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Architecting the System of Systems Enterprise: Enabling Constructs and Methods from the Field of Engineering Systems

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Abstract. Engineering systems is a field of scholarship focused on developing fundamental theories and methods to address the challenges of large-scale complex systems in context of their socio-technical environments. The authors describe facets of their recent and ongoing research within the field of engineering systems to develop constructs and methods for architecting enterprises engaged in system-of-systems (SoS) engineering,. The ultimate goal of the research is to develop a framework for characterizing, designing, and evaluating SoS enterprise architectures throughout the system lifespan as various forces result in entering/exiting of constituent systems, changing environment, and shifting enterprise profile. The nature of systems-of-systems demands constructs for multi-dimensional architectural descriptions, as well as methods for design and evaluation that employ dynamic approaches. In this paper, two important elements in an emerging framework are described, including a holistic enterprise architecting framework and an epoch-based analysis method for examining possible futures of the SoS enterprise.

Keywords – engineering systems, system of systems, architecting framework, epoch-based analysis, stakeholder analysis, enterprise

I. INTRODUCTION

The complexity and nature of technological systems and their associated enterprises have evolved significantly in recent years due to such factors as net-centricity, complexity of the human-system interface, global engineering environment, and shifting geo-political forces. The field of *engineering systems* has emerged to address the challenges inherent in these systems, or systems-of-systems (SoS). This has necessitated an expansion of the systems approach, intensified focus on system properties (such as changeability, flexibility, agility, etc.), and recognition of the inseparability of technological system and the enterprise developing and operating such systems.

SoS are comprised of multiple systems that are managed and operated independently, but also deliver value at the SoS level. Similarly, the enterprises at the systems level have managerial and operational independence, but together these constituent enterprises perform together to develop and operate the SoS. The importance of research to support advanced systems practices was underscored by a 2004 US Air Force/Lean Aerospace Initiative[1] workshop on systems engineering, calling for identifying "Considerations for SoS/Enterprise Engineering" as one of six recommended research initiatives. Experts attending this workshop agreed that system-of-systems engineering and complex enterprise engineering present new challenges in identifying and achieving convergence in the enterprise stakeholder needs, and further require new ways of thinking about and managing systems [1]. Over the past decade *engineering systems* has evolved as field of scholarship that takes an integrative holistic view of large-scale, complex, technologically-enabled systems which have significant enterprise level interactions and socio-technical interfaces [2]. Within this field, an important area of inquiry focuses on understanding how to architect, integrate, manage and transform large-scale enterprises, taking into consideration their overall environment or context.

II. ENTERPRISE FOCUS

The interest in evolving a "science" of enterprises [3] has grown rapidly in recent years as evidenced by increased research, new academic programs, and centers for the study of enterprises. Yet, the practice of enterprise architecting and transformation has yet to encompass a more holistic paradigm, largely continuing to be performed from a single "lense" approach such as information technology focused [4], process re-engineering focused [5], or organizational transformation focused [6]. While these individual lenses can be used to improve non-complex enterprises in the short run, they fall short in meeting the challenges of SoS in the long run.

The *engineering systems* paradigm is highly suitable to modern enterprises, where the technological solution is deeply interconnected to all facets of its associated enterprise. Further, in contemporary SoS, the synergistic architecting and evolution of technological solution (product line, services, or solution offerings) and associated enterprise becomes even more critically important as the dependencies and co-influences increase significantly.

Two major trends have emerged that enrich the understanding of the enterprise for the purpose of developing successful SoS. The first is the evolution of the field of

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[1] In 2008, the Lean Aerospace Initiative was renamed the Lean Advancement Initiative.

enterprise architecting from an IT-centric field to one that considers the enterprise from a holistic perspective encompassing multiple views and their interrelationships. The current practice of enterprise architecting has been a significant contribution to creating and sustaining modern enterprises; however, the current practice is not sufficient for the structural and behavioral complexities inherent in SoS enterprises, where multiple enterprises participate as constituents in the meta-level enterprise. A broad holistic approach is needed in context of the engineering systems perspective, drawing on the emerging systems architecting field, and taking into account new paradigms and environmental drivers. Nightingale and Rhodes [3] describe enterprise systems architecting as an emerging art and science within the overall field of engineering systems, involving a strategic and holistic approach. This expanded view is evident in research at many universities today, and builds on early work in the field, for example, Rechtin [7] who proposed the principles of systems architecting as being extensible to architecting organizations.

The contemporary architectural descriptions of enterprises are fairly comprehensive. Multiple views of an enterprise are now well enumerated, and there are numerous enterprise architecture frameworks [8]. These frameworks serve to ensure the enterprise architecture is fully described from its multiple perspectives and that this information is communicated to all the stakeholders for defining, developing, and sustaining the system. Along with these frameworks, new toolsets for modeling the enterprise have come into the market. There are limits to the frameworks in the SoS realm, for example, these lack the ability to describe such concepts as layering. The frameworks are typically oriented toward the 'simpler' case of enterprise as delivering a product line or service. Thus, they are insufficient for many contemporary enterprises that are (or are evolving into) large-scale, global systems integrators or solution providers. Further, these current frameworks are overly complex and emphasize an aggregated rather than holistic architecture.

A second trend in recent years has been the ongoing effort to merge the systems engineering and enterprise engineering practices, as *enterprise systems engineering* [9]. This new approach involves applying the principles of systems engineering to the enterprise itself, as a complex entity including the product system(s). It involves many different engineering projects which co-exist and evolve, each with its own unique lifecycle. In taking an engineering systems perspective, products and enterprises are recognized as intimately connected.

Enterprise systems engineering, or ESE, is a promising approach, but falls short if limited to a classical systems engineering perspective. Carlock and Fenton [10] describe ESE as expanding "beyond the classical base to consider the full range of systems engineering services increasingly needed in a complex organization where information-intensive systems are becoming central elements in the organization's business strategy."

The concept of enterprises as systems is well accepted, yet the research landscape for an enterprise science remains somewhat limited to classical fields of study, for example, management science, information technology, and knowledge management. The structure of modern enterprises is complex, and new approaches are needed to conceptualize and assess interrelationships of enterprise elements, as well as communicate these at multiple levels of abstraction. The challenge is to do so simply enough for effective decision making given cognitive limitation of decision makers,

III. ENGINEERING SYSTEMS CONSTRUCTS AND METHODS

Engineering systems, as a field of scholarship, is evolving new constructs and methods more suitable for addressing the development and operations of socio-technical systems. As shown in Table 1, the system engineering perspective is appropriate under certain conditions (e.g., developing well-specified systems), while the engineering systems perspective offers a more extensive perspective suited to SoS.

TABLE 1. Comparison of SE and Engineering Systems Perspective [11]

Systems Engineering versus Engineering Systems Perspective		
	Systems Engineering Perspective	**Engineering Systems Perspective**
Scope	May be applied to small scale to large scale efforts including subsystems, systems, system of systems	Applies to very large-scale, complex open systems which are technologically enabled and have extensive social implications
Policy	Policies are viewed as fixed and a constraint in the system solution	Policies are viewed as variables (at appropriate points in lifecycle) that can be created/adapted for overall system solution
Socio-technical	Socio-technical aspects of the system are viewed as considerations in engineering	Socio-technical aspects of the system are viewed as primary drivers in an overall system solution
Stakeholders	Primary focus on the customer and the end-users of the product system	Balanced focus on all stakeholders impacted by engineering system including product system, enterprise, environment
Engineering Processes	Engineering processes are applied to the product system	Engineering processes are applied to both the product system and the enterprise
Practitioners	Practitioners are systems architects, systems engineers, and related specialists performing systems engineering process	Practitioners include systems architects, enterprise architects, systems engineers, specialty engineers, operations analysts, project managers, policy makers, environmental scientists, social scientists, and others
Goal	Predictably develop systems with optimal performance for value to satisfy primary stakeholders	Predictably develop evolvable, sustainable engineering systems with value to society as a whole

The prominence of enterprise focus is evidenced by

ongoing university research programs[2] focused on developing constructs and methods suitable for the challenges of designing SoS, considering all of the facets of the overall enterprise and its environment. A research goal is to develop a framework for characterizing, designing, and evaluating architectures throughout the system lifespan. In SoS, complex driving forces include entering/exiting of constituent systems, changing socio-technical environment, and the respective shifts in the enterprise profile. In order to architect a new or future instantiation of the SoS, a descriptive architectural construct is needed to enable a holistic perspective to be taken. Additionally, methods for design and evaluation are required that accommodate the dynamic of the situation. Recent research has resulted in a framework and method contributing to the effective architecting SoS enterprises:

1. *Multi-view Framework for Enterprise Architecting.* Through descriptive studies of real-world enterprises, an enterprise architecting framework that takes an engineering systems perspective has been developed. It characterizes interrelationships of enterprise views having structures and behaviors, and including sequential influences. The framework has been tested on in a number of case studies across multiple domains, and feedback shows use of the framework yields an enriched understanding of eight dimensions or views of the enterprise, as well the interrelationships between these.

2. *Epoch-based Analysis Method for Evaluating Enterprise Architectures in Dynamic Contexts.* The continuous need to make adaptations to modern enterprises implies that impact analysis is both important and very challenging. For high performing enterprises, an embedded 'enterprise architecting function' is essential, particularly in regard to anticipating future enterprise needs and contexts. Decisions concerning the enterprise must be made as the world continues to change around it. Enterprise leadership has an important role in evaluating how various enterprise design interventions will likely result in increased, sustained or decreased value delivery by the enterprise to its stakeholders in the new context. Epoch-Era Analysis [12] is a time-based analysis method used for conceptualizing system timelines using natural value-centric timescales wherein the context itself defines the timescales. Epoch-Era Analysis has been applied to evaluation of technological systems as a visualization/communication approach and also more rigorously in tradespace exploration [13]. The approach has the potential to enable the enterprise designers to think in a more continuous and anticipatory manner in a world that demands an enterprise match the cadence of a changing environment.

[2] Two examples at MIT are Lean Advancement Initiative (LAI) and Systems Engineering Advancement Research Initiative (SEAri).

The holistic enterprise architecting framework provides a mechanism for design, evaluation and selection of a preferred SoS architecture. Time-based analysis methods, such as Epoch-Era Analysis, enrich architectural decision-making through a dynamic approach. The current limitation of the former is that architectural decisions are made in context of a single future timeframe. The current experience base with the latter is that Epoch-Era Analysis has been applied primarily to the technological system only. Ongoing research seeks to link these two constructs, along with other enabling constructs and methods, to architect the SoS, addressing both technological and socio-technical systems in context of possible futures.

A. An ES-based Framework for Enterprise Architecting

Nightingale and Rhodes define enterprise architecting as "applying holistic thinking to conceptually design, evaluate and select a preferred structure for a future state enterprise to realize its value proposition and desired behaviors" [14]. In order to fully understand an enterprise in accordance with an engineering systems perspective, its constituent elements must first be elaborated and described. Through descriptive studies of real-world enterprises, a framework has been developed to characterize the interrelationships of the enterprise views, including their sequential influences. The framework, as shown in Figure 1, represents preliminary generalized results based on several years of empirical studies. It should be noted that this framework is adapted for a specific enterprise based on the nature and context of that enterprise. The solid lines show primary relationships and influences of the elements or views, and the dotted lines are secondary ones.

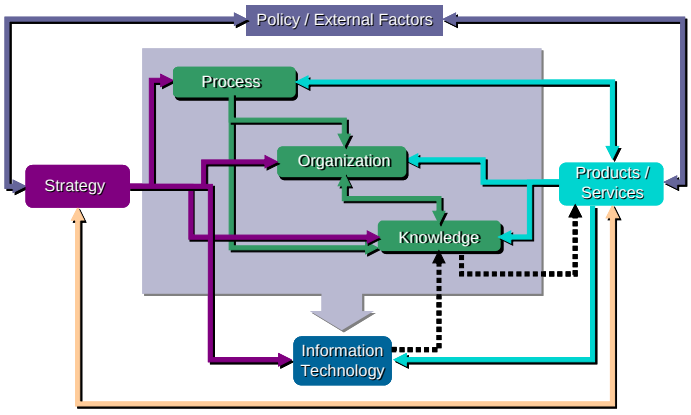


FIGURE 1. A Holistic EA Framework (Nightingale & Rhodes 2007)

In order to fully understand complex enterprises in accordance with an engineering systems perspective, its elements must first be elaborated and described. Eight views have been identified as important in building a comprehensive picture of the enterprise. The strategy view is primary, with strategy driving process, organization, and knowledge. These latter three contribute to the overall competency of the SoS. Policy and external factors influence strategy, including the products/services. Products and services influence the

competency, and may also be directly driven by the policy and external factors, such as regulatory requirements. The information technology needs are then derived from the needs of multiple stakeholders in the system. Table 2 below provides a brief summary of these views.

TABLE 2. Views of an Enterprise.

Views	Description
Strategy	*Goals, vision and direction of the enterprise, including business model and competitive environment.*
Policy/ External Factors	*External regulatory, political and societal environments in which the enterprise operates.*
Organization	*Organizational structure as well as relationships, culture, behaviors, and boundaries between individuals, teams and organizations.*
Process	*Core processes by which the enterprise creates value for its stakeholders.*
Knowledge	*Implicit and tacit knowledge, capabilities, and intellectual property resident in the enterprise.*
Information	*Information needs of the enterprise, including flows of information and systems/technologies for information availability.*
Product	*Products produced by the enterprise for use by its stakeholders.*
Services	*Services of the enterprise, including services as a primary objective or in support of product.*

In order to further describe the enterprise, each of the elements can be further elaborated in terms of its characteristics; as shown in Table 3 below. These may include structure, behavior, artifacts, measures and periodicity. By elaborating the elements of the enterprise architecture, the relational characteristics become clear, resulting an enhanced ability to understand complex enterprises from a holistic perspective.

The framework is designed to describe an architecture for an enterprise, taking an *engineering systems perspective* to result in a holistic understanding. The SoS enterprise is complex by nature, and use of this framework encourages increased discovery of the critical relationships among elements in the enterprise.

A current limitation of enterprise architecting is that temporality is undertreated. In developing a strategy for a future state enterprise, the architect defines the "as-is" enterprise, and then a "to-be" architecture to meet some desired future state.

TABLE 3. Enterprise View Elaboration: Example for Process

PROCESS	Core, enabling, and leadership processes by which the enterprise creates value for its stakeholders.
Structure	The configuration characteristics of the processes, for example: ▪ Integrated versus stove-piped process design ▪ Global versus local orientation of processes
Behavior	The operational characteristics of the processes, for example: ▪ Repeatability of processes ▪ Degree of standardization of processes
Artifacts	The items produced to document the process architecture, for example: ▪ Process and value stream maps ▪ Process documentation libraries
Measures	Quantification of process performance, for example: ▪ Productivity and cycle time measures ▪ Capability maturity level ▪ Process compliance measures
Periodicity	The temporal aspects of process definition and deployment, for example: ▪ Process lifespan ▪ Frequency of process audits

Enterprise architecting has advocated the development of several candidate future state architectures, rigorous evaluation of these candidates, and selection of a preferred to-be architecture to address the desired future enterprise vision [3]. In applying this approach to real world enterprises, the importance of context and its relationship to value delivery of system and enterprise in the lifespan has been observed.

B. Epoch-Era Analysis for SoS Enterprise Architecting.

Epoch-Era Analysis, as illustrated in Fig 2, is a new approach that addresses the need to consider systems (and their delivery of value to stakeholders) in context of a changing world [11, 12, 15]. It provides insight into decisions, for example, when in the evolution of the SoS new constituent systems should added, and when investments should be made in a new technology. With Epoch-Era Analysis, the system lifespan is divided into a series of epochs, defined as time periods when significant needs and context are fixed.

Multiple consecutive epochs can be strung together to create an era, or scenario, which represents a long-run view of the changing system needs and context. Within each epoch, analysis can evaluate various systems for a fixed set of contexts and needs. Significant changes in the system and its context (such as a new threat to the system, or a need for a new type of constituent system in a SoS) can be represented by defining a new epoch. Path analysis across a series of epochs, an era, can then identify system evolution strategies that provide continued high value delivery to the stakeholders.

In recent research, Epoch-Era Analysis has been applied to the design of systems, and considerations for its application to SoS have been elaborated [16]. With this focus on SoS, the interest in applying this analysis in the architecting of enterprises has grown.

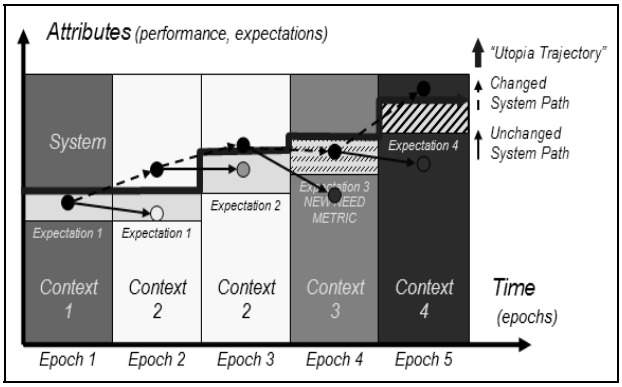


FIGURE 2. Epoch-Era Analysis. Each epoch has fixed context and expectations. System value may degrade in a new epoch; changing the system may restore it. The "utopia trajectory" is the optimal value delivery strategy across epochs.

Architectural thinking provides the essential mindset for the conceptual phase of enterprise transformation. During the startup of new endeavor, architecting is an activity in the initial phases. It is not atypical for an enterprise to bring in an expert 'enterprise architect' to develop a grand design for an enterprise transformation. But the reality is that architectural thinking is needed continuously in enterprises because enterprises are 'living things," and in SoS enterprises this need is even greater.

This continuous need to make adjustments to the enterprise implies that impact analysis is both very important and very challenging. In high performing enterprises an embedded 'enterprise architecting function' is essential, particularly in regard to anticipating future contexts. Decisions concerning the enterprise must be made as the world changes around the enterprise, and the world will always change. Enterprise leadership has an important role in evaluating how various enterprise design interventions will likely result in increased, sustained or decreased value delivery to stakeholders in new contexts.

Epoch-Era Analysis has been applied rigorously in the tradespace exploration of systems, and this type of analysis may be extensible to SoS enterprises. At present, the constructs of epoch and era can be used as conceptual mechanisms for enhancing the temporal-based understanding of enterprises. These constructs enable the enterprise architects to think about dynamic context in a world that demands an enterprise match the cadence of its changing environment.

Systems are often described using the construct of a lifecycle, and enterprises, like systems, also have lifecycles. Typically the enterprise lifecycle might be described in terms of organizational maturity, for example, including phases such as emerging phase, growing phase, maturing phase, declining phase. While such lifecycle constructs are important, they are insufficient for understanding the temporality of enterprises. Another common temporal construct for an enterprise is that of fiscal driven periods such as quarters; it should be recognized that this is an 'artificially imposed' temporal perspective.

The role of the enterprise architect is to define several viable candidate 'to-be' architectures, evaluate these candidates, and select the preferred architecture. The first step in thinking about SoS using epoch-based analysis is to think more deeply about the enterprise context and what future contexts might occur in the lifespan of the SoS. Exogenous to the enterprise design activity, potential epochs – periods of fixed contexts and needs – are defined and envisioned as having approximate time durations. Whereas the typical enterprise architecting activity focuses on meeting a vision for some single future point in time, using an epoch-based analysis approach encourages more thinking and elaboration of the overall 'environments' in which the future state enterprise may exist and its influences on the enterprise.

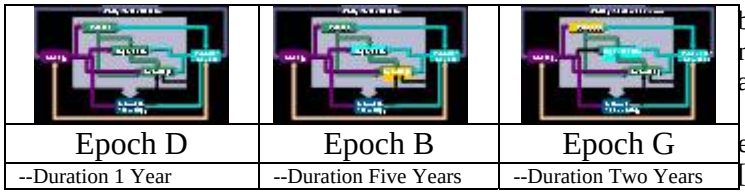
Once the possible epochs are elaborated and a preferred architecture is selected for each, these epochs can be strung together into one or more possible envisioned "Enterprise Eras" as shown notionally in Fig 3. For any given era, the necessary architectural shifts can be more clearly envisioned and transformation planning can be thought about at a multi-epoch level.

As an example, suppose the enterprise architect has identified an unordered set of eight possible envisioned epochs, identified as Epoch A to Epoch H. Once the epoch-based analysis is completed, several epochs can be strung together as Era, showing a possible SoS lifespan (in this case, three epochs D, B, and G are combined to form a possible SoS era). Fig 3 illustrates three epochs, with the enterprise architecture represented notionally using variations on the EA framework for illustrative purpose. Given the "best" architectures for each epoch, in an anticipatory analysis, the architect can develop strategies for SoS enterprise transformation for "best of best" across these epochs. In real-world enterprises, enterprise transformation efforts may be ongoing when a context or needs shift occurs, and the architect's role is to find strategies to respond in a timely manner to the epoch change.

As a specific example, the contextual conditions and stakeholder needs in Epoch D may be suitable to the existence of "Collaborative SoS", whereas changes in Epoch B (such as a new threat environment) drive the need for a "Directed SoS". In collaborative SoS, the component systems interact more or less voluntarily to fulfill agreed upon central purposes. Central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards. Directed SoS are those in which an 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 component systems maintain an ability to

operate independently, but their normal operational mode is subordinated to the central managed purpose. To accomplish this shift from Collaborative SoS to Directed SoS, particular enterprise transformation strategies will be necessary in addition to any specific technology system changes.

Enterprise architecting using Epoch-Era Analysis has been explored conceptually in recent research, and in the future may be extended to include model-based tradespace exploration.



Epoch D	Epoch B	Epoch G
--Duration 1 Year	--Duration Five Years	--Duration Two Years

FIGURE 3. Notional illustration of SoS Enterprise Architecture with architectural changes in response to new epoch influences.

IV. DISCUSSION AND CONCLUSION

The architecture of the SoS enterprise is highly complex, largely due to both the number of and variation of interrelationships among the constituent enterprises that participate in the SoS level enterprise. The SoS enterprise architecture is highly dynamic as the participants, and nature of participation of constituents, is always changing driven by changes in context and shifts in stakeholder needs. Many questions must be answered in order to develop an effective practice for SoS enterprise architecting. Two of the most fundamental questions are: (1) how can the SoS enterprise be characterized in a complete and holistic manner; and (2) can the SoS architect incorporate the temporal dimension of the SoS in enterprise transformation strategies to account for the dynamic nature of the SoS?

The efforts to characterize enterprises in general has led to a plethora of enterprise architecture frameworks [8]; however most are suited to the single 'firm' rather than SoS enterprise. Relatively few enterprise architecture frameworks [17] have focused on SoS and enterprise engineering challenges at this level [18]. The complexities of architectural frameworks also drive the architect to extensive levels of detail, making it difficult to examine higher-order aspects of SoS enterprises. The enterprise architecting framework presented in this paper is intended for this purpose, and to capture the influences of the fundamental enterprise views on other views. Understanding the essence of the SoS enterprise constituents, and the SoS enterprise as a whole, is enabled through this eight view framework.

A number of constructs for dynamic analysis have been used across various fields. These include *scenario analysis*, [19]; e*environmental scanning* [20]; *morphological analysis* [21], and *scenario planning* [22]. These may prove useful for temporal analysis of enterprises as systems. Understanding the temporal nature of the SoS enterprise continues to be an important area of research, including the development of constructs and methods to enable decision making that is responsive to dynamic context shifts.

Hall [23] asserted the need for synthesis of systems methods for "revealing value truths by matching the properties of wanted systems, and their parts, to perform harmoniously with their full environments over their entire lifecycles." Epoch-Era Analysis is such a method, enabling dynamic analysis of the SoS enterprise. While the analysis approach is not fully developed to address enterprises, it may in the future be useful for extensive model-based level analyses to enable multi-epoch tradespace exploration of enterprises architectures.

The principles and methods for SoS architecting are emerging as experience grows with these types of systems [24] and enterprises. The constructs and methods come from many fields, including engineering systems, which may be particularly well suited for SoS enterprises. Further research is needed to explore the suitability and effectiveness of these methods, with a goal of developing an overall framework for supporting the SoS enterprise architecting practice.

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