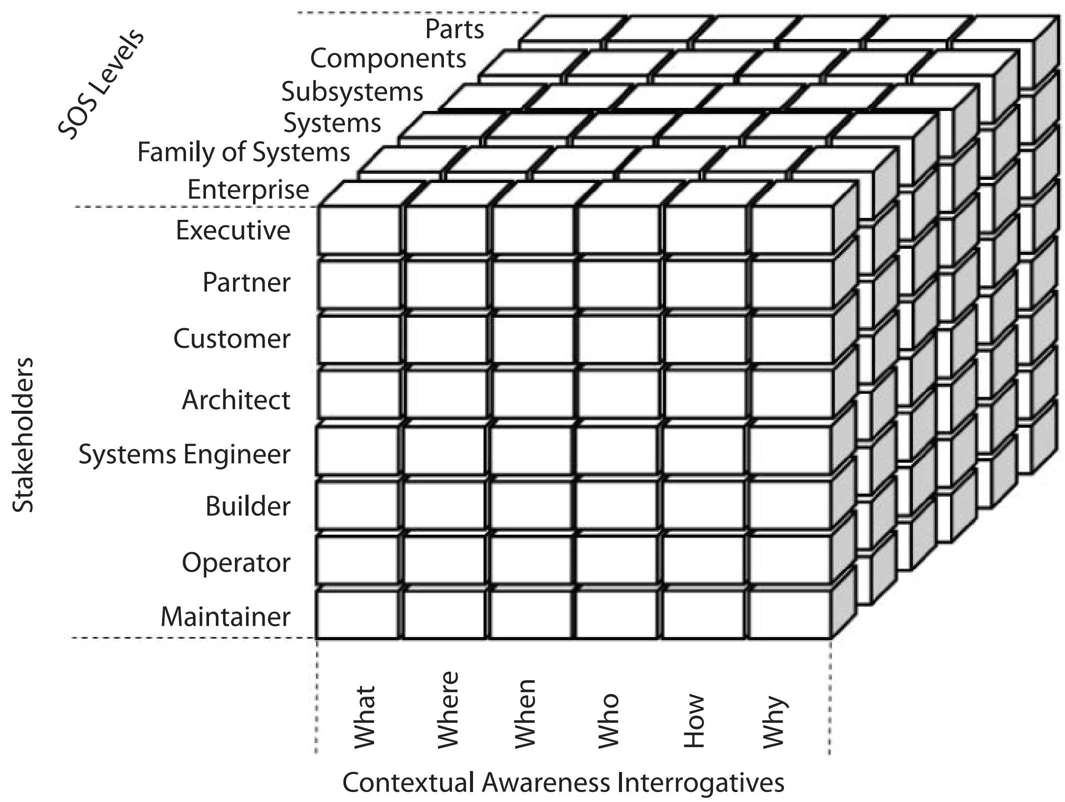
SoS Engineering (SoSE) is described as "The design, development, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results" (Keating, Rogers et al., 2003). A metasystem is an SoS "comprised of multiple embedded and interrelated autonomous complex subsystems that can be diverse in technology, context, operation, geography, and conceptual frame" (Keating, 2005). The mix of constituent systems may include existing, partially developed, and yet-to-be-designed independent systems. The engineering and management is about "design for influence" versus point or single system engineering of ordinary systems. It is about influence versus control; therefore, it could be said that design for influence is the ability to influence other systems in such a way that the SoS interoperation fulfills the stakeholder's objectives. SoSE fosters the definition, coordination, development, and interface control of the independent systems while providing controls to ensure their autonomy. This difference introduces the need for SoSE unique aspects for governance and interoperability.

Governance and Interoperability

Governance is usually a body of authority that includes, but is not limited to, structures of authority and collaboration in order to allocate resources and coordinate management control activity. Governance is also the process and systems by which an SoS is managed and built. For a single system, the majority of stakeholders manages only a single system and has very specific roles in systems engineering. This governance is hierarchical with a lead engineer and program manager. For an SoS, the stakeholders tend to be more diverse because they have interest in other systems as well. In addition, the SoS involves other stakeholders as "unanticipated users" as the SoS is more dynamic and its diversity becomes more apparent as it matures.

Governance is a primary problem in managing, developing, and deploying SoS because most, if not all, current governance structures are at the individual constituent system levels. This is because the structure is focused upon the individual systems

Exhibit 3. Three Dimensional Architectural Framework (Morganwalp and Sage, 2002/2003)



due to the Work Breakdown Structure (WBS), in reference to the Department of Defense (DoD), as it is designed to support incremental acquisition of operational capabilities (Wang, Lane et al., 2006) and promotes management and engineering in a reductionist manner promoting individual systems and components versus a systems composition manner that promotes SoS. The SoSE and SoS acquisition is new to the DoD community and requires new perspectives and training in transforming existing contract and program structures to an SoS acquisition model.

Interoperability has many domain-oriented definitions. A definition used in this context is "the ability of a collection of communicating entities to share specified information and operate on that information according to shared operational semantics in order to achieve a specified purpose in a given context" (Carney, Fisher et al., 2005). Systems interoperability or interoperation assumes that systems have a relationship and that a system provides some service to another. In other words, in an SoS context there are cooperative interactions among loosely autonomous systems to adaptively fulfill a system-wide purpose. The constituent systems of an SoS must communicate in some form, otherwise it is not realizable (DiMario, 2006). Syntactic communication is the initial step of interoperability whereby a connection is established and semantic communication is necessary for the communicating systems to know what to do with the information that is communicated adding value to the SoS.

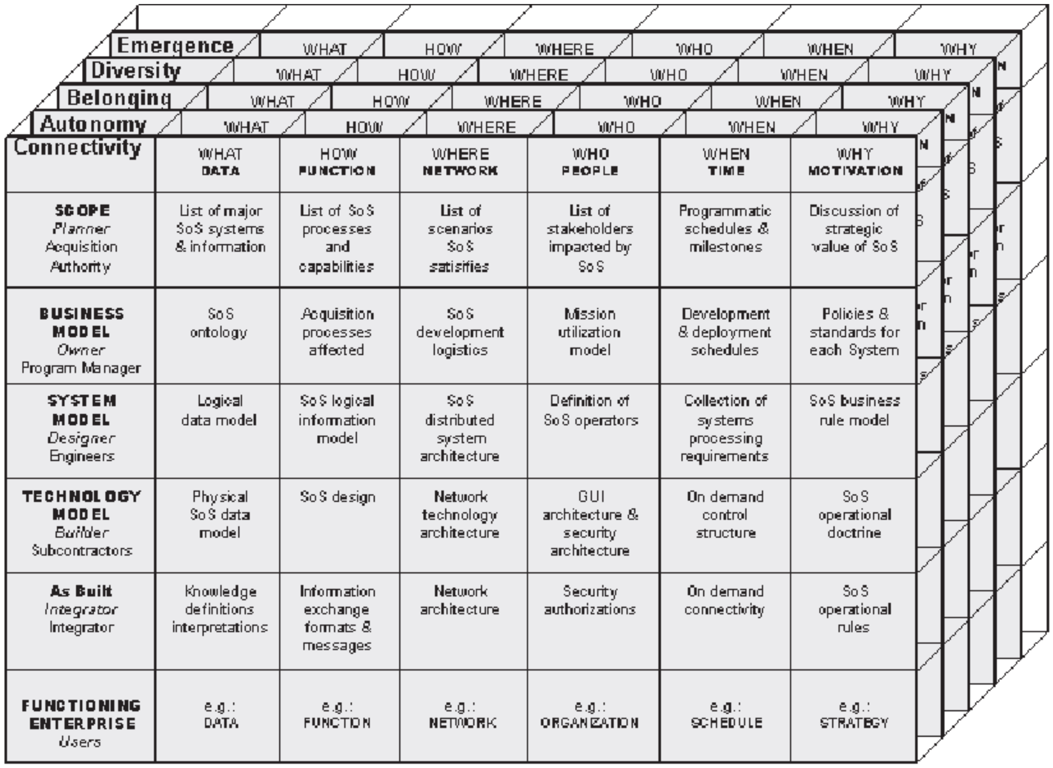
System of Systems Framework

A goal of SoS development is to place an emphasis on how systems interact to accomplish their common collective purpose with a de-emphasis on the individual systems. The continuing development and independence of the constituent systems as well as the common collective purpose is difficult to achieve solely through the selection of correct interfaces (Kuras and White, 2005). In addition, changes and evolution of the constituent systems are difficult to align individual system priorities with the SoS holistic priorities due to the lack of governance. Even though the constituent systems may continue to connect, their ability to transfer and make use of the information may be hindered or result in unanticipated emergent behavior. The difficulty arises due to the disparate management of all the independent systems. Decision making and control is distributed without governance.

The ZF provides the flexibility of organizing the necessary information to disparate stakeholders of an enterprise of mutual interest. This flexibility readily supports an extension of a three dimensional perspective for an SoS by adding the SoS attributes as a third dimension. A three dimensional SoS architecture framework employing the Zachman architectural framework is not new; an example is shown in Exhibit 4 whereby the various hierarchical SoS levels are mapped (Morganwalp and Sage, 2002/2003). This graphical representation represents the systems engineering life cycles focused on the stakeholder views of engineering a system, contextual awareness interrogatives, and the SoS levels.

The essence of an SoS is consituted by the five attributes shown in Exhibit 1. The SoS enterprise architecture should be engineered with consideration of the SoS attributes to operate as a whole. The constituent systems of the SoS must operate independently and are generally managed independently of one another contributing to the whole when required. There is a need for a suitable architectural framework to support the

Exhibit 4: SoS Connectivity Attribute Information Architecture Using Zachman Framework



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SoS environment of systems that adapt, evolve, and possess emergent behavior. Systems engineering is the management of technology that controls the total life-cycle process that meets user needs and a suitable framework to enable the engineering of a system.

The SoS attributes may be managed by mapping them to the Zachman architectural framework of stakeholders that share interests and concerns and express their interests and concerns via the contextual awareness interrogatives as shown in Exhibit 4. The cell intersection of the stakeholders (Acquisition Authority, Program Manager, Engineers, Subcontractors, and Integrator), and the Contextual Awareness Interrogatives (What, How, Where, Who, When, Who, and Why) for each of the SoS attributes provides a unique perspective and abstraction. Through creating a set of unique perspectives and abstractions for each attribute, the SoS may be developed, deployed, and managed in a design for influence in a manner achieving holistic capabilities and that maintains constituent system management and independence. The goal of performing SoSE in a compositional manner may be achievable aligning the priorities of an SoS as well as the individual systems.

The SoS attribute connectivity is chosen to show the unique abstractions for an SoS attribute and will most likely be very different for the other attributes, even though the stakeholders remain the same. Connectivity was chosen for this example since an SoS cannot exist if the constituent systems cannot connect and exchange information. The SoS connectivity attribute is about interoperation among constituent systems and must support the flow of data and knowledge syntactically and semantically. The abstractions shown in the individual cells indicate actions or artifacts required to achieve connectivity in the SoS environment aligning SoS and individual system priorities.

Conclusions

This article describes the nature of an SoS and the application of the ZF in defining the enterprise architecture for SoSE. The ZF was modified and extended using the SoS attributes as functions for the stakeholders and contextual awareness interrogatives. The important points presented in this article include:

- ZF lends itself easily to adaptation and SoS usage
- SoS attributes provide focus for the stakeholders
- Artifacts for SoSE and management are identified for the connectivity attribute
- Abstractions and perspectives per attribute provide SoS composability
- Constituent system and SoS priorities are adjudicated by using same stakeholders
- The problems introduced due to the absence of SoS governance may be adjudicated through the interaction of the attribute cell results of interrogatives and stakeholders
- SoS Design for Influence is enabled through the modified Zachman Framework

Recommendations for Future Research

Future research and investigation is required to extend this methodology to the other attributes. The collective interactions of the artifacts contained in any single ZF cell on a single plane are complex. The addition of multiple planes or dimensions to the ZF to represent the unique SoS attributes compounds the complexity of those interactions. The effects of this complexity on the ZF require further investigation. Validation of the cells in real projects is required to fully test this methodology. Thorough validation will provide sensitivity of the attributes in an SoS environment and may reveal improved processes to manage the priorities of individuals systems and the SoS creating processes for SoSE and management.

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