Accelerating System of Systems Engineering Understanding and Optimization through Lean Enterprise Principles

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***Abstract*—By applying a lean enterprise lens to studies of the evolving field of system of systems engineering (SoSE), it has been observed that many SoSE teams are developing processes that are consistent with many lean enterprise principles. These SoSE processes are designed to efficiently evolve the group of systems to meet new needs using limited resources. This paper provides further insights and recommendations for the evolution of system of systems processes using lean concepts. We conclude with a discussion of the potential conflicts between SoSE and lean paradigms and provide thirteen SoS case studies to illustrate the emphasis on lean thinking.**

Keywords-lean enterprise principles; system of systems; system of systems engineering

I. INTRODUCTION

A recent study of systems engineering processes used by system of systems engineering (SoSE) teams showed how these teams transformed traditional systems engineering processes to support systems engineering at the SoS level [1]. A further analysis of these SoSE processes indicate that some of the changes from traditional systems engineering are well aligned with some key lean principles and practices. This paper presents an analysis of SoSE processes from a lean perspective, shows the motivation for these lean practices, and provides insights for further optimization of SoSE through lean principles. By understanding the role of lean principles on the evolution of systems engineering processes to better manage a set of systems across an enterprise, organizations can better apply lean thinking to further optimize the SoSE processes.

II. BACKGROUND

A. Systems of Systems Engineering Studies

Realizing that many systems today are integrated with other systems to form larger systems (referred to as system of systems (SoS)) and that engineering at the SoS level presents new challenges, studies were initiated in 2007 to better understand SoSE activities and practices. The United States (US) Department of Defense (DoD) studied 18 SoS organizations and documented their findings in a report [1]. Through conversations with these SoSE teams, it became clear that traditional systems engineering (SE) processes must be tailored at the SoS level to both guide the evolution of the SoS and at the same time allow the SoS constituent systems to evolve to meet the needs of their stakeholders. While these SoS organizations were using fundamental systems engineering practices, they organized these engineering activities into seven core elements at the SoS level that focused on:

1. **Translating SoS capability objectives into high-level SoS requirements:** SoS stakeholders and users typically request high level capabilities whose solution often cuts across multiple SoS constituent systems. The SoSE team must develop a basic understanding of the expectations of the SoS capability and then translate the capability into a set of requirements for meeting the expectations.
2. **Understanding the SoS constituent systems and their relationships:** To manage and evolve an SoS, the SoSE team must understand the current capabilities of the SoS, the contributors to those capabilities, the relationships of the contributing systems, and the current status of those systems. This is the "as is" state of the SoS.
3. **Assessing the extent to which actual SoS performance meets capability objectives:** To be able to understand current SoS operational performance and ascertain the impact of constituent system changes, the SoSE team establishes SoS metrics, defines methods for assessing performance, and conducts evaluations of actual performance using the metrics and methods. The performance characteristics often of interest to the SoSE team include timing, throughput, security, precision, reliability, flexibility, ease of use, availability, fault tolerance, and dynamic reconfigurability to respond to changing needs.
4. **Developing, evolving, and maintaining an architecture for the SoS:** As soon as systems start interfacing with each other and sharing data, there is an implied architecture for the collection of systems (or SoS). One of the key responsibilities of an SoSE team is to establish and maintain a sustainable framework to support the evolution of the SoS to meet user needs.

Evolutionary changes include changes in systems functionality, performance, or interfaces. These needed changes often require systems to migrate from the early "implied" architecture to a more robust architecture or framework.

5. **Monitoring and assessing potential impacts of constituent system (non-SoS) changes upon the SoS performance:** Because constituent systems are typically "owned" and managed by different organizations, the SoSE team must constantly monitor proposed or potential changes to them. In addition, the SoSE team assesses change impacts to a) identify opportunities for enhanced functionality and performance, and b) preclude or mitigate problems for the SoS and other constituent systems.
6. **Addressing SoS requirements and solution options:** The SoSE team reviews, prioritizes, and determines which SoS requirements to implement next. Part of this activity is evaluating various options for implementing the capability and requires the participation of the affected constituent systems.
7. **Orchestrating upgrades to the SoS:** This activity is the actual implementation of the desired capabilities and includes the planning, coordination, integration, and testing of changes in the constituent systems to meet SoS needs. The SoSE team does not typically implement changes, but is responsible for coordinating and monitoring the capability-related changes implemented by the SoS constituent systems.

Figure 1 shows the relationships between the various core elements and external entities or systems not considered to be part of the SoS.

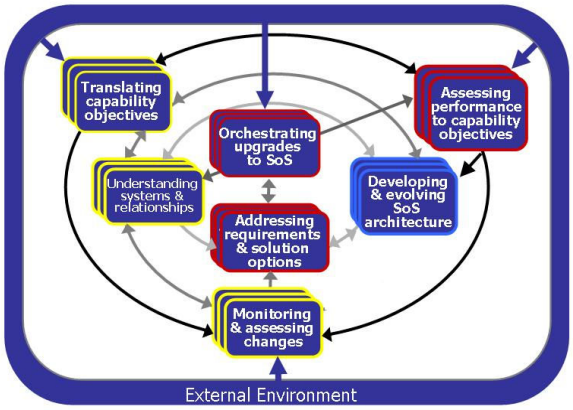

Figure 1. SoSE core elements [1].

An SoS is defined as a set of independently owned and managed systems that can function on their own as well as join together with other systems to provide capabilities not available from any single system [2]. These systems that belong to one or more SoS are often referred to as "constituent systems". Another key finding of SoS studies [1, 2] is that there are different management strategies for SoSs. These different strategies have different levels of authority and responsibility with respect to the constituent systems and include:

- Virtual SoS [2]: No SoSE team and constituent systems do not typically know about each other (little to no authority or responsibility).
- Collaborative SoS [2]: No SoSE team, but constituent systems have responsibility to collaborate for cross-cutting issues and needs.
- Acknowledged SoS [1]: SoSE team with responsibility, but limited authority over the constituent systems.
- Directed SoS [2]: SoSE team with both responsibility and considerable authority over the constituent systems.

The SoSs studied in [1] were identified as "acknowledged" SoS. These types of SoSs have an engineering team at the SoS level that is empowered to guide the evolution of the SoS. However, while these teams have engineering and oversight responsibilities, they often have little authority over the constituent systems within the SoS. Rather, these constituent systems are typically owned and managed by other organizations.

While the focus of this study was on defense-related SoSs, many of these findings also apply to SoSs in other government agencies as well as enterprise-wide SoSs in the business community.

B. Lean Concepts

Lean processes have their roots in the automobile manufacturing arena. These processes evolved so that Toyota could successfully compete with US automobile manufacturers [3]. The goal of lean processes were to be more efficient, both with respect to costs and time, while at the same time improving the quality of the product. As other organizations and businesses watched Toyota's success with their lean processes, they began to study and incorporate these processes into their own organizations, primarily in the area of manufacturing. In more recent times, efforts have been initiated to define and apply lean principles in software engineering [4], systems engineering [5], and at the more encompassing enterprise level [6]. According to [7], irrespective of the domain in which lean principles are being applied, the fundamental objectives are to:

- Minimize waste
- Be responsive to change
- Strive to have the right thing at the right place, at the right time, and in the right quantity
- Establish and maintain effective relationships (people and organizations) with the value stream
- Continuously improve processes and products
- Focus on quality from the beginning.

We propose that these objectives provide insights into SoSE since they encompass the broader concept of enterprise

transformation, focus on stakeholder considerations, and adopt holistic views of the enterprise.

Grand Questions of Enterprise Transformation: In order for an enterprise to become lean it must employ a larger transformation strategy. This approach of enterprise transformation, as defined by Nightingale [8], is guided by four "grand questions" shown in Fig. 2. The first question focuses on understanding the current state of the enterprise which is critical to plan any improvement. The second question explores possible future states that can result in improved outcomes. The third question considers strategies that can help an enterprise move from its current state to the possible future states. The fourth question explores the notion of change management, a key ingredient to process improvement.

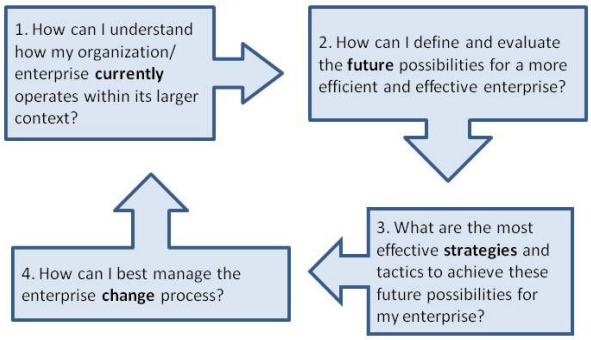

Figure 2. Four grand questions of enterprise transformation [6].

Stakeholder Considerations: Another fundamental concept of lean enterprises is the variety of considerations of multiple stakeholders. To ensure that one is doing the right job and doing it in a way that provides value, one must identify the important stakeholders and balance their needs and desires.

Holistic Enterprise Views: The idea of holism is that the properties of a given system cannot be determined or explained by its component parts alone. Instead, the system as a whole determines how the parts behave. When lean is applied to an enterprise, one must view the enterprise through multiple lenses in order to identify the properties that need to be improved. These views include strategy, process, organization, knowledge, products/services, policy/external factors and information technology [8].

The concepts of enterprise transformation, stakeholders, and holistic enterprise views are next discussed in the context of SoSE.

III. Analysis of SoSE with Respect to Lean Principles

Seldom does the development of an SoS start with a clean sheet of paper. More typically, an SoS is identified from a set of existing systems that currently interface in some manner with each other. Up until the point that the SoS is acknowledged and an SoSE team is established to guide its evolution, the engineers for each constituent system are left to collaborate with each other to solve cross-cutting problems or implement new capabilities that cross constituent system boundaries.

When an SoSE team is put in place, they need to begin by understanding the systems within the SoS and the relationships between them. Next, they analyze the current issues and desired new capabilities and then organize to start guiding SoS-level changes. From the interviews with the SoSE teams conducted as part of the SoSE studies [1], it was noted that a key driving force in their processes was to focus on what was important at the SoS level and leave the constituent systems changes to those organizations that best understood the single system, i.e., the constituent system engineers. It was also noted that with the limited engineering resources at the SoS level, it is not possible to participate in all decisions made at the constituent system level. Therefore, it is imperative to partner with the engineers responsible for each constituent system in the SoS to build an environment of trust and transparency at the SoS level, to encourage teamwork across the constituent systems, and to continually anticipate and analyze new SoS needs.

From the mapping provided in Table I it is evident that most successful SoSE teams apply the four lean principles in order to achieve SoS value using limited resources. Lean thinking is defined in [7] as "*the dynamic, knowledge-driven, and customer-focused process through which all people in a defined enterprise continuously eliminate waste with the goal of creating value".*

In some cases, some of the SoSE teams actively apply lean principles to set up the SoSE processes and establish a "battle-rhythm" to identify, assess, and implement SoS new capabilities and performance enhancements. This battle-rhythm is a cyclic process to synchronize the asynchronous upgrades of the various constituent systems in the SoS and to coordinate the rollout of new capabilities and performance enhancements that often require multiple incremental constituent system upgrades.

A. Lean Enterprise Concepts in SoSE

This section presents the results of an analysis conducted to identify lean enterprise practices that SoSE teams are applying within their organization , either implicitly or explicitly (in a few cases). For the purposes of this analysis, the enterprise is defined as the organization that includes the SoS stakeholders, the SoSE team, the constituent system engineering teams, and the constituent system stakeholders. Finally, this analysis used the lean enterprise grand questions shown in figure 2 to represent lean enterprise concepts. Table I summarizes this analysis.

Table 1 shows that the SoSE core elements map to the lean enterprise grand questions (LEGQs), stakeholder considerations, and holistic enterprise view quite well. In addition, both the SoSE and LEGQ frameworks have a similar process focus with the SoSE framework breaking out key aspects of the SoS to engineer and manage: functionality (capabilities), overall performance of the SoS, and overarching SoS architecture. It can also be noted that all of the SoSE core elements map to at least one of the lean enterprise grand questions:

TABLE I. SUMMARY OF LEAN ENTERPRISE CONCEPTS IN SOSE

SoSE Core Element	Lean Enterprise Grand Questions				*Stakeholder Considerations*	*Holistic Enterprise View*
	Q1: Understand Current	*Q2: Future Possibilities*	*Q3: Strategies and Tactics for Future*	*Q4: Change Process*		
Translating Capability Objectives		X			X	X
Understanding Systems and Relationships	X				X	X
Assessing Performance to Capability Objectives	X	X			X	X
Developing and Evolving an SoS Architecture	X	X	X			X
Monitoring and Assessing Changes	X			X	X	X
Addressing Requirements and Solution Options			X	X	X	X
Orchestrating Upgrades to SoS				X	X	X

- *Translating Capability Objectives* focuses on the long-term goals and needed capabilities for the SoS as well as on a holistic view of the SoS and its stakeholders. This is the first step in defining future possibilities for the SoS (LEGQ 2).
- *Understanding Systems and Relationships* focuses on the "as is" state of the SoS. The "as is" state is reflected by the systems that comprise the SoS, their relationships, and their ability to accommodate change going forward both short term and long term (LEGQ 1).
- *Assessing Performance to Capability Objectives* evaluates both the current performance of the SoS (LEGQ 1) as well ability of the SoS to meet future needs with respect to overall SoS performance (LEGQ 2).
- *Developing and Evolving an SoS Architecture* captures the "as is" architecture (LEGQ 1), defines the future goals for the SoS (LEGQ 2), then specifies the "to be" architecture to support the long term goals (LEGQ 3).
- *Monitoring and Assessing Changes* focuses on understanding the current non-SoS changes being implemented by the constituent systems in parallel with SoS-requested changes (LEGQ 1) and identifying and mitigating any potential impacts to SoS performance before they become a problem (LEGQ 4).
- *Addressing Requirements and Solution Options* decides which SoS-related changes to implement in each upgrade cycle (LEGQ 4), determines how to implement the cross-cutting changes (i.e., which systems to modify) (LEGQ 3), and develops constituent system agreements and a management strategy for the implementation of the changes so that as parts of the solution are rolled out in an asynchronous manner, it does not adversely impact the SoS as a whole (LEGQ 4).
- *Orchestrating Upgrades to SoS* executes the agreements and strategies developed in Addressing Requirements and Solution Options. This includes overseeing the change implementation in the constituent systems, working to resolve issues and remove obstacles that are impeding progress, and verifying/validating changes before they are deployed in order to ensure a continuity of operation within the SoS (LEGQ 4).

B. SoSE Exceptions to Lean Enterprise Concepts

Even though there are clear synergies between SoSE core elements and lean enterprise concepts there are a few caveats that should be noted. The following exceptions to lean enterprise concepts were identified:

- *Redundancy*. The duplication of critical components of a system with the intent of increasing reliability is generally a good design principle. However, this is in conflict with the objective of lean to minimize product (system functionality) waste. In addition, within an SoS, redundancy is difficult to eliminate due to the fact that many constituent systems must perform similar functions when operating outside of the SoS as an independent system or when operating as part of multiple SoSs.
- *Minimize process waste*. In general, there appears to be no conscious effort to minimize process waste. However, the SoSE teams have limited resources and hence focus on the most value-adding activities to help guide the evolution of the SoS. This means that they do not tend to maintain information that is already maintained by the single systems, they do not develop comprehensive documentation at the SoS level, and they only participate in constituent system activities that are related to SoS capabilities and issues. Rather, they tend to "pull" the information they need, on demand, from the constituent systems. SoSE teams realize that they cannot do everything and must therefore decide which engineering and management activities are necessary for the continued success and evolution of the SoS,
- *Enterprise boundaries*. Deterministic manufacturing systems that were the traditional unit of analysis for lean systems have the benefit of clearly defined boundaries. In contrast, SoS are notorious for having fluid enterprise boundaries, as mentioned above. SoSs are typically not a static entity. Rather, the constituent systems come together to support a mission, then dynamically reconfigure to support a single system mission or new SoS missions. The Regional Area Crisis Response System (RACRS) illustrated in Figure 3 shows a fictional example SoS (similar to some in the DoD) that can be dynamically configured to respond to any number of crises: fires, floods, hazard material spills, terrorist activities, etc.

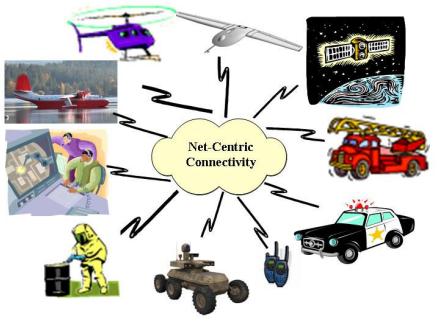

Figure 3. Overview of RACRS Constituent Systems [9]

The systems that come together to form an SoS depend upon the nature of the crisis. Then, when the crisis is over, the systems go back to operating in their more typical single-system mode.

- *Control of external variables*. Traditional application of lean assumes there is tight control of the value stream. In practice, SoSs are rarely controlled by a single person or organization. In fact, the definition of an SoS is one with collaboratively integrated systems that possess two additional properties: operational and managerial independence [2].
- *Ability to stop the process and fix problems as they are detected*. A feature of lean manufacturing systems is the ability to stop the production line when a defect in the process is observed. This ensures quality is always upheld even at the price of delivery speed. In the case of SoS, it is impractical to stop processes to correct defects. Due to the asynchronous nature of SoS constituent system upgrades, it may take considerable time to deploy all of the parts of a new capability and the final assessment of that capability is often done in the operational environment. So, it is often not apparent that there is a problem until one or more constituent systems have been updated, tested, and fielded. At this point, it is difficult to "stop". The more typical options are to continue with the current system releases (if they present no serious adverse affects) or to roll back to the previous system release(s) where the problem(s) were not apparent. In any case, "fixes" are typically made in the next SoS upgrade cycle. It is this SoS "battle rhythm" for upgrades that determines opportunities to "fix" problems.

These exceptions to conventional lean concepts should not diminish the application of lean within the SoSE environment. At the enterprise level, there can be multiple views of the organization with stakeholders and objectives that are sometimes in conflict with each other. With these limitations in mind, the applicability of lean enterprise concepts to SoSE can be better appreciated.

IV. Reflecting on DoD Case Studies

After analyzing the coherence between the SoSE core elements and the lean enterprise grand questions, the authors reviewed the 2007-2008 data from 13 of the initial 18 SoS programs that were the basis for the identification of the SoSE core elements. (Detailed data from the other SoSE organizations were not available for this analysis.) These programs were reviewed through the lean enterprise lens and include (in alphabetical order):

- Air Operations Center
- Ballistic Missile Defense System
- Common Aviation Command and Control System
- Distributed Common Ground Station
- DoD Intelligence Information System
- Ground Combat Systems
- Military Satellite Communications
- National Security Agency
- Naval Integrated Fire Control-Counter Air
- Naval Surface Warfare Center Dahlgren Division
- Space and Missile Systems Center
- Theater Medical Information Systems-Joint
- United States Coast Guard Command and Control Convergence.

Table II presents the results of this analysis. Note that the entries in this table are in a random order in order to protect the identities of the specific SoSs with respect to their processes.

The assessment of specific SoS processes with respect to the lean enterprise grand questions shows considerable coherence. The one area where there is not a strong correlation is Grand Question 4. This result is not surprising since all of these SoS are considered to be acknowledged SoSs and "monitoring" versus "managing" is an artifact of an "acknowledged" SoS. More often in the commercial world, an enterprise belongs to a single organization. However, with government agencies, and in particular the DoD, constituent systems often are owned and managed by a multitude of organizations which may not necessarily be part of the SoSE organization. In this situation, the best an SoSE team can hope to do is build trust and transparency, thereby gaining the support of the constituent system owners so that they can effectively guide the evolution of the SoS.

The other interesting observations are with respect to the scope of key stakeholders and the breadth of the holistic view. Many of the DoD SoSs are joint efforts supporting all of the services (Air Force, Army, and Navy) and comprised of constituent systems that may belong to any one of the services. In addition, many of these SoSs can be used in coalition missions with other nation systems and SoSs. This presents a considerable number of stakeholders with different objectives and in the case of coalition SoS, multiple national cultures. Add to this the stakeholders associated with each of the constituent systems (which are typically owned and managed independent of the SoS) and the various levels of constituent system maturity (new systems, COTS products, and older legacy systems that are close to being retired), one can appreciate the challenges associated with the evolution of both the constituent systems and the SoS.

TABLE II. RELEVANCE OF LEAN ENTERPRISE GRAND QUESTIONS TO SOSE CASE STUDIES

SoS ID	Lean Enterprise Grand Questions				Scope of Key Stakeholder Considerations	Number of Constituents
	Q1: Understand Current	*Q2: Future Possibilities*	*Q3: Strategies and Tactics for Future*	*Q4: Change Process*		
1	X	X	X	Monitor and attempt to guide, but do not manage	Across all DoD services/coalitions	16
2	X	X	X	Work in concert with constituent systems to manage upgrades	Across multiple DoD services and government agencies	9
3	X	X	X	Monitor and attempt to guide, but do not manage	Across all DoD services	10
4	X	X	Coordinated by larger overarching SoS	Managed from above – this SoS is also part of a larger SoS	Single service	Many – exact number not available
5	X	Weak evidence in this area	X	Monitor and attempt to guide, but do not manage	Across all DoD services	12
6	X	X	X	Monitor and attempt to guide, but do not manage	Multiple DoD services and government agengies—includes coalitions	Data not availabe
7	X	X	X	X	Across all DoD services	40+
8	X	X	X	Some high level management and guidance	Across multiple DoD services and government agencies	Data not available
9	X	X	X	X	Across multiple DoD services and government agencies	Data not available
10	X	X	X	X	Across multiple DoD services and government agencies	264
11	X	Sparse data	Sparse data	Monitor and ateempt to guide, but do not manage	Across multiple DoD services and government agencies – includes international customers	Many—exact number not availalble
12	X	X	X	In general, monitor and guide. Manage some aspects.	Across multiple DoD services and government agencies	Many—exact number not availalbe
13	X	X	Sparse data	In general,monitor and guide. Manage some aspects.	US and international services and agencies	25

It is only through respecting the needs of the various stakeholders, looking at the SoS from a holistic viewpoint, and balancing these perspectives that an SoSE team can achieve an environment of cooperation, transparency, and trust needed to successfully evolve an SoS to meet new capability needs.

V. CONCLUSIONS

The analysis presented in this paper shows how lean concepts manifest themselves in the SoSE environment. It is evident that SoSE teams are employing lean concepts whether or not they are aware of it. By realizing this fact, these teams can have a better appreciation of and confidence in the process changes they have adopted as well as a vision to guide further optimization of their processes. This vision also guides how they engage with the constituent systems engineering teams and work to meet both the needs of the constituent system stakeholders and the SoS stakeholders.

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