System of Systems Management in the Cannon Artillery Portfolio

Eugene Conner

20 May 2020

Published By Defense Acquisition University

Table of Contents

List of Figures

List of Tables

Abstract

There is an urgent need to understand how System of Systems Engineering (SoSE) theory and practice can be leveraged to enable the US Army Field Artillery to dominate in a conflict against a near peer adversary. The intent of this research is to identify opportunities for the application of System of Systems Engineering theory and practice within the US Army Cannon Artillery portfolio in support of this objective. Systems of Systems Engineering (SoSE) management addresses the development of complex systems made up of constituent "component" systems.The application of SoSE has become necessary to manage the increasingly complex systems that the Army will develop and field in the near future, as well as manage the complex systems of systems that already exist. The last significant guidance provided by DoD on system of systems engineering is in excess of ten years old. Theory and thought on System of Systems Engineering have advanced in that time. This paper seeks to examine how thought on System of Systems Engineering has progressed and identify opportunities to improve outcomes by implementing these new ideas into the development and acquisition of new capabilities for the US Army. This paper examines the applicability of SoSE to the Army cannon artillery portfolio and provides recommendations for the application of SoSE within that portfolio. In this paper, a literature search will be conducted to identify innovative thought on the management of systems of systems. Relevant themes are then drawn from the research to identify opportunities for implementation in the cannon artillery portfolio. Finally, recommendations will be made for future inquiry into this area of research.

Chapter 1 – Introduction

Background

There is an urgent need to understand how System of Systems Engineering (SoSE) theory and practice can be leveraged to enable the US Army Field Artillery to dominate in a conflict against a near peer adversary. The intent of this research is to identify opportunities for the application of System of Systems Engineering theory and practice within the US Army Cannon Artillery portfolio in support of this objective. Systems of Systems Engineering (SoSE) management addresses the development of complex systems made up of constituent "component" systems. SoSE management is not merely an extension of Systems Engineering principles as presently employed to manage DoD programs. But rather, Systems Engineering and System of Systems Engineering are paradoxical in their approaches. The application of SoSE has become necessary to manage the increasingly complex systems that the Army will develop and field in the near future, as well as manage the complex systems of systems that already exist. Presently SoSE is not widely practiced outside of select ACAT I DoD programs. In addition, the last significant guidance provided by DoD on system of systems engineering is in excess of ten years old. Theory and thought on System of Systems Engineering have advanced in that time. This paper seeks to examine how thought on System of Systems Engineering has progressed and identify opportunities to improve outcomes by implementing these new ideas into the development and acquisition of new capabilities for the US Army. This paper examines the applicability of SoSE to the Army cannon artillery portfolio and provides recommendations for the application of SoSE within that portfolio.

Problem Statement

The general problem is that implementation of System of Systems Engineering (SoSE) to address increasingly interconnected and complex weapon systems, other than specific ACAT I programs, is not widely understood. In addition to this circumstance, the DoD guidebook on System of Systems Engineering was published in 2008 and has become a dated reference on the topic. The specific problem is that there is no established formal framework to manage SoSE for programs within the cannon artillery portfolio.

Purpose of This Study

The intent of this paper is to identify current thinking and practice for System of Systems Engineering implementation, investigate the role that SoSE could be playing within the cannon artillery portfolio and provide recommendations for the application of SoSE within that portfolio. In order to accomplish this aim, research in this paper will examine the advancement of system of systems engineering, with intent of identifying opportunities to implement these ideas within Army engineering processes to improve outcomes within the cannon artillery portfolio. A robust discussion of how best to manage the cannon artillery portfolio can them entered into with a new perspective.

Significance of This Research

The intent of this research is to develop an understanding of the benefits of applying SoSE practice and theory to a portfolio of Army systems. As the Army pursues its aggressive modernization agenda, increasingly complex materiel solutions will be required to provide the necessary capabilities to address the near peer threat posed by our nation's potential adversaries. SoSE will be required to manage these systems of systems. The concepts examined in this paper may have application in other Army weapon portfolios, in addition to the cannon artillery portfolio. At present, SoSE has not been formally applied to programs below the ACAT I designation. Exploring the application of SoSE to systems of systems, consisting of multiple lower ACAT systems, will provide insight into how this approach can be leveraged to obtain better outcomes in the acquisition of the cannon artillery priorities.

Overview of Research Methodology

The central question to be addressed in this paper is:

What opportunities are there to introduce SoSE management into the cannon artillery portfolio and what benefits could be realized?

Secondary or guiding questions relevant to the central question are:

- What is the current thought and practice of SoSE management?
- How is System of Systems Engineering Management currently practiced within the Army/ DoD?

A qualitative historical research case study approach will be taken in this paper. A literature review will be undertaken to examine the answers to the secondary questions and support the response to the primary question of this research. This literature search will be conducted via the Defense Acquisition Library resources such as the ProQuest database of peer reviewed literature. The literature review will be supplemented by data from other open sources that bear on the discussion of SoSE implementation. This literature review and data analysis will then be used to evaluate the potential for application of SoSE within the cannon artillery portfolio. It is desired that the points taken from this research will fuel a robust debate of how to better implement SoSE within the cannon artillery portfolio and more widely within Army acquisition.

Limitations

This paper is limited to a historical review due to the limitation on use of interviews and surveys. An institutional Review Board (IRB) does not exist at Defense Acquisition University, presently. Without IRB review and approval, human research cannot be conducted.

The scope of this paper has been limited to the cannon artillery portfolio due to the limited time and resources available to conduct research in support of this paper. Further examination of other weapon portfolios would require time and resources not available within the duration of the DAU Senior Service College Fellowship.

Additionally, the paper must be published under distribution statement A. This fact will limit the level of technical detail presented in order to maintain that disclosure level. Therefore, open sources and distribution 'A' sources will be utilized for this paper. If this paper could be published at a higher distribution level, additional technical detail and themes could be examined and discussed, providing a richer discussion of the topic.

Chapter 2 –Literature Review

Introduction.

The literature review for this paper is conducted by examining relevant literature that addresses the secondary questions of what the current thinking on system of systems engineering is within industry and within the DoD. References will be sought that discuss implementation of system of systems engineering within DoD, as a third segment of inquiry within the literature.

The process utilized for this literature search is to conduct searches on the ProQuest database for the system of systems engineering management topic. This initial search is conducted using the key words 'system of systems engineering' and management. Variations on the key words are utilized to open the aperture for sources. Google searches to identify related topics for follow up within the ProQuest database are utilized as well. The intent of the search process is to generate a representative portrayal of the current thinking on system of systems engineering. A number of thought leaders, widely cited by others, on this topic are identified and focused searches to gain a broader view of their work is leveraged to gain additional insight.

Thought on System of Systems Engineering Management

Management of system of systems.

Gorod, Sauser and Boardman argue in their paper, "System-of-Systems Engineering Management: A Review of Modern History and a Path Forward," that a management framework did not yet exist for rapidly changing technology and operational environments (2009). An in-depth review of the pertinent literature up to 2008 is made to build the case for a framework to manage System of Systems. Based on the review, Gorod, Sauser and Boardman conclude that "1) SoS can be defined by distinguishing characteristics and 2) SoS can be viewed as a network where the 'best practices' of network management can be applied to SoSE (2009, p.484)." A basis for a SoSE management framework is then created anchored on these two points. The paper concludes with a case study of a known system to demonstrate the implementation of the new framework. This paper is strong in that it conducts an exhaustive literature review to include academic, industry and Government sources. This circumstance has the effect of creating a historical baseline as of 2008. The establishment of the proposed framework for managing SoSE advances the practice of the discipline and places key concepts into context.

Keating and Katina provide a view on the SoSE discipline and discuss issues bearing on the further advancement of the field in their paper "Systems of systems engineering: prospects and challenges for the emerging field (2011)." Utilizing a literature review to provide the state of the discipline, an organizing framework is provided, a set of issues impacting the advancement of the field is provided and the paper concludes with thoughts on the meaning of the work. The particular strength of this paper is the identification of three distinct axes of emphasis in SoSE and the implications of these differences. The paper identifies an academic, enterprise and military perspective on SoSE. The weakness of this paper, if it must be called that, is that no solutions are provided but rather a call for dialogue is given to the academic, industry and Government communities to work towards the advancement of the discipline.

Robertson asserts that system of systems management is necessary in a capabilities focused effort (2015). The author argues that the acquisition system, focused on individual systems, is fundamentally at odds with management of a system of systems. Increasing interoperability demands a cited as a key driver of the need for system of systems management. After a literature review the study evaluates three case studies for lessons learned out of previous system of systems experiences by the Army. Robertson provides a number of process and organizational changes necessary to shift from a system focus to a system of systems focus. The work identifies non Major Defense Acquisition Programs as an area for further study, as only MDAPs were addressed. The strength of this paper is that it takes a fresh look at how the Army manages programs and provides some very provocative suggestions on a path forward.

Katina and Keating "explore the concept of metasystem pathology in the context of problem formulation for system based approaches designed to enhance complex system governance (2014)." The paper identifies a lack of research in this area. The paper seeks to combine systems theory and management cybernetics to be able to identify issues constraining desired system performance. The paper contains a detailed and diverse literature review to provide a basis for the joining of the two concepts. The strength of the paper is that it provides fresh perspective on a little studied problem. The weakness of the paper is that it is highly theoretical and does not provide a clear approach, but rather issues to be considered.

In their paper, "Systemic Analysis of Complex System Governance for Acquisition," Keating, Bradley and Katina view the Government acquisition system as a complex system to be managed (2016). The paper provides a definition for the term Complex System Governance and provides a framework by which underlying issues, adversely impacting outcomes, can be identified. This framework is a rubric of system based pathologies that the authors call M-Path Method (Keating, Bradley and Katina, 2016). The paper concludes by identify three areas of effort to further the acquisition field by utilizing the concepts articulated in this paper. The strength of this paper is that it provides a fresh perspective in examining a complex system to identify issues that require resolution in order to maximize desired outcomes.

In their paper, "Systemic Intervention for Complex System Governance Development," Keating, Katina, Pyne, and Jaradat explore the challenges surrounding intervention in complex systems (2017). The paper indicates that disciplined study into systemic interventions has not been undertaken previous to this paper. The paper provides a summary of Complex System Governance as a point of reference. Three discussion points are covered: 1) a discussion of system intervention 2) forms and roles in systemic intervention 3) a path to introduce Complex System Governance into a team. The work concludes with seven considerations for the implementation of Complex System Governance. The strength of the paper is that it addresses an area when little work has been done and provides a possible path forward.

Keating and Katina provide the most recent review of Complex system Governance (2019). Their paper provides an overview of the CSG process, CSG pathologies and a discussion of the challenges of development of the field. The paper concludes with thoughts on how CSG could be matured. The particular strength of this paper is that it reflects the latest thinking on complex system governance and integrates the works on this topic that preceded this paper.

DiMario, Cloutier and Verna offer a paradigm to more effectively manage Systems of Systems via the Zachman Framework (2008). They argue that systems need to be managed in a fundamentally different way than System of Systems and that the Zachman framework is a means of managing System of Systems architecture. The differences between a system and a system of systems and the governance of system of system management is reviewed in the literature. The Zachman framework is then adapted to provide a means to manage system of systems. The conclusion outlines a number of benefits of implementing the Zachman framework to this problem. It is posited that the framework could be extended, but further research would be necessary to assess the impact of doing so. The strength of this paper is that it provides another perspective on a possible path to managing a system of systems that leverages existing thinking in the field.

Carter presents a novel architectural framework for complex system governance in his work (2016). A lack of research in this area in support of complex system governance is cited as the need driving this research. Carter conducts a grounded theory based literature search with open coding, followed by axial coding to establish interconnections and relevance to theory. Finally, selective coding and interrelationships were used to define the framework. Peer review was used to validate the work. This work adds to the body of knowledge by providing a practical means to translate theory into practice.

DiMario, Boardman and Sauser discuss the collaboration of independent component systems driven by an overarching system of systems social function (2009). A case study utilizing an auto battle management aid is provided to demonstrate the concept. The computer simulation showed that component systems, within their own design space, will collaborate when driven by an overarching collective social function. An additional finding was that systems will collaborative within their own utility functions and resources in the absence of an overarching directive. This work utilizes simulations to provide a robust underpinning for the theory.

Gomez examines the feasibility of utilizing traditional system engineering technical development procedures to assess a complex system of systems, as the systems engineering community assumed was possible (2010). A literature review and examination provided the basis for a survey to establish the ability of traditional systems engineering methods to function in a system of systems. A second survey was conducted to establish whether confirmed discrepancies could be resolved. The study found that it was not possible to use traditional systems engineering methods due to significant deficiencies in the application of the process to a system of systems. The process would work for mature systems with a number of adjustments. However, systems in development possessed significant disconnects and a large degree of uncertainty that rendered the process deficient. Further research to delve into the issues is recommended. This research is significant in that it provides a rebuttal to a commonly (at that time) held belief that traditional systems engineering processes could be applied to a system of systems.

McClary provides a perspective on potential applications of system of systems engineering in a cross domain context (2014). It is identified that system of systems engineering is not developed as a field of thought and the application of the theory is not well understood. McClary utilizes a number of case studies in civilian and military contexts to offer possible approaches to system of systems engineering management. McClary offers traditional systems engineering, in concert with concurrent engineering and multi domain optimization, as a means of addressing emergent behavior and holarchical duality (2014). This work is significant as it utilizes case study method to synthesize new approaches to applying system of systems engineering.

Akers provides a set of system archetypes that can be employed to analyze a system of systems (2015). The research leverages knowledge in the existing discipline of systems theory to establish a new set of categorizations via a visual coding model. The work then uses the analogy of energy, entropy and time to define and distinguish between the archetypes. The paper then provides a case study to illustrate each of the archetypes. This work provides a fresh perspective to view and assess the behavior of a system of systems.

Hernandez, Karimova, and Nelson propose mission engineering as a means to manage complex problems (2017). The concept merges the military decision making process with systems engineering processes. In addition the definition of the system begins with the mission to be performed and concludes with the delivery of the solution to the operational force. The significance of this work is that the acquisition process is taken as a subsystem of the larger system. Hernandez, Karimova, and Nelson designate “the mission and mission plan, which may include weapon system development, as the complete system of interest (2017).” A case study is presented to illustrate the concept. This paper presents a new perspective on how to manage complex systems. The authors conclude that this approach is a viable means to manage complex problems.

Jaradat provides an instrument for assessing the system thinking capability of an individual (2014). It is asserted that the methods for managing complex problem are dependent upon the capability of the individuals managing the effort to utilize system thinking. A data set of over one thousand articles was utilized to establish the framework for systems thinking characteristics (Jaradat, 2014). An instrument was created and given to 242 subjects as a pilot study. Validity checks provided assurance the instrument was viable and was capable of identifying persons with the capacity for system thinking. The work is helpful in advancing the field by providing a methodology that has vetted by a high sample size and statistical rigor.

Jaradat, Keating and Bradley discuss “individual capacity and organizational competency for systems thinking (2017, p. 1).” The paper addresses the need individual capacity and organizational competence as a means to operate within the complex problem environment facing organizations. A framework for these concepts is presented, followed by an examination of the difficulties and opportunities for maturation of the field. The strength of this paper is that it builds upon previous work and articulates a framework for competencies that could be applied to an organization.

Philbin proposes a four-frames system view as a means to manage complex technical problems (2008). This proposal was in response to the results of a survey conducted within the UK that indicated systems architecture design and integrated systems design were key to positive outcomes on contemporary engineering efforts. As an example the method was applied to a civilian UAV project. The study also provides some insight on the need for systems thinking capacity and system flexibility. The strength of the paper is that it provides a perspective on how to manage a complex project. Although based on feedback from UK based engineers, the real world perspective adds to the credibility of the paper.

Albakri provides a process model for the integration of existing systems into a system of systems (2011). This model is present in lieu of the more typical model for systems in development as an addition to the body of knowledge. Four case studies are presented to illustrate the model. This work reflects the more technical approach to system of systems management by the military as indicated by Keating and Katina (2011).

Requirements for a system of systems.

Keating, Padilla and Adams make the argument that the usual systems engineering methods to generate requirements will not be successful when executed in the context of a SoSE problem set (2008). The paper establishes the differences between SE and SoSE domains, reviews the traditional paradigm for requirements generation via SE, discusses the particular considerations for the SoSE problem set and provides twelve principles for requirements within SoSE efforts (Keating, Padilla and Adams, 2008). The paper ends with five impacts on the practice and further development of SoSE. The strength of this paper is that it establishes the difference between SE and SoSE in developing requirements and provides a basis for further exploration of this circumstance.

Walker utilizes inductive research design to provide a method for establishing requirements for a system of systems (2014). A lack of guidance or methods of addressing requirements development in a system of systems is identified as the driving force for the study.

It is asserted that typical systems engineering approaches are not adequate in a system of systems setting due to the complexity of the problem set. Walker provides a quantitative and flexible method to define system of system requirements, while still preserving constituent system autonomy (2014). This is accomplished via a mixed-method research approach and applied case studies. This work is significant in that it attacks the problem of a practical method to accomplish requirements development.

System of systems complexity.

Gorod, Gandhi, Sauser and Boardman discuss the concept of the flexibility of System of Systems (2008). The premise is that the five system characteristics of “autonomy, belonging, connectivity, diversity and emergence (Gorod, Ghandi, Sauser and Boardman, 2008, p. 23)” are polarities between the system and the system of systems that must be managed. The ability to balance the factors are called the flexibility dynamic of the system of systems. A case study using the Yellow Cab system in New York is presented to illustrate the application of the concept (Gorod, Ghandi, Sauser and Boardman, 2008). The paper concludes that, “How we manage the flexibility of a SoS should enhance our ability to independently develop, manage and operate autonomous systems that can function within one or more SoS (Gorod, Gandhi, Sauser and Boardman, 2008).” This strength of this paper is that it provides additional points for consideration when managing a system of systems and is grounded in existing work.

Jovel and Jain examine the factors driving integration complexity for systems of systems such as Ballistic Missile Defense (2009). The authors identify a dynamic requirements environment as a significant challenge. The discussion in the paper is based upon a survey conducted by the second author as part of another piece of research. The research identifies interoperability as the driving factor for integration complexity and provides detailed discussion of the issue. Open architecture is identified as a means to address complexity issue. The strength of this work is that is it based on a level of real world experience in addition to analysis. While not prescribing a path, options to address the problem are provided.

Johnson provides a concept for complex adaptive system of systems (CASoS) as a means to address rapidly changing technology and operational requirements (2015). Using a grounded theory methodology, the disciplines of complexity and systems theory were reviewed to establish the proposed new methodology. The significance of the new system designation is that the component systems adapt to their environment via a paradigm of self-organization. Additionally, these systems will be able to learn and foresee end effects of their actions. This top down view of a system of systems assumes design and development will proceed, concurrent with operational use of the system. This concept adds to the body of knowledge and provides for another means to address complex problems.

Konur, Farhangi and Dagli "formulate and analyze a SoS architecting problem representing a military mission planning problem with inflexible and flexible systems as a multi-objective mixed-integer-linear optimization model (2017, p. 967)." The methods proposed are applicable to additional problems. The study concludes that the mathematical approach presented is more efficient is solving a given problem without a loss in accuracy. Additionally the study found that the quantity of flexible constituent systems contained within the system of systems positively impacted solution desirability. The strength of this paper is that it examines the question of flexibility and provides an example of how this technique could be applied to a military system of systems.

Supporting work.

Lane and Boehm discuss the task of determining the costs to conduct the Lead System Integrator activities on System of System development projects (2007). The paper provides the results of research done to identify the lead system Integrator activities for System of systems vice traditional System Engineering efforts. Several large programs were examined to identify the high value tasks that drive program performance. This data was then utilized to create a cost model for System of System integration costs. The significant finding of the work was that utilization of traditional System Engineering processes to manage System of Systems is unaffordable and the program will not meet schedule requirements. The strength of this paper is that it provides analytical rigor to a significant question bearing on how system engineering should be conducted on System of Systems programs.

Mattila presents an argument that the development of System of Systems could be explained by evolutionary theory, combined with system thinking (2017). A case is built based on the Darwinian theory of evolution. It is argued that the environmental conditions and cultural characteristics of an organization will drive the form a system will take over time. The evolution of military tactics is used as an example. The strength of this paper is that it takes a different perspective on the problem. The paper is weak in that it does not provided significant detail on how the concept could be applied. The significant point to be taken from this paper is that experience and experimentation may be more valuable than rigorous systems engineering in developing a system of systems.

Champion conducts a case analysis for the use of the Participants, Engagement, Authority, relationships, Learning (PEArL) software framework to provide for collaboration in the design of automobiles (2018). The automobile has become a complex system of systems due the introduction of technology. The complexity of automobiles and the diverse vendor base has driven the need for collaboration. The work also determined that the use or the PEArL framework prompted changes in the enterprise organization to engrain the collaborative design process paradigm (Champion, 2018). This work provides a practical application of theory in industrial practice.

Cotter and Quigley provide an approach to integrate non-technical factors into statistical models in order to increase the statistical engineering body of knowledge (2018). A lack of knowledge for integrating stochastic with engineering models had identified by the authors. After defining terms, a mathematical basis for accomplishing this end state was provided. The paper advances knowledge by integrating the concepts of control theory, general systems theory and complex systems governance (Cotter and Quigley, 2018). The paper also provides for a measure of system viability and integrates system constraints into a Bayesian model. This work is highly theoretical and does not provide practical application of the new concepts.

Lock proposes using system safety methodology to address the risks of unconstrained constituent system evolution (2012). Unconstrained evolution is cited as a key issue that decreases organizational efficiency, leading to higher costs and poorer schedule performance. The autonomy of constituent systems is cited as a significant challenge. Lock provides a case study of an RAF aircraft incident as supporting argument for his points. His conclusion is that a system similar to that used for safety assessment is required to assess the risks within a system of systems. This paper adds to the discussion of the issues in governing a system of systems.

Conclusion.

A recurring theme, encountered during this literature search, was a view that management of system of systems engineering or (system of systems) was an emerging field and that thought on the discipline was still diverging. Much of the literature encountered focused on defining concepts and identifying issues to be resolved. A number of themes in the literature did emerge, however.

The issue of managing a system of systems dominates the discussion in the literature. The consensus of the literature is that traditional systems engineering methods are not appropriate for managing a system of systems. Of particular note is the idea that the military, industry and academia view system of systems engineering management in a different light (Keating and Katina, 2011). The concepts of Complex System Governance and Meta-system Pathology appear multiple times in the literature. A significant point for management of a system of systems is the need to merge management and systems theory. Systems engineering and managing a system of systems are considered a paradox that must be managed. The literature also addresses the distinguishing characteristics of a system of systems. These characteristics are the points about which the previously discussed paradoxes operate.

The generation and management of requirements for systems of systems is discussed in the literature. The theme of traditional systems engineering approaches not be appropriate continues. In fact it is asserted that traditional approaches will be counterproductive. However, the requirements process must be managed to facilitate the continual evolution and growth of the system of systems.

Complexity is a key driving force in the issue of managing a system of systems. Constituent system flexibility is a key factor driving complexity. The literature provides a discussion of the issues and possible approaches to this concern.

Chapter 3 – Research Methodology

This chapter will discuss the research methodology followed for this paper. The central research question and supporting secondary questions will be reviewed. The research design will be discussed and a discussion of bias and error will be conducted.

Research Questions

The primary question is: What opportunities are there to introduce SoSE management into the cannon artillery portfolio and what benefits could be realized?

Secondary or guiding questions relevant to the central question are:

- What is the current thought and practice of SoSE/ SoS management?
- How is System of Systems Engineering Management currently practiced within the Army/ DoD?

Research Design

A qualitative historical research case study approach was utilized in this paper. A literature review was undertaken to examine the answers to the secondary questions and identify sources of data to support the response to the primary question of this research. This literature search was conducted via the Defense Acquisition Library resources such as the ProQuest database of peer reviewed literature. The initial search was conducted with the key words ‘system of systems engineering management.’ Research was focused from 2008 onward. A significant source from 2008 was identified that provided an excellent summary of system of systems engineering management thought through that time. Subsequent searches were conducted using author name and topics to seek additional related work. ‘Complex System Governance’ was identified as a complimentary term for ‘system of systems’ and was utilized to conduct searches. A group of thought leaders in the field of system of systems engineering management quickly emerged. This group has published much literature on the topic and key papers utilized for this research were widely cited as authoritative sources. A number of late breaking papers that were only published during the timeframe the research for this paper were obtained directly from the authors via the Research Gate website.

The literature review is supplemented by data from other open sources that bear on the discussion of SoSE implementation. Specifically, DoD documentation governing the application of System of Systems Engineering within DoD were reviewed. These included but are not limited to the DoD 5000 series Instructions, the Defense Acquisition Guidebook available on the Defense Acquisition University website, and the DoD Guidebook for System of Systems Engineering. The International Council on Systems Engineering online knowledge repository was searched to identify current best practices for System of Systems management. Where possible, documents detailing specific application of system of systems engineering examples from the cannon artillery portfolio are utilized to provide context for the discussion of the research questions. The release-ability of specific information on programs is a significant impediment to the richness of the data set. Conducted at a higher information security level, the discussion could delve deeper and provide better insight on the questions.

In conducting the research, an understanding of where thought within the field has progressed was sought. Literature published over the time period from 2008 to the present were utilized to develop this understanding. Themes quickly developed in the literature and the evolution of these ideas became clear as sources were developed. The year 2008 was chosen as a starting point for the literature search due to the fact that there was a source in literature that provided a history of the topic to that point. In addition, the DoD Guidebook was published in that year. Thus, there was a common baseline from which to proceed with the discussion in this paper.

Bias and Error

In order to mitigate the time and resource limitations for this paper, the research was focused on developing an understanding of who the thought leaders were in the field of system of systems engineering. This was done in order to obtain an accurate view of thought within the field. A variety of authors were sought to seek out any diversity in thought that might indicate disagreement with the perceived thought leaders. Themes within the various papers were sought to identify points of agreement between authors. The fact that the field of system of systems engineering is an emerging one and the literature is relatively sparse on the topic, leads to a circumstance where statistical characterization of viewpoints is not possible or even desirable within the timeline afforded for this paper. The authors who have been identified as thought leaders in the field have had their papers widely cited. A large number of citations was taken as an indicator that the work was accepted.

The methodology chosen for this work has yielded sufficient data to support a discussion of the research questions. Data developed has application beyond the cannon artillery portfolio. There is insufficient time and resources to completely develop the discussion beyond the immediate research questions and this effort is consigned to future work in this area. Within the scope of this work, the supporting research questions can be answered and support for the central research question developed. The conceptual framework of this research is considered successful, in that new thought with application to system of systems management within the cannon artillery portfolio has been identified and can be discussed.

Researcher bias has been successfully mitigated. Conscious effort to detect biases that might influence the outcome of the research has been made. Opposing views were sought to address confirmation bias. A careful examination of the literature search caused a reframing of the research from a purely technical view of the topic to a technical and organizational development view of the questions. This circumstance revealed a bias towards a purely technical answer, which was corrected. By widening the aperture, additional richness of the research is realized and relevant thought and research included within the scope of this paper.

Chapter 4 – Findings

Collected Data

What is current thought and practice on SoSE management?

Definitions.

The definition of the terms 'System' and 'System of Systems' must be established to provide a point of reference for use in the discussion of this topic. The definition of a system is discussed extensively in the literature (DiMario, Cloutier, and Verna, 2008; Gorod, Sauser and Boardman, 2008). There is consensus are around the definition of people, processes and products (to include hardware and software) arranged in a manner to accomplish a stated purpose. The definition of system of systems has likewise been discussed extensively (DiMario, Cloutier, and Verna, 2008; Gorod, Sauser and Boardman, 2008; Keating and Katina, 2011) in the literature. Gorod, Sauser and Boardman indicate that attempts have been made to define system of systems engineering and System of Systems, but no broadly adopted definition exists (2008). DiMario, Cloutier and Verna offer that systems of systems are composed of numerous independent constituent systems that combine to provide capabilities that cannot be provided independently by the constituent systems (2008). Keating and Katina assert that "operational independence of the elements, managerial independence of the elements, evolutionary development, emergent behavior, and geographical distribution" differentiate a system of systems from a system (2011).

The International Council on Systems Engineering provides the following assessment of a system of systems.

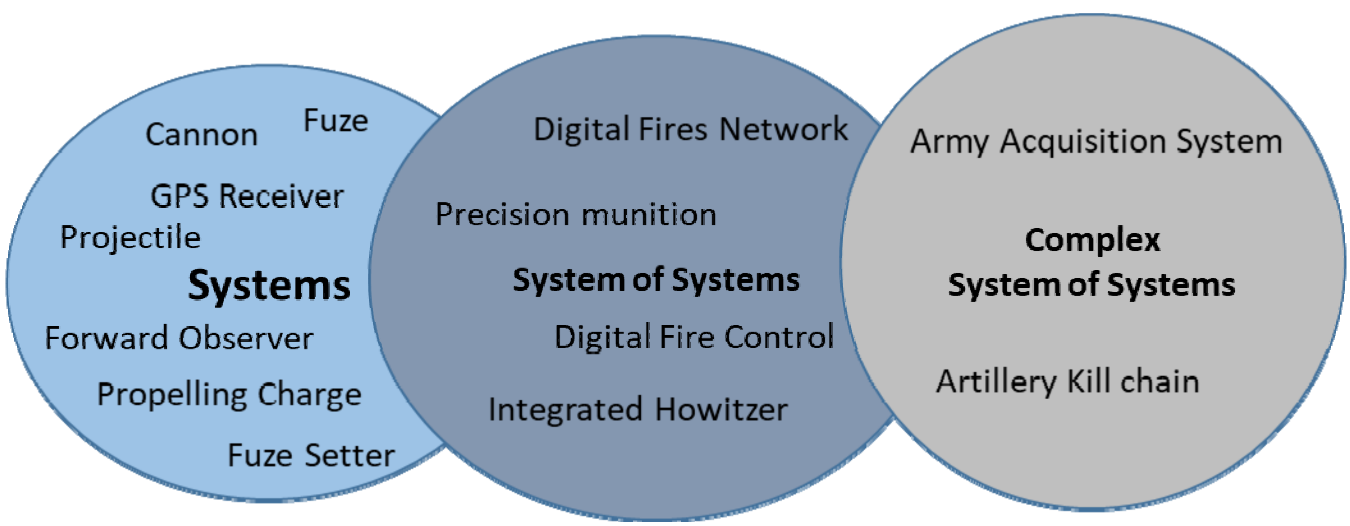
> *"A System of Systems (SoS) is a collection of independent systems, integrated into a larger system that delivers unique capabilities. The independent constituent systems collaborate to produce global behavior that they cannot produce alone. This type of collaboration is powerful, but brings major challenges for systems engineering:*
> *• Because they are independent, constituent systems may make decisions or upgrades without considering the rest of the SoS. Sometimes this unintentionally forces others to make changes too*
> *• Constituent systems may withdraw (possibly without warning) from the SoS if their own goals conflict with SoS goals*
> *• Separate constituent systems are often drawn from different engineering disciplines, and the SoS itself is commonly large-scale and usually highly complex. It's difficult to produce accurate predictive models of all emergent behaviors, and so global SoS performance is difficult to design*
> *• Testing and verifying upgrades to an SoS is difficult and expensive (sometimes prohibitively) due to scale, complexity and constant evolution* (INCOSE, 2018, p. 2)"

Characteristics of a system of systems.

In the absence of a clear definition for a system of systems, Sauser and Boardman identify a set of characteristics which provide a contrast of the system and system of systems, which are: "Autonomy, Belonging, Connectivity, Diversity and Emergence (2008)." These characteristics represent a polarity between a system and a system of systems that must be managed. Keating, Padilla and Adams support this thought when they assert that it is an error to assume that systems engineering and system of systems engineering exist either independently or that one or the other encapsulates the other (2008). Keating and Katina, in their early work, offer a set of elements that are present in a system of systems, which are: "operational independence of the elements, managerial independence of the elements, evolutionary development, emergent behavior, geographic distribution, interoperability, complementarity, holism (2011, pp. 237-238).” In later work this list is evolved to include: “holistic problem space, ambiguity, uncertainty, highly contextual, non-ergodicity, and non-monotonicity (Katina, Keating, Bobo and Toland, 2019, p. 6).” Other articulations of this list exist (Katina and Keating, 2019), but they encompass the same thoughts on the characteristics of a complex system of systems.

A review of the DoD Systems Engineering Guide for Systems of Systems reveals that the characteristics and elements for a system of systems articulated above are addressed with the exception of emergence, non-ergodicity, and non-monotonicity (2008). The handbook also recommends the application of systems engineering processes to the system of system. This direction is at odds with the prevailing thinking on system of systems management previously discussed.

Figure 1. Examples of system of systems in the cannon artillery portfolio.



Alternate view points on system of systems management.

Keating and Katina discuss three viewpoints on system of systems engineering (2011). There is a military, academic and enterprise view of system of systems engineering.

Military viewpoint.

It is asserted that the military view dominates the discussion on system of systems engineering and is focused on four themes:

“1. Emphasis of technology as primary…

2. Interoperability of technology as a central objective…

3. Extrapolated from systems engineering…

4. Heavy emphasis on acquisition… (Keating and Katina, 2011)”

Keating and Katina further note themes from the DoD handbook which hamper the development of system of systems engineering: 1) There is no difference in systems engineering between a system and a system of systems 2) The only uniqueness of a SoS is that no one is in control 3) SoS should treated as an additional hierarchy to the cascade of systems and subsystems in SE (2011). It is argued that a dialogue should be held to provide the ability to introduce other perspectives so that the field of system of systems engineering management might mature.

Academic viewpoint.

The academic view of system of systems engineering lies along three themes (Keating and Katina, 2011):

- A search for what makes system of systems management unique
- An investigation into the theoretic underpinnings of the field.
- A grounding in systems theory

Enterprise viewpoint.

The enterprise perspective of system of systems engineering is focused on a widening of perspective. This perspective seeks to distance itself somewhat from the mechanistic nature of systems engineering. If fact the word 'engineering' will often be dropped (Keating and Katina, 2011). Key themes for the enterprise view are:

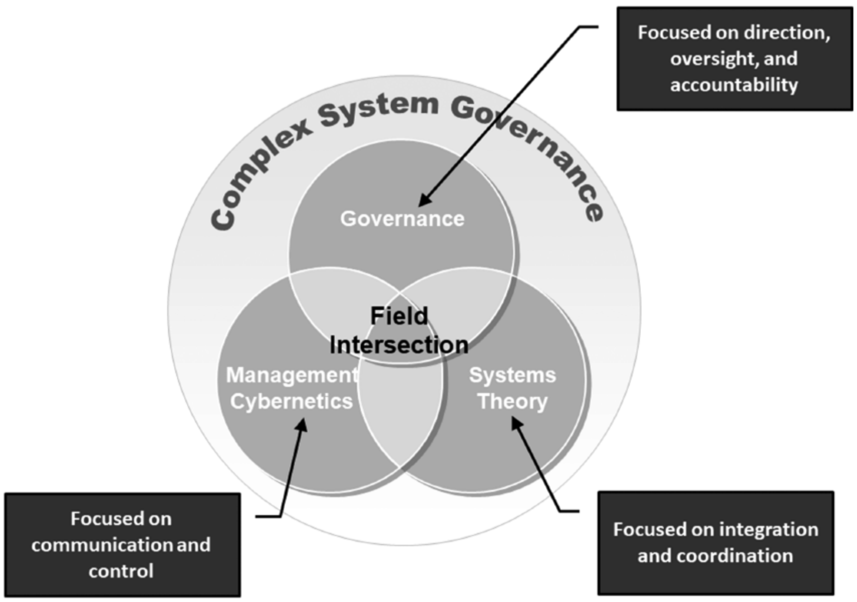
- Broadening of the view beyond the technical
- De-emphasis of engineering
- Pre-eminence of architecture

Complex system governance.

A framework for Complex System Governance, that combines the fields of management cybernetics, systems theory and system governance, has been proposed (Katina, Keating, Bobo and Toland, 2019; Keating and Katina, 2019; Keating and Bradley, 2015). "Complex system governance (CSG) is an emerging field, focused on design, execution, and evolution of (meta) system functions that produce control, communications, coordination, and integration of a complex system (Keating and Katina, 2019)." Figure 1 presents a conceptualization of these three fields coming together to provide the basis of Complex system Governance (Keating and Katina, 2019).

Systems theory moves thinking from the realm of problem solving to that of a dialogic examination to comprehend multiple valid realities and the relationship among the components of the whole. Management cybernetics provides a framework, by which, to describe and evaluate the communication and control mechanisms necessary to assure the viability of the system of systems. That is the degree to which the system of systems will meet its performance requirements on an on-going basis. Governance addresses processes, structure and policy necessary to establish sufficient regulatory capacity to maintain system balance (Keating and Katina, 2019). Keating and Katina indicate that governance is distinct from management and

Figure 2. Complex System Governance Model*

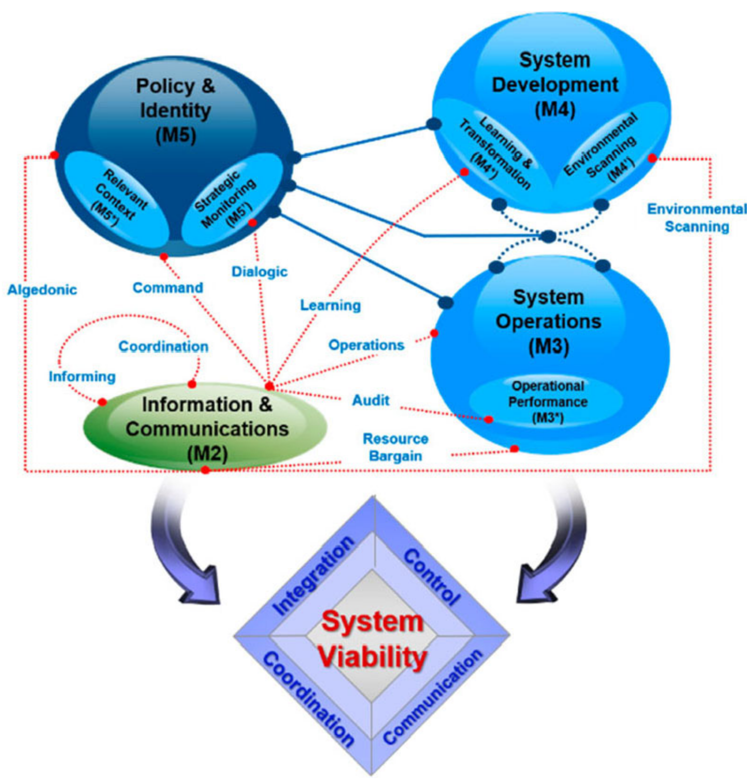


*Reprinted from Keating and Katina, (2019). Complex system governance: Concept, utility, and challenges. Systems Research and Behavioral Science. 10.1002/sres.2621.

provide specific commentary on these distinctions (Keating and Katina, 2019). A key concept, related to governance and system theory, is minimum critical specification. The implication is that any controls, beyond the minimum required to assure performance of the system, wastes resources, restricts autonomy or degrades system performance (Keating and Katina, 2019). CSG considers the design, development and acquisition process for the solutions to be an integral part of the system of systems. CSG provides a means to integrate the "technology/technical, human/social, information, organizational/managerial, and policy/political aspects of the acquisition system problem domain (Keating, Bradley and Katina, 2016)."

Figure 3 presents the complex system governance model (Katina, Keating, Bobo and Toland, 2019). The model is formed around four areas of concern "(System Identity, System Development, System Operations and System Information)" and a set of metasystem functions associated with each area (Katina, Keating, Bobo and Toland, 2019). These metasystem functions are linked to Beer's Viable System Model (Keating and Bradley, 2015). The metasystem functions enable the system to remain viable on an on-going basis and facilitate the coordination and integration necessary to ensure the system provides the necessary performance required of it (Katina, Keating, Bobo and Toland, 2019). The Viable System Model also provides control to ensure a system's existence in changing environments, to assert limited constraints required to ensure system performance and function, to preserve autonomy, and to be a process specifically designed for a complex system (Keating and Bradley, 2015).

Figure 3 Complex System Governance Model*



*Reprinted from Katina, P. F., Keating, C. B., Bobo, J. A., & Toland, T. S. (2019). A Governance Perspective for System-of-Systems. *Systems*, *7*(4), 54. doi:10.3390/systems7040054

Metasystem functions.

The metasystem functions are: (Katina, Keating, Bobo, and Toland, 2019)

Metasystem 5 – policy and identity. This function is concerned with guidance of the system along the intended path, while keeping a near and far term view of the system.

Metasystem 5* - System Context. This function is concerned with the operating environment and concept of operations for the system.

Metasystem 5' – strategic system monitoring. This function provides for the cognizance of system performance measures at a top level.

Metasystem 4 – System Development. This function provides for the establishment and update of present and future models of the system with an emphasis on future viability.

Metasystem 4* - Learning and transformation. This function enables organizational learning derived from the resolution of design flaws and enables the prioritization of future upgrades.

Metasystem 4' – Environmental scanning. This function focuses on the watching the operating environment for patterns that may impact the system viability in the present and future.

Metasystem 3 – System operations. This function attends to executing the day to day tasks to assure system performance.

Metasystem 3* - Operational development. This function assesses system performance to identify undesirable behaviors and deficient system performance.

Metasystem 2 – Information and communication. This function provides for the creation of communication channels and movement of information necessary to conduct the metasystem functions.

Communication channels.

The Complex System Governance model identifies ten communication paths. These paths are necessary for the transfer of information and consistent understanding of communications within the system (Keating and Katina, 2019).

CSG communication channels:

- “Command
- Resource bargain/ Accountability
- Operation
- Coordination
- Audit
- Algedonic
- Environmental scanning
- Dialogue
- Learning
- Informing (Keating and Katina, 2019, p.9)”

Determinants of system performance.

“Control, communication, coordination and integration are determinants of system performance” under the CSG construct (Keating and Katina, 2019). Keating and Katina are clear that control is not taken in the dictatorial sense. Rather, control is the effort necessary to ensure system viability in the present and future, while navigating a changing environment. This is accomplished through maximizing autonomy while maintaining system performance and function. Over constraint of a system is inefficient, stifles innovation and diverts precious resources that could be better employed elsewhere (Keating and Katina, 2019).

Communication is an indispensable component of the governance and function of a system. Not only is information flow enabled but consistent interpretation of communication is facilitated. Communication modes within a system are unique to that system and should not be left to chance but planned for in order to obtain desired outcomes.

Coordination addresses the interaction of the internal and external entities within a system. Keating and Katina state that “there must be sufficient standardization to provide routine interface as well as sufficiently robust design to absorb emergent conditions. (2019).” Coordination is necessary to provide consistency and prevent undue variability in the system.

Integration is necessary to establish common goals across a system of systems, create accountability and manage the tension between system level requirements and individual autonomy. This balance of tension will be driven by changes in context, environmental conditions or system performance.

In order to adequately accommodate the variability being induced by the environment, a system must have a control mechanism with sufficient capacity to address the number of states that are being controlled. Keating, Katina, Jaradat, Bradley and Hodge provide the following interrelationship of system performance to variety in a system:

“*The regulatory capacity of a system is responsible for system performance and is a function of the interaction of system design, execution of that design, and system de-velopment (redesign). Inadequacies in system design, execution, or development pro-duce pathologies that degrade system performance.* (2019)”

Metasystem pathologies.

Metasystem pathologies are aberrant behavior within a system. Keating and Katina provide a definition of metasystem pathology, “A circumstance, condition, factor, or pattern that acts to limit system performance, or lessen system viability <existence>, such that the likelihood of a system achieving performance expectations is reduced. (2012, p. 214).” Keating and Katina have identified 53 metasystem pathologies that have been aligned with the nine metasystem functions (2019).

Performance improvement of CSG.

Keating, Katina, Jaradat, Bradley and Hodge offer a framework for utilizing the CSG model and metasystem pathologies to improve the performance of systems of systems (2019). The three phases of this framework are discovery, classification and engagement. In the discovery phase system pathologies are identified. During the classification phase the source of the pathologies are identified, the significance of system impact is reviewed and the possibility of addressing the pathology is evaluated (Keating, Katina, Jaradat, Bradley and Hodge, 2019). Keating, Katina, Jaradat, Bradley and Hodge indicate that “limitations in context, culture, technology, resources or other local conditions may preclude resolution of the pathology (2019).” CSG is not offered as a silver bullet, but rather, it is an opportunity. Careful study of the system in the context of the pathologies will lead to deep insight into the system and its functionality. A baseline of pathologies matched to CSG functions can be established to measure progress of the system governance. The identification of specific pathologies can lead to wider insight of conditions negatively impacting system performance. Pathologies can be prioritized and a plan for deliberate development of the system in a disciplined fashion created.

In applying the framework, three conditions must be met (Keating, Katina, Jaradat, Bradley and Hodge, 2019). The personnel applying the framework must have sufficient system thinking capacity. Otherwise, the full potential of the framework cannot be realized. The support structure for the system must be considered within the system boundary. Failure to do so will not permit the discovery and address of issues related to the support structure. The system of interest must be clearly defined. Considerations for determining the system of interest are:

Boundary conditions

Entities

Environment

Responsibilities

Roles

Functions

Complex system governance summary.

Complex System Governance is an emerging approach to managing systems of systems. It is based in system thinking, management cybernetics and governance theory. CSG is intended to operate in the volatile, uncertain, complex and ambiguous (VUCA) environment prevalent in today's complex development problems. CSG is distinct from traditional systems engineering, in that its characteristics are a polarity to the characteristics of traditional systems engineering. CSG incorporates the non-technical factors impinging on system performance not accounted for by traditional systems engineering. Focused on the viable system model and nine metasystem functions, CSG provides a basis to evaluate the performance of a system of systems. By evaluating a systems of systems through the lens of the metasystem functions and the metasystem pathologies associated with them, deficiencies in the design, execution and improvement of the system of systems may be identified and an effort to improve system performance implemented (Keating, Katina, Jaradat, Bradley and Hodge, 2019). Each application of CSG is distinct and tailored to the particular facts of each system to which it is applied.

Systems thinking.

Individual capacity and organizational competency for systems thinking have been identified as critical in applying the complex system governance model for managing systems of systems (Jaradat, Keating and Bradley, 2017; Jaradat, 2014; Keating, Katina, Pyne and Jaradat, 2017; Keating, Katina, Jaradat, Bradley and Hodge, 2019). Jaradat, Keating and Bradley identify three elements for developing systems thinking:

1) "*Individual capacity* is focused on the degree to which individuals can engage in ST necessary to deal effectively with complex systems and their derivative problems. This is achieved through development and propagation of methods, mindset, and worldview to assist individuals in more effectively grappling with the inherent complexities of modern systems.
2) *Organizational competencies* are focused on the degree to which an organization holds and develops the knowledge, skills, abilities, and attributes necessary to effectively deal with the range of complex system problems it faces.
3) *Supporting infrastructure compatibility* between worldviews, enabling infrastructures, alternative approaches, and expectations is essential. This compatibility is necessary to formulate contextually consistent approaches to complex system problems. (2019, p. 1)"

A tool for determining individual thinking capacity has been developed by Jaradat (2014). This assessment focuses on seven systems thinking characteristics: "Complexity, Autonomy, Interaction, Change, Uncertainty and Ambiguity, Hierarchical View and Flexibility (Jaradat, 2014)." Individuals taking a systems thinking assessment answer 39 binary questions and the results are plotted on a scale for each factor, indicating the degree to which the individual possesses capacity for systems thinking. The ability to engage systems thinking is deemed essential to effective engagement with the issues presented in this complex environment, in order to attain higher system performance. Keating, Katina and Jaradat assert that the administration of a systems thinking assessment tool is a necessary component of a CSG entry into a CSG intervention (2017).

The organizational competencies are represented by a three by nine matrix. The vertical axis of the matrix is composed of three personal capability characteristics, performance, temporal relationship and leadership. The horizontal axis is composed of 9 propositions based in the system thinking axioms (Jaradat, Keating and Bradley, 2017; Whitney, Bradley, Baugh, and Chesterman, 2015). This framework can be used to assess an organization's core competency model to provide an assessment of system thinking competence and a basis for improvement efforts.

Table 1 provides a snapshot of the emerging environment for systems engineers (Jaradat, Keating and Bradley, 2017). While systems engineering is appropriate for some problems, the requirement to address complex systems drives the systems engineer to access systems thinking capacity, in order to be successful under these challenging conditions.

Table 1.*

ATTRIBUTES OF THE SHIFTING PROBLEM DOMAIN

Attribute	Traditional Problem Domain	"New Normal" Problem Domain
Objective	Solution/Resolution	Understanding/Improvement
Interpretation	Objective	Subjective
Environment	Static	Turbulent
Boundaries	Defined/Stable	Ambiguous/Shifting
Structure	Elements	Relationships
Behavior	Deterministic/linear	Uncertain/nonlinear
Preferred Representation	Symbolic (mathematical/model/precision)	Interpretative (relationships/diagram/approximate)
Quantification	Comprehensive	Limited
Understanding	Part/Reducible	Holistic/Irreducible
Solution Form	Optimal	Satisficing
Viewpoints	Unitary (singular/rational)	Pluralist (many/potentially irrational)
Approach	Standardized-Replicable-Method	Unique-Not Replicable-Methodology

*Taken from Jaradat, Raed & Keating, Charles & Bradley, Joseph. (2017). Individual Capacity and Organizational Competency for Systems Thinking. IEEE Systems Journal. PP. 1-8. 10.1109/JSYST.2017.2652218.

Jaradat, Keating and Bradley (2017) articulate a number of challenges for increasing systems engineering effectiveness:

Increasing the level of systems thinking capacity

Continued development of organizational competency for systems thinking

Compatibility of supporting infrastructure with systems thinking

Focus on building sustainable foundations for systems thinking

Uniqueness, not prescriptive application

Shifting from thinking to action (pp. 7-8)

"Individual capacity and organizational competency in systems thinking" (Jaradat, Keating and Bradley, 2017) is increasingly necessary to address the complex problems presented by the contemporary engineering environment. Organizations must orient themselves on systems thinking in order to position the organization to be able to address the complex challenges confronting the modern profession. Frameworks are available to assess progress towards these goals.

Complexity of systems of systems.

The International Council on Systems Engineering (INCOSE) has published a white paper discussing complexity as it applies to systems engineering (INCOSE, 2016). The white paper acknowledges the shortcomings of traditional systems engineering when confronting complex problem sets. INCOSE views the degree of complexity of a system as a continuum rather than a binary reality. Traditional systems engineering tools may work well for 'simpler' systems of systems but new tools are required for more complex systems. Attempting to simplify a problem runs the risk of losing the essence of the problem or the possible solution domain INCOSE, 2016). In consequence, engineers must adapt to working in the context of complexity. A number of guiding principles for complexity thinking are provided (INCOSE, 2016). These principles resonate with systems thinking discussed previously. The white paper goes on to provide a significant number of suggestions for methods to deal with complexity. The systems engineer must assess the system in question and select those methods which are most appropriate for the system in question (INCOSE, 2016).

The literature contains much discussion of flexibility of systems of systems (Gorod, Ghandi, Sauser, and Boardman, 2008; Philbin, 2008; Jovel and Jain, 2009; Johnson, 2015; Carter, 2016; Konur, Farhangi and Dagli, 2017). Flexibility is offered as a means to address the variety, fluidity of requirements, rapidly changing environment and emergence of capabilities in systems of systems.

Gorod, Ghandi, Sauser, and Boardman leverage the concept of the five paradoxical characteristics of the system of systems and Volberda's Organizational Flexibility model to describe what they call a flexibility dynamic (2008). By managing the paradoxes of the system characteristics, the flexibility of a system of systems can be increased. The flexibility of the system is a function of the extensiveness of the flexibility dynamic (Gorod, Ghandi, Sauser and Boeardman, 2008). There is an optimal point that is desirable where flexibility is maximized. If the flexibility dynamic is too high or too low system adaptability is lost and system risk increases.

Konur, Farhangi and Dagli conducted mathematical modeling in an effort to identify optimal system of system solutions in a multi-variate system (2017). The modeling was done with flexible and inflexible systems. An outcome of the work was the discovery that more flexible systems yield better optimal results than less flexible systems.

Architecture.

System architecture is identified as a means to address complexity in a system of systems. Jovel and Jain look at flexibility through the lens of interoperability (2009). The authors leveraged the survey data from a previous work to assess the drivers of integration complexity in a system of systems. The findings of their work indicate that system architecture is important. Specifically, opens systems, physical modularity and functional modularity of hardware and software decreased integration complexity (Jovel and Jain, 2009). Philbin's work identifies system architecture as a key aspect of managing complex systems (2008). Johnson, in her work on Complex Adaptive System of Systems, indicated that openness and adaptive architectures are needed to provide the level of flexibility require to make CASoS viable (2016). The DoD System of Systems Engineering Handbook emphasizes the need for open architecture and modularity as a means to address complexity in DoD systems (2008). INCOSE indicates "The SoS architecture does not define systems details but concentrates defining on how systems work together (2018)." Carter relates the Department of Defense Architecture Framework (DoDAF) to the metasystem functions of CSG (2016). While only an initial effort, it shows promise for future development. Based on the literature surveyed open/ common architecture is a significant prerequisite for managing a system of systems.

Summary.

Complexity drives the approaches to be taken in managing systems of systems. Systems of systems must be assessed to determine the appropriate tools to successfully execute the effort. Flexibility is a necessary attribute of system of systems in order address complexity and to provide optimal system level performance (Gorod, Ghandi, Sauser and Boardman, 2008). The means to get to this level of flexibility is through management of the system architecture to promote openness, interoperability and modularity.

Requirements for systems of systems.

Keating, Padilla and Adams challenge the efficacy of applying traditional systems engineering requirements development approaches to system of systems engineering (2008). Keating, Padilla and Adams provide a set of distinctions that differentiate systems engineering from System of Systems Engineering, contained in Table 2 (2008, p. 25).

Table 2. SE and SoSE Distinctions*

Area	SE	SoSE
Focus	Single complex system	Multiple integrated complex systems
Nature	Technical	Socio-technical
Objective	Optimization	Satisificing
Approach	Process	Methodology
Expectation	Solution	Initial response
Problem	Well defined	Emergent
Analysis	Technical dominance	Contextual influence criticality
Goals	Unitary	Pluralistic
Boundary	Fixed and defined	Fluid and ambiguous

*Reprinted from Keating, C. B., Padilla, J. J., & Adams, K. (2008). System of systems engineering requirements: Challenges and guidelines: EMJ EMJ. *Engineering Management Journal, 20*(4), 24-31. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/208948101?accountid=40390

As a consequence, Keating, Padilla and Adams offer the following guidelines for system of systems requirements (2008, pp. 26-29).

"System of systems framing requirements:

Establish the purpose for the system of systems

Establish system of systems boundaries

Establish system of systems objective iteratively

Establish relevant stakeholders and contextual issues

Establish metasystem representation

System of systems performance requirement:

Establish an index of performance

Establish measures of subsystems autonomy and system of systems integration

Establish resource level - authority – accountability

System of systems design requirements:

Establish coordination, integration and standardization

Establish design for dealing with emergence

Establish and maintain identity

Establish framework for system of systems transformation

(Katina, Padilla and Adams, 2008, pp. 28-29)"

This work has several implications to the practice of system of systems engineering

- *"SoSE is based on a different paradigm than systems engineering,*
- *The nature of the SoSE problem domain suggests that requirements are simultaneously loose and tight.*
- *Requirement resolution should increase with additional understanding of the complex SoS problem domain and emergent conditions.*
- *Requirements for the SoS are of a different class than requirements for constituent subsystems being integrated into the SoS.*
- *Balance must be achieved in the requirements for the SoS.*

(Katina, Padilla and Adams, 2008, p. 30)"

How is system of systems engineering management practiced within the Army/ DoD?

DoD Guidebook.

The authoritative reference on System of Systems Engineering within DoD is the Systems Engineering Guide for Systems of Systems version 1.0 (DoD, 2008). Table 3 provides a summary of the comparison of Systems Engineering to System of Systems Engineering made by the DoD handbook (DoD, 2008) p. 11). The handbook acknowledges the complexity of the SoS environment, the diversity of systems comprising the SoS, and the diverse set of recognized and unrecognized stakeholders (DoD, 2008). Collaboration is emphasized as the preferred means of governance. The fact that SoS objectives may be in conflict with system objectives is noted and the systems engineer is warned that this will add to the complexity of the problem set. It is indicated that a number of Program Executive Offices, Program Management Offices and other Government agencies will drive the governance of the SoS. The systems engineer is advised that

Table 3 Comparison of Systems Engineering to System of Systems Engineering*

Aspect of Environment	System	Acknowledged System of Systems
Management & Oversight		
Stakeholder Involvement	Clearer set of stakeholders	Stakeholders at both system level and SoS levels (including the system owners), with competing interests and priorities; in some cases, the system stakeholder has no vested interest in the SoS; all stakeholders may not be recognized
Governance	Aligned PM and funding	Added levels of complexity due to management and funding for both the SoS and individual systems; SoS does not have authority over all the systems
Operational Environment		
Operational Focus	Designed and developed to meet operational objectives	Called upon to meet a set of operational objectives using systems whose objectives may or may not align with the SoS objectives
Implementation		
Acquisition	Aligned to ACAT Milestones, documented requirements, SE with a Systems Engineering Plan (SEP)	Added complexity due to multiple system lifecycles across acquisition programs, involving legacy systems, systems under development, new developments, and technology insertion; Typically have stated capability objectives upfront which may need to be translated into formal requirements
Test & Evaluation	Test and evaluation of the system is generally possible	Testing is more challenging due to the difficulty of synchronizing across multiple systems' life cycles; given the complexity of all the moving parts and potential for unintended consequences
Engineering & Design Considerations		
Boundaries and Interfaces	Focuses on boundaries and interfaces for the single system	Focus on identifying the systems that contribute to the SoS objectives and enabling the flow of data, control and functionality across the SoS while balancing needs of the systems
Performance & Behavior	Performance of the system to meet specified objectives	Performance across the SoS that satisfies SoS user capability needs while balancing needs of the systems

*Reprinted from Department of Defense (2008). Systems engineering guide for systems of systems. Retrieved from http://acqnotes.com/wp-content/uploads/2014/09/DoD-Systems-Engineering-Guide-for-Systems-of-Systems-Aug-2008.pdf

their role is "to instill technical discipline in this process (DoD, 2008)." Boundaries, interfaces, performance and behavior are the focus of the systems engineer.

The DoD handbook indicates that formal recognition of SoS are essentially ad hoc and are driven by considerations held by leadership. Essentially when something is "important enough" it is designated as a SoS. This designation is accompanied by the assignment of a responsible organization and a broad definition of objectives for improved capability. Specific technical performance measures are not provided. SoS are characterized as an assemblage of existing and new systems with the objective improving the way the systems operate together (DoD, 2008). The role of Systems Engineering is to evolve the capability over time.

The DoD handbook indicates that SoS Systems Engineering has seven core elements (2008):

- *"Translating SoS Capability Objectives into High-Level SoS Requirements over Time*
- *Understanding the Constituent Systems and Their Relationships over Time*
- *Assessing Extent to Which SoS Performance Meets Capability Objectives over Time*
- *Developing, Evolving and Maintaining an Architecture for the SoS*
- *Monitoring and Assessing Potential Impacts of Changes on SoS Performance*
- *Addressing SoS Requirements and Solution Options*
- *Orchestrating Upgrades to SoS* (DoD, 2008, p. 17-20)"

The DoD handbook matches sixteen existing Systems Engineering technical processes against these core elements to define the scope for a SoS systems engineer. Table 4 is extracted from the DoD handbook to illustrate the point (2008, p. 25).

A number of emerging principles are articulated by the DoD guide (2008):

- *"Addressing organizational as well as technical issues in making SE trades and decisions*
- *Acknowledging the different roles of systems engineers at the system versus the SoS level and the relationship between the SE done at the two levels*
- *Conducting balanced technical management of the SoS*

- *Using an architecture based on open systems and loose coupling*
- *Focusing on the design strategy and trades both when the formal SoS is first established and throughout the SoS evolution (DoD, 2008)"*

Table 4. SE Technical and Technical Management Processes Applied to SoS SE*

	Technical Processes								Technical Management Processes							
	Rqts Devl	Logical Analysis	Design Solution	Implement	Integrate	Verify	Validate	Transition	Decision Analysis	Tech Planning	Tech Assess	Rqts Mgmt	Risk Mgmt	Config Mgmt	Data Mgmt	Interface Mgmt
Translating Capability Objectives	X											X	X	X	X	
Understanding Systems and Relationships		X											X	X	X	X
Assessing Performance to Capability Objectives							X		X		X		X		X	
Developing and Evolving an SoS Architecture	X	X	X						X	X		X	X	X	X	X
Monitoring and Assessing Changes									X				X	X	X	X
Addressing Requirements and Solution Options	X		X						X	X		X	X	X	X	X
Orchestrating Upgrades to SoS				X	X	X	X	X	X		X	X	X		X	X

*Taken from DoD Systems Engineering Guide for Systems of Systems (DoD, 2008, p. 25)

The DoD guidebook presents an adaptation of systems engineering process to the problem of systems of systems. Keating and Katina's concerns with this approach (2011) have been documented earlier in this paper.

Army policy.

Of note is the fact that a literature search yielded no specific formal Army policy on Systems of Systems Engineering that was published within the last five years. The position of the ASA(ALT) Chief Systems Engineer has been recently filled. It is anticipated that the Chief

Systems Engineer will be overseeing the development of updated guidance. However, no current policy was available at the time of this research paper.

Acquisition related viewpoints.

Robertson provides observations and recommendations for acquisition in a system of systems environment (2015). Robertson argues that acquisition must shift from the current systems based construct to a system of systems construct for acquisition (2015). Robertson argues that a system acquisition must be considered in the context of the greater system of systems (2015). Further, the System of Systems must be placed in the context of the Combatant Commanders needs to fight and win the country's conflicts (Robertson, 2015). The downside of the present system based acquisition model is that the COCOMS receive a force with redundant capabilities. Robertson asserts that the requirements process must include systems engineers to provide the system of systems viewpoint (2015). Doing this will force the requirements community and the engineering community to think critically and in a holistic sense when defining requirements and designing systems. The DoD SE Guide for SoSE agrees with Robertson on this point. The Integration of SoS SE into the JCIDS process is identified as an area requiring exploration. Finally Robertson indicates system of systems thinking must be integrated into the acquisition process. He asserts Program Managers should be held accountable for the interoperability of their systems.

Emerging DoD thought.

Late in the process of writing this paper, information emerged from OUSD(R&E) discussing mission focused engineering (Ridgely, 2020). In response to criticism from Congress over a focus on systems rather than a focus on mission, OUSD(R&E) is bringing forward a concept that will take a system of systems view with emphasis on analysis from concept to deployment, mission blueprints, modular open systems architecture, an environment for sharing analytical tools, research on automated applications to model system interdependencies, and partnership with COCOMS to develop Concepts of Operations (CONOPS) for mission based capabilities. The specific mission areas identified for this concept are Close Air Support, Air Defense/ Counter-Air, Interdiction, and Intelligence Surveillance and Reconnaissance. The effort is intended to maximize enterprise effects over platform effects (Ridgely, 2020). Individual programs will be scored against Mission Success Measures, which will facilitate program decisions. The Mission Blueprint process will reside above the current requirements process to provide input on the System of Systems requirements relative to individual systems. The products of the Mission engineering process will be a mission description, mission return on investment, system maturation strategy, and mission reference architecture (Ridgely, 2020). Two new Office of the Secretary of Defense documents will be forthcoming: DoDI 5000.ENG and a Mission Engineering and Mission Integration Management Handbook. It is envisioned that a mission engineering lead will exist at DoD and the Component level. This information is just emerging but is an indicator of intent to move beyond the original 2008 Guidebook.

Analysis.

The central question of this paper is: What opportunities are there to introduce SoSE management into the cannon artillery portfolio and what benefits could be realized? To answer this question the discussion will begin with points of agreement and then move to a discussion of points where there is no consensus or the path forward is murky.

Opportunities where there is agreement.

Requirements.

There is agreement on the need to adopt a holistic approach to requirements generation for a system of systems. Robertson advocates for systems engineers to be included in the requirements process from before the Initial Capabilities Document creation (2015). The 2008 DoD Guidebook identifies the relationship of system engineering to the requirement generation process as a future challenge (DoD, 2008). Recent thought from OUSD(R&E) proposes that a system of systems requirements process be placed ahead of the JCIDS process (Ridgely, 2020). Keating, Padilla and Adams provide a number of guidelines for system of systems requirements generation (2008). Although there is agreement that system of systems thinking must be part of the requirements process, no requirements presently exist for a system of systems within the cannon artillery portfolio.

At least two possible views of a system of systems within the cannon artillery portfolio are possible. The first is the end to end "Kill Chain" for artillery. A detailed discussion of the form and composition of that system of systems is beyond the scope of the present paper. However, there are a significant number of systems composing that entity. The Army requires a complete understanding of this system of systems in order to adequately assess the performance of the artillery kill chain, identify opportunities to improve performance in the future, and identify the critical legacy component systems that must be sustained or replaced to retain capability. The artillery will be a key component of Multi-Domain Operations (MDO). A detailed understanding and requirement for this artillery system of systems is essential, if Army Fires are to be effectively integrated into the MDO construct. An Operational View – 1 is provided to illustrate the Fires system of systems in Fig 4 (USAFAS, 2014).

The second system of systems view is the field artillery battalion. The field artillery battalion is a complex system of systems, necessary to enable the field artillery to accomplish its mission on the battlefield. A detailed description of this systems of systems is beyond the scope of this paper, but, an understanding of the operations of this entity and its interfaces with the rest of the Army is essential to ensure the continuing viability of the system of systems and to seek

Figure 4. Artillery System of Systems OV-1

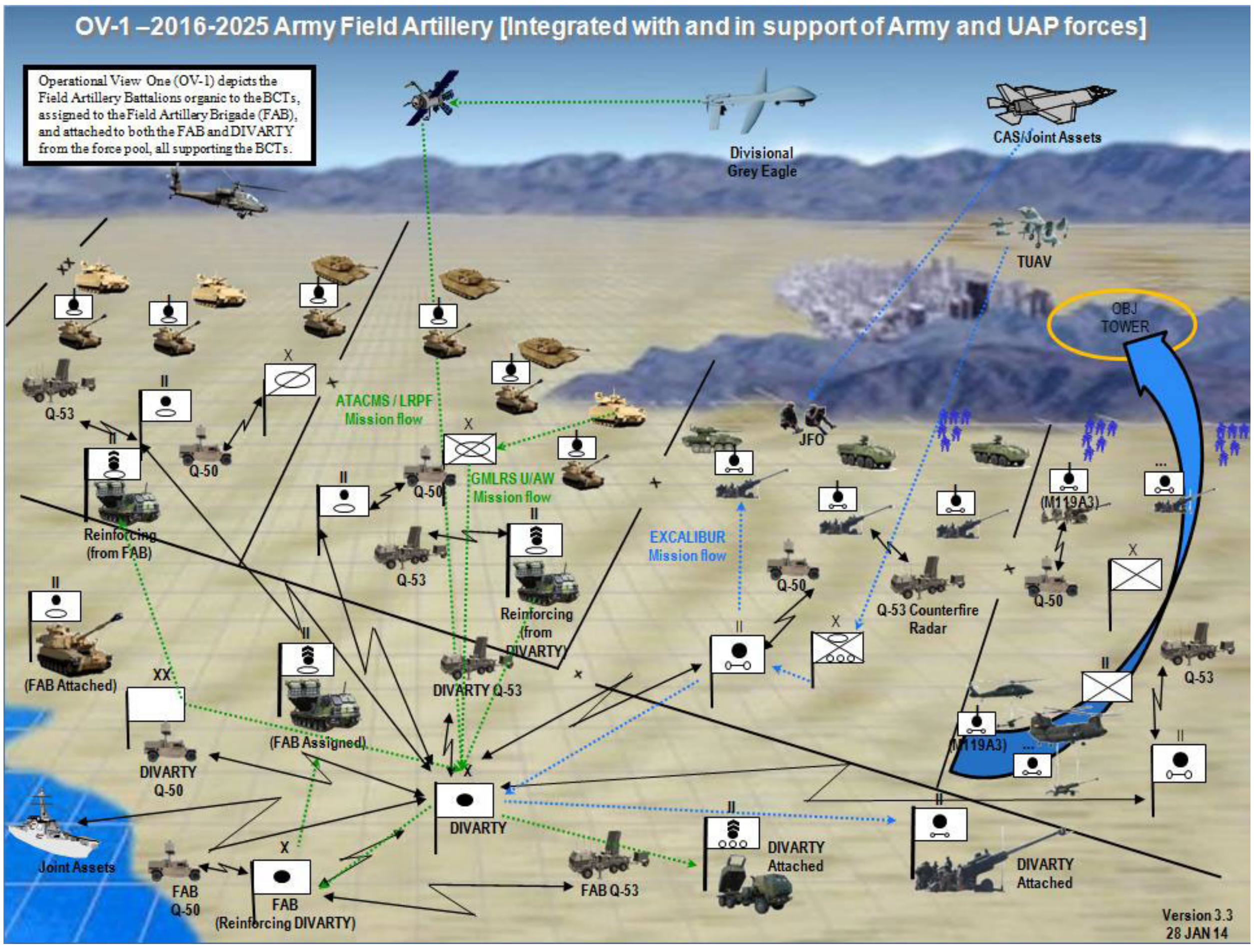


Figure 4 – reprinted from US Army Field Artillery School (2014, Nov-Dec) DIVARTY: a force multiplier for the BCT and division.

future performance improvements. After the restructuring associated with the stand up of Army Futures Command, the Commanding General of the Combined Arms Center at Ft Leavenworth holds the authority for operational force design and structure (Army Force Management School, 2020, p. 3). At present, the Army Force Management process is funding driven and involves identifying "bill payers" for any organizational structure changes. This process (Army Force Management School, 2020, pp. 4-5) drives incremental change and is not well suited to providing transformational change at the pace that has been asked for by Army leadership (Murray, 2018). The Army, as an institution, must develop the capability to look at the field artillery battalion as a complex system of systems in order to assess the current structure and organization's impact on the accomplishment of the fires mission. There must be capacity and motivation to seek transformational paths to magnify the fires capability, while minimizing manpower and funding requirements required to provide that capability. The solutions provided by these transformational paths may require radical restructuring of the force structure and organization to accomplish. The Army, as an institution, must gain the capacity to seize these opportunities, without having to resort to senior leader intervention to realize any significant transformation.

A system of systems requirement for field artillery is necessary to protect the viability of the present set of capabilities and to provide a platform to obtain increased capability in the future. In addition to being pressed to obtain increased performance in terms of lethality and survivability on the battlefield, the Army is continually being pressed to gain more value from fewer resources. This is evidenced by the recent "Night Court" sessions conducted by the Secretary of the Army (Judson, 2019). A complete understanding of the field artillery system of systems and an attendant system of system requirement will enable the field artillery community to adequately communicate the need to sufficiently support the critical systems composing the system of systems. Focus on system solutions in the absence of a system of systems view could result in significant erosion of the overall artillery capability, through funding cuts to critical components of the system of systems. An artillery system of systems requirement will provide for a means to grow the overall artillery capability over time. Having an overarching system of systems requirement will permit assessment of overarching capability and permit trades among the components systems to achieve an improved system of systems performance level. Having an overarching requirement will also permit the field artillery community to take a fresh look at the problem set for the capability and seek new solutions that require fewer men and resources to obtain a superior result. In short, a systems of systems requirement and approach will enable thought and effort to support revolutionary advancement of artillery capabilities.

Architecture.

The academic, enterprise and DoD view of the role of system architecture align. The 2008 DoD guidebook identifies architecture as a core element of managing systems of systems (2008). Emerging thought from OUSA(R&E) emphasizes the need to a system of systems level management of architecture in order to effectively integrate the myriad systems comprising the DoD enterprise level kill chains (Ridgley, 2020). The academic literature emphasizes the importance of architecture to the system of systems (Keating, Padilla and Adams, 2008; Keating and Katina, 2011). The INCOSE Systems of Systems Primer emphasizes the need to establish and evolve a system of systems architecture (2018).

A detailed discussion of specific architectures for the cannon artillery portfolio, those in place or potential candidates, is beyond the scope of this paper and will make the present discussion somewhat awkward. That being said, there is opportunity to utilize architecture to more effectively manage the cannon artillery system of systems that should be discussed.

Interoperability at the system of systems level is assured through intensive management of the functional interfaces within the system, currently. The development and evolution of architectures, beyond those presently in place, must be a priority. The community can no longer afford to develop capabilities for each artillery platform in stove-piped fashion. A unique architectural implementation for particular functionality on each platform is no longer acceptable. Architectures must be established and design efforts going forward must be bound to those architectures. Ideally, a particular architectural solution should work across all platforms and permit its embodiment in forms that suit the needs of the particular system that it is applied to. In developing the architectures, maximum flexibility in the implementation of a function should be sought. Designs should be modular enough to permit essential components, providing a function, to be integrated in multiple ways. To use the vernacular of academia, what is the minimum satisficing requirement to address the variety present in the system of systems and permit the implementation of a particular function on a constituent system with minimal disruption and conflict with that system's requirements? Examples of these architectures are, but not limited to, software interfaces, functional interfaces, electrical connector interface standardization, circuit card standardization, mechanical interface standardization, and physical form factors where appropriate. This thought process can apply to weapons, projectiles, fuzes, propelling charges and all of the supporting systems that comprise the cannon artillery system of systems. Individual constituent systems must be designed and evolved to accommodate emergent capabilities, so the receiving system does not need to be completely re-engineered when a new capability must be integrated. The payoff for an emphasis on architectures is overall reduced cost to the portfolio, reduced development time for initial development and proliferation of capability across the portfolio and the potential for better solutions on platforms.

Models of system of system performance.

Academia, the Government and the enterprise agree on the need for holistic system of system level models of performance. The DoD Guidebook (2008) and recent OUSD thought (Ridgely, 2020) affirm the need to have system of systems level measures of performance. Ridgely's brief is innovative in that it indicates that the system of systems requirement must drive constituent system requirements. Keating, Padilla and Adams state the need for an index of system performance as part of a requirements process (2008). INCOSE indicates that knowing the system objectives is key to enabling the systems engineers to align the constituent systems requirements to the system of systems objectives (2018). Ridgely discusses the need to have mission based analytics to support the assessment of constituent system contribution to the system of systems performance (2020).

The assessment of system of systems performance is tied to the development of concepts of operations (CONOPS) and system of systems requirements. As previously discussed, individual systems have requirements that they are measured against. The measures are not explicitly tied to system of systems level performance. At present there is no top level requirement for or measure of the cannon artillery system of systems.

A top level set of performance measures, combined with a sound analytical basis to evaluate performance, presents a significant opportunity for the cannon artillery portfolio. Notionally, a top level performance requirement for artillery could be the need to engage particular targets with an expected effect in a particular scenario(s) on a certain timeline from the time a target is identified to the point it is engaged. That statement of performance leads to a variety of analyses to characterize the path to that end and assess the ability of the artillery system of systems to attain the stated end. The power of having a model of system of system performance is that it permits trade-off at the systems of systems level. Individual constituent systems may be sub-optimized in order to attain a system of system optimization. Sensitivity analyses can be conducted to assess the investments which will yield the highest system of systems performance gain for the time and funding invested. By taking a broader systemic view, previously undiscovered possibilities may be identified and opportunities seized. The pay-off for having comprehensive system of system level models of performance is the ability to make data driven decisions on investments, to seize low investment/ high return opportunities, to astutely manage the portfolio of constituent systems and to open the aperture to consider revolutionary ways of reorganizing the artillery system of systems to attain overmatch.

Opportunities that represent a departure in how DoD does business.

Governance.

The concept of Complex Systems Governance (Keating and Katina, 2019) presents a significant opportunity, but it also represents a significant departure for how systems of systems have been approached within DoD in the past. The 2008 DoD Guidebook approach to, and more recently the OUSD thought on, system of systems engineering has been an adaption of the systems engineering principles to the problem. To be fair, these documents acknowledge the VUCA environment of systems of systems and the need to manage stakeholders, but they do not address the management of systems of systems at the socio-technical level (Keating and Katina, 2011). The significant difference between academia and the DoD is grounded in the need to consider the integration of the "technology/technical, human/social, information, organizational/ managerial, and policy/political aspects of the acquisition system problem domain" as articulated by Keating, Bradley and Katina (2016). Complex System Governance is an alternate way to approach the management of systems of systems; which emphasizes systems thinking, management cybernetics and governance (Keating and Katina, 2019).

Complex System Governance is not a prescription of how to execute a program. Rather, it is a lens through which to view programs. The framework provided by Keating and Katina is a set of nine metasystem functions, ten communication channels and a set of fifty-three metasystem pathologies (2019). These pathologies are conditions, factors or patterns that act to limit the performance of the system or threaten the existence of the system (Keating and Katina, 2019). The Complex System Governance framework permits an examination of a particular system of systems to detect pathologies and informs subsequent effort to remove those pathologies from the system. Each system is unique with its own set of realities. Therefore, it is inadvisable to assume that a standard approach will work in all situations. It is more likely that principles will emerge over time that are useful to governance for particular classes of systems of systems. However these should not be turned into rules.

Complex System Governance makes use of requirements, architectures and models of system performance. In the context of system governance, requirements are larger than just the technical requirements. These additional requirements include process requirements, structural conditions and policy bearing on the system of systems. An understanding of the top level performance measures is necessary to evaluate the effectiveness of the system of systems. As discussed previously, no system of system requirements for the cannon artillery portfolio have been documented in a formal fashion. The constituent system requirements are not the system of system requirements. These system level requirements are targeted at the constituent systems and may conflict with the system of systems performance requirement. In order to implement a

Complex System Governance model, a minimum satisficing system of system performance requirements must be defined for the system of systems to be governed. Only sufficient requirements to ensure performance of the system of systems must be articulated. The implication is that any controls beyond the minimum required to assure performance of the system wastes resources, restricts autonomy or degrades system performance (Keating and Katina, 2019).

Models of system performance provide the means by which to understand the relationship of the various constituent systems and assess the performance of the system of systems. Under the system of systems construct, constituent system optimization is not the focus. A combination of sub optimized systems may yield superior system of systems performance. Models of system of system performance will permit examination of these sorts of conditions and permit trade-offs to optimize system of system performance while conserving resources and ensuring the viability of the system of systems.

Architectures articulate the relationships of the constituent systems and provide a means to regulate the system of systems. Ridgley's thoughts on Mission Focused Engineering (2020) in significant ways align with the concept of Complex System Governance. The idea that architecture is a means to understand relationships and redefine relationships going forward resonates with systems theory. Architecture can also be used to preserve autonomy for constituent systems by only specifying the minimum requirements to assure system of system performance. In the context of Complex System Governance, architecture extends beyond the realm of information technology. The previous discussion of architecture explored this space.

Complex System Governance provides a new framework to manage systems of systems and embraces top level requirements, architecture and system models of performance as important components of this approach. To implement a Complex System Governance approach for managing systems of systems, a shift in viewpoint by the community is necessary.

Systems thinking.

Individual capacity and organizational competency for systems thinking have been identified as critical for managing systems of systems (Jaradat, Keating and Bradley, 2017; Jaradat, 2014; Keating, Katina, Pyne and Jaradat, 2017; Keating, Katina, Jaradat, Bradley and Hodge, 2019). Keating, Katina, Pyne and Jaradat assert that the effectiveness of any system intervention in a complex system of systems will be limited if the capacity for systems thinking is insufficient within the team managing the system of systems (2017). Organizational environment and predominate world view are also cited as impediments to positive change in managing systems of systems (Keating, Katina, Pyne and Jaradat, 2017). Jaradat, Keating and Bradley provide the following thoughts on systems thinking in discussing a framework for individual capacity and organizational competency for systems thinking.

> *"The promise of ST is support*
> *for alternative thinking capable of generating more informed*
> *decisions, actions, and interpretations, where more traditional*
> *thinking/approaches fall short…*
> *it is a particular mindset, informed by language,*
> *which offers alternative perspectives on the nature of*
> *complex systems and their problems. Given individual capacity*
> *and organizational competency for ST, systems engineers*
> *and organizations have the potential for alternative decisions,*
> *actions, and interpretations to better understand the nature of*

complex systems and problems. Thus, different paths forward,

not accessible from traditional modes of thinking rooted in reductionism,

become available to the ST systems engineer. (Jaradat, Keating & Bradley, 2017, p. 4)"

Herein lies the great opportunity for the cannon artillery portfolio in particular and the Army as an institution in general. If a shift in mindset to systems thinking can occur, the Cannon artillery portfolio will open itself to new possibilities and be better able to deliver on the leap ahead capabilities that leadership has asked for. Systems thinking is the key enabler for managing systems of systems in the VUCA environment that the Army finds itself in, currently and for the foreseeable future. Systems thinking will enable the previously discussed opportunities to be seized. Systems thinking is not a technical problem to be solved, nor is it a tool to be applied. It is a mindset and way of doing business.

Chapter 5 - Interpretation

Conclusions.

This paper arrives at two sets of conclusions in response to the central question of this research. The first set are technical in nature and the second are related to management of system of systems.

Technical approaches to the portfolio.

Three activities will provide benefit to the cannon artillery portfolio. First, the establishment of an overarching system of systems requirement for cannon artillery will provide for the optimization of Fires as a function within the Army. Specific measures of performance will guide decision making for the portfolio. In support of this system of systems requirement comprehensive models of system performance will permit the assessment of the attainment of system of system performance and facilitate informed decision making in terms of required constituent system requirements and priority for development. A set of architectures for the system of systems will permit maximum flexibility to accommodate emergent capability in the system of systems and minimize the cost to constituent systems to support the emergent capability. These approaches facilitate the attainment of increased capability, while minimizing the cost of acquiring and supporting the cannon artillery system of systems. In the present environment of flat budgets and evolving threats, this approach allows the fires community to better manage the development of new capability and prioritize its investments in the portfolio.

Management approach to the portfolio.

The concepts of Complex System Governance and Systems Thinking provide a significant opportunity for the cannon artillery portfolio to conduct a self-examination and assess what changes could be made to the governance structure of the cannon artillery system of systems. Complex System Governance provides a framework by which to judge the effectiveness of the current organization and identify opportunities to improve governance. This would not be a wholesale revamp of the portfolio, but rather, would occur in measured steps. The literature specifically warns against large scale change, especially as an initial effort. The most significant and immediate step is the assessment of the degree to which systems thinking is embodied and displayed in the organization and personnel of the cannon artillery portfolio. To be clear, systems thinking does not equate to traditional systems engineering competence. It is systems thinking in the classical sense of the definition. The initial effort in implementing Complex System Governance may need to be to develop “individual capacity and organizational competence for systems thinking”, as discussed by Jaradat, Keating and Bradley (2017). Once these take root, further assessment and development could occur.

The benefits of embracing Complex System Governance and System Thinking are an enhanced ability to adapt and thrive in a VUCA environment where traditional thinking will falter or fail. The Army has a problem solving culture. Complex systems demand a more dialogic approach. That is, complex systems possess multiple viewpoints and realities, that must be reconciled and accounted for. There is more than one “right” answer. Systems thinking and Complex System Governance embrace that concept and provide a means by which to approach complex systems and assess the degree to which the system of systems is being successful. Complex System Governance are not tools to be wielded. But rather, they are a worldview and approach to complex situations.

Achieving individual capacity and organizational competence in systems thinking is an Organizational Development (OD) issue in the sense that Anderson defines Organizational Development. It is a planned change intended to improve organizational effectiveness through the alignment of external/internal influences, mission, strategy, leadership, organizational structure, work processes and motivational means (Anderson, 2017, pp. 2-3). The constituent stakeholders of the cannon artillery portfolio must transform their community by adopting systems thinking as a world view and integrate it into their processes and culture. Benchmarks to assess individual capacity and organizational competence in systems thinking exist (Jaradat, Keating and Bradley, 2017; Bradley, Unal, Pinto and Cavel, 2015) and provide a point of departure for any improvement effort. An Organizational Development effort, built around the goal of assimilating this world view into critical organizational elements managing the cannon artillery portfolio, should be undertaken.

Recommendations.

This research has identified a number of opportunities to better manage the cannon artillery system of systems. This research has, also, identified a number of areas that merit further examination and discussion. The conclusions of this work have application beyond the cannon artillery portfolio and could be extended to other portfolios within the Army.

Technical recommendations.

The following recommendations should be implemented as soon as is feasible:

- A system of systems requirement should be established for cannon artillery
- Development of architectures to guide the development of the cannon artillery system of systems should be undertaken
- Models of performance tied to performance requirements developed in recommendation one should be created and used to inform development of the portfolio.

Given that the constituent systems that comprise the artillery system of systems cut across Program Executive Offices, Combat Capability Development Command Centers and a number of other supporting organizations within the Army, a lead organization for driving these efforts will be necessary. With the stand up of Army Futures Command and the eight Cross-Functional Teams (Judson, July 2019), the Long Range Precision Fires CFT would be a logical sponsor for the effort. Technical leadership this effort should be provided by the Office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology ASA(ALT) Chief Systems Engineer. The Office of the Chief Systems Engineer will have the ability to cross-cut organizations and provide the focal point for technical leadership on this effort.

Further lines of inquiry beyond this paper that will support these efforts would include:

- A comprehensive examination of an appropriate architectural framework for the cannon artillery portfolio.
- An exploration of appropriate models for the characterization of cannon artillery system of system performance.
- An inquiry into what the minimum satisficing requirements would be for a cannon artillery system of systems.

Management recommendations.

Widespread implementation of a Complex System Governance approach is infeasible and unreasonable for the reasons cited previously in this paper. However, the concept has merit and could provide benefit to the cannon artillery portfolio. It is recommended that Joint Program Executive Office Armaments & Ammunition and Combat Capability Development Command, Armaments Center explore the issue of system thinking and Complex System Governance for application to the cannon artillery portfolio, within that community at Picatinny Arsenal. An initial step could be an assessment of the degree to which systems thinking is expressed within the organization. If sufficient capacity and competence are present, the application of the Complex System Governance model to a select effort could be undertaken as a pilot.

Further research into Complex System Governance and systems thinking is merited. Possible lines of inquiry include:

- An exploration of the degree to which individual capacity and organizational competence in systems thinking exists within an organization as a case study
- An exploration of the scope of an organizational development effort required to instill systems thinking in an organization
- An assessment of an existing system of systems effort in the context of Complex Systems Governance and provide recommendations to improve management of the system of systems as a case study.
- An inquiry into what issues, beyond those already identified, exist when trying to implement Complex Systems Governance as a practice within an organization.

Limitations.

The limitations of this paper are those that have been previously identified. This paper is limited to a historical review due to the limitation on use of interviews and surveys. An institutional Review Board (IRB) does not exist at Defense Acquisition University, presently. Without IRB review and approval, human research cannot be conducted.

The scope of this paper has been limited to the cannon artillery portfolio due to the limited time and resources available to conduct research in support of this paper. Further examination of other weapon portfolios would require time and resources, not available within the duration of the DAU Senior Service College Fellowship.

Additionally, the paper must be published under distribution statement A. This fact will limit the level of technical detail presented in order to maintain that disclosure level. Therefore, open sources and distribution 'A' sources were utilized for this paper. If this paper could be published at a higher distribution level, additional technical detail, themes and case studies could be examined and discussed, providing a richer discussion of the topic.

Final Thoughts.

The Complex System Governance field of study, examined by this paper, is nascent, and strong consensus does not yet exist for an established standard of theory and practice. This paper captures the sentiment of the thought leaders within this area of study. The literature and artifacts brought within the scope of this paper have circumscribed the span of thought on this topic at this time. This paper is weighted in theory, because the practice of these ideas is not widespread nor widely accepted. Practical application of these concepts to real world systems of systems is needed. The relative immaturity of this discipline invites further study to challenge and enlarge upon the ideas presented in this paper and in the literature at large. In spite of this lack of maturity, the practice of Complex System Governance still holds significant promise of better management and program outcomes for the increasingly complex systems of systems that make up the Army combat force.

The Army is continually being confronted with evermore complex and vexing problem sets. These problems require increasingly complex solutions. What is certain is that the methods of the past are no longer adequate to solve the problems of the future. Therefore, it would behoove the Army to take up the challenge to mature and integrate the practice of Complex System Governance, for use in addressing the pressing dilemmas presented in the present and future environment. Standing still is not an option.

References

Akers, W. (2015). *An approach for the development of complex systems archetypes* (Order No. 10187988). Available from ProQuest Dissertations & Theses Global. (1964032936). Retrieved from https://search.proquest.com/docview/1964032936?accountid=40390

Albakri, G. M. (2011). *Application of system of systems engineering to facilitate integration of complex legacy systems* (Order No. 3449285). Available from ProQuest Dissertations & Theses Global. (862090994). Retrieved from https://search.proquest.com/docview/862090994?accountid=40390

Anderson, D. L. (2017). Organizational development, The process of leading organizational change. Thousand Oaks, CA: Sage

Army Force Management School. (2020). Why force management. Briefing received as part of the DAU Senior Service College Fellowship program.

Beer, S. (1984) 'The viable system model: its provenance, development, methodology and pathology', *Journal of the Operational Research Society*, Vol. 35, No. 1, pp.7–25.

Ben-Dyke, A., Cusack, M., Hoare, P., Lycett, M., & Paul, R. J. (2003). Assessing the impact of components on future military command systems. *Benchmarking, 10*(4), 355-366. doi:http://dx.doi.org.dauknowledgerepository.idm.oclc.org/10.1108/14635770310698361

Carter, B. (2016). *Systems theory based architecture framework for complex system governance* (Order No. 10247010). Available from ProQuest Dissertations & Theses Global. (1873603773). Retrieved from https://search.proquest.com/docview/1873603773?accountid=40390

Champion, D. (2018). A case analysis for PEArL: Software on wheels: SSIS. *International Journal of Information Management, 41*, 93. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/2090259581?accountid=40390

Cotter, T. S., & Quigley, P. A. (2018). *SYSTEMS STATISTICAL ENGINEERING – SYSTEMS HIERARCHICAL CONSTRAINT PROPAGATION*. Huntsville: American Society for Engineering Management (ASEM). Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/2193093422?accountid=40390

DiMario, M., Cloutier, R., & Verma, D. (2008). Applying frameworks to manage SoS architecture: EMJ EMJ. *Engineering Management Journal, 20*(4), 18-23. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/208948261?accountid=40390

DiMario, M. J. (2009). *System of systems collaborative formation* (Order No. 3388324). Available from ProQuest Dissertations & Theses Global. (305099603). Retrieved from https://search.proquest.com/docview/305099603?accountid=40390

DiMario, M.J., Boardman, J. and Sauser, B. (2009). System of systems collaborative formation. IEEE Systems Journal 3(3):pp. 360 – 368. doi: IEEE Systems Journal 3(3):360 - 368

Department of Defense (2008). Systems engineering guide for systems of systems. Retrieved from http://acqnotes.com/wp-content/uploads/2014/09/DoD-Systems-Engineering-Guide-for-Systems-of-Systems-Aug-2008.pdf

Gomez, D. A. (2010). *System of systems engineering: Prescribing the technical development effort to engineer a constituent system* (Order No. 3433358). Available from ProQuest Dissertations & Theses Global. (845287701). Retrieved from https://search.proquest.com/docview/845287701?accountid=40390

Gorod, A., Gandhi, S. J., Sauser, B., & Boardman, J. (2008). Flexibility of system of systems. *Global Journal of Flexible Systems Management, 9*(4), 21-31. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/201708643?accountid=40390

Gorod, Alex & Sauser, Brian & Boardman, John. (2009). System-of-Systems Engineering Management: A Review of Modern History and a Path Forward. Systems Journal, IEEE. 2. 484 - 499. 10.1109/JSYST.2008.2007163.

Gorod, A. (2010). *System of systems engineering management framework: A "satisficing" network approach* (Order No. 3428853). Available from ProQuest Dissertations & Theses Global. (758283571). Retrieved from https://search.proquest.com/docview/758283571?accountid=40390

Hernandez, A. S., PhD., Karimova, T., & Nelson, D. H., PhD. (2017). *Mission Engineering And Analysis: Innovations In The Military Decision Making Process*. Huntsville: American Society for Engineering Management (ASEM). Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/2010277927?accountid=40390

Hossain, N. U. I., & Jaradat, R. M., PhD. (2018). *A Synthesis Of Definitions For Systems Engineering*. Huntsville: American Society for Engineering Management (ASEM). Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/2193094846?accountid=40390

International Council on Systems Engineering. (2016, July). A complexity primer for systems engineers: TP-2016-001-01.0. INCOSE: San Diego, CA

International Council on Systems Engineering. (2018). INCOSE systems of systems primer. INCOSE-TP-2016-001-01.0. Retrieved from https://connect.incose.org/Pages/Product-Details.aspx?ProductCode=SoSPrimer

Jaradat, R. M. (2014). *An instrument to assess individual capacity for system thinking* (Order No. 3662373). Available from ProQuest Dissertations & Theses Global. (1652469947). Retrieved from https://search.proquest.com/docview/1652469947?accountid=40390

Jaradat, Raed & Keating, Charles & Bradley, Joseph. (2017). Individual Capacity and Organizational Competency for Systems Thinking. IEEE Systems Journal. PP. 1-8. 10.1109/JSYST.2017.2652218.

Johnson, B.W. (2015). A framework for engineered complex adaptive system of systems. Calhoun. Retrieved from https://calhoun.nps.edu/handle/10945/63463

Jovel, J., & Jain, R. (2009). Impact of identified causal factors to "system of systems" integration complexity from a defense industry perspective. *Global Journal of Flexible Systems*

Management, 10(4), 45-54. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/733945455?accountid=40390

Judson, J., (2019, July 17). Army futures command is ready for prime time. Defense News. Retrieved from https://www.defensenews.com/land/2019/07/17/army-futures-command-is-ready-for-prime-time/

Judson, J., (2019, October 14). Tougher decisions are coming in the US Army's night court budget review. Defense News. Retrieved from https://www.defensenews.com/digital-show-dailies/ausa/2019/10/14/tougher-decisions-are-coming-in-the-us-armys-night-court-budget-review/

Katina, P. F., & Keating, C. B. (2014). *Metasystem Pathologies: Towards A Systems-based Construct For Complex System Deficiencies*. Huntsville: American Society for Engineering Management (ASEM). Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/1705171280?accountid=40390

Katina, P. F., Keating, C. B., Bobo, J. A., & Toland, T. S. (2019). A Governance Perspective for System-of-Systems. *Systems*, *7*(4), 54. doi:10.3390/systems7040054

Keating, C. B., Bradley, J. M., (2012). Complex system governance reference model. *Int. J. System of Systems Engineering, Vol. 6, Nos. 1/2, 2015,* Retrieved from https://pdfs.semanticscholar.org/3ee3/b8a211211e7216b10fcd845d58d70be39278.pdf

Keating, C. B., PhD., Bradley, Joseph M,PhD., P.E., & Katina, P. F., PhD. (2016). *Systemic Analysis Of Complex System Governance For Acquisition*. Huntsville: American Society for Engineering Management (ASEM). Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/2010277753?accountid=40390

Keating, C. B., Bradley, J. M., (2015, January). Complex system governance reference model. *International* Journal of System of Systems Engineering 6(1/2) doi: 10.1504/IJSSE.2015.068811

Keating, Charles & Katina, Polinpapilinho. (2019). Complex system governance: Concept, utility, and challenges. Systems Research and Behavioral Science. 10.1002/sres.2621.

Keating, Charles & Katina, Polinpapilinho. (2011). Systems of systems engineering: Prospects and challenges for the emerging field. International Journal of System of Systems Engineering 2(2/3):234-256 doi: 10.1504/IJSSE.2011.040556

Keating, C. B., Katina, P. F., Jaradat, R., Bradley, J. M., and Hodge, R. (2019, Spetember). Framework for improving complex system performance. INCOSE International Symposium. Obtained from author.

Keating, C. B., PhD., Katina, P. F., PhD., Pyne, James C,PhD., P.E., & Jaradat, R. M., PhD. (2017). *Systemic Intervention For Complex System Governance Development*. Huntsville: American Society for Engineering Management (ASEM). Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/2010278756?accountid=40390

Keating PhD, C., Calida, B., Sousa-Poza PhD, A., & Kovacic, S. (2010). *Systems thinking*. Rolla: American Society for Engineering Management (ASEM). Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/1704369682?accountid=40390

Keating, C., Rogers, R., Unal, R., Dryer, D., & al, e. (2003). System of systems engineering: EMJ EMJ. *Engineering Management Journal, 15*(3), 36-45. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/208982079?accountid=40390

Keating, C. B., Padilla, J. J., & Adams, K. (2008). System of systems engineering requirements: Challenges and guidelines: EMJ EMJ. *Engineering Management Journal, 20*(4), 24-31. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/208948101?accountid=40390

Konur, D., Farhangi, H., & Dagli, C. H. (2016). A multi-objective military system of systems architecting problem with inflexible and flexible systems: Formulation and solution methods. *OR Spectrum, 38*(4), 967-1006. doi:http://dx.doi.org.dauknowledgerepository.idm.oclc.org/10.1007/s00291-016-0434-2

Lane, J. A., & Boehm, B. (2007). System-of-systems cost estimation: Analysis of lead system integrator engineering activities. *Information Resources Management Journal, 20*(2), 23-32. doi:http://dx.doi.org.dauknowledgerepository.idm.oclc.org/10.4018/irmj.2007040102

Lock, R. (2012). Developing a methodology to support the evolution of System of Systems using risk analysis. *Systems Engineering*, *15*(1), 62–73. https://doi-org.library3.webster.edu/10.1002/sys.20194

Mattila, J. (2017). *Using evolutionary theory in studying the development of system of systems*. Kidmore End: Academic Conferences International Limited. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/1967313832?accountid=40390

McClary, D. B. (2014). *The six key concepts of system-of-systems engineering: A review of current and potential applications, and a call for further study* (Order No. 1591606). Available from ProQuest Dissertations & Theses Global. (1693857973). Retrieved from https://search.proquest.com/docview/1693857973?accountid=40390

Murray, J.M., (2018, December 9). US Army Futures Command chief: How the new command will change the service. Defense News. Retrieved from https://www.defensenews.com/outlook/2018/12/10/us-army-futures-command-chief-how-the-new-command-will-change-the-service/

Philbin, S. P. (2008). MANAGING COMPLEX TECHNOLOGY PROJECTS. *Research Technology Management, 51*(2), 32-39. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/213801829?accountid=40390

Ridgely, D. (2020). Mission focused engineering. Unpublished briefing. OUSD(R&E)

Robertson, C.J. (2015). Applying a system-of-systems engineering perspective to current and future army acquisitions. Retrieved from http://hdl.handle.net/10945/45930

Sauser, B., & Boardman, J. (2008). Taking hold of system of systems management: EMJ EMJ. *Engineering Management Journal, 20*(4), 3-8. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/208984634?accountid=40390

Sousa-Poza, A., & Kovacic, S. (2008). Research agenda for complex situations: EMJ EMJ. *Engineering Management Journal, 20*(4), 32-39. Retrieved from https://search-proquest-com.dauknowledgerepository.idm.oclc.org/docview/208954402?accountid=40390

US Army Field Artillery School (2014, Nov-Dec) DIVARTY: a force multiplier for the BCT and division. Fires. Retrieved from https://sill-www.army.mil/firesbulletin/archives/2014/nov-dec/05_DIVARTYWP.html

Walker, R. G. (2014). *A method to define requirements for system of systems* (Order No. 3581842). Available from ProQuest Dissertations & Theses Global. (1619591357). Retrieved from https://search.proquest.com/docview/1619591357?accountid=40390

Whitney, K., Bradley, J. M., Baugh, D. E. and Chesterman, C. W. (2015, January). Systems theory as a foundation for the governance of complex systems. International Journal of Systems Engineering. doi: 10.1504/IJSSE.2015.068805

Glossary of Acronyms and Terms

ACAT I…........Acquisition Category I

AFC…………Army Futures Command

CASoS….........Complex Adaptive System of Systems

CFT……........Cross Functional Team

COCOMS…...Combatant Commands

CONOPS…....Concept of Operations

CSG…………Complex System Governance

DAU……........Defense Acquisition University

DoD………….Department of Defense

DoDAF………Department of Defense Architecture Framework

INCOSE……..International Council On Systems Engineering

IRB…………..Internal Review Board

JCIDS………..Joint Capabilities Integration and Development System

MDAP……….Major Defense Acquisition Program

MDO…………Multi-Doman Operations

OUSD(R&E)…Office of the Under Secretary for Defense (Research and Engineering)

PEArL ………..Participants, Engagement, Authority, relationships, Learning

SE……………Systems Engineering

SoS…………..System of Systems

SoSE…………System of Systems Engineering

UK……………United Kingdom

VUCA……….Volatility, Uncertainty, Complexity and Ambiguity

Author Note

It is quite gratifying when conducting a piece of research changes one's outlook on a problem set as a result. I entered this project with a bias that the problem of managing a system of systems was purely a technical issue and all that was required was a way to apply all that I had learned about systems engineering over my career. After diving into the literature search, it quickly became apparent that much of the past failures were rooted in that faulty assumption. Complex systems of systems are not subject to one correct answer. They possess multiple perspectives and realities existing within the same world. The concept of Complex System Governance recognizes that fact and seeks to provide a means to make sense of that world. It is my hope that that my colleagues and others who read this paper come to that same conclusion and seek to change their outlook and approach to managing the ever more complex systems that exist within our world.

I would like to thank my Research Advisors, Darrin Rhyne and Tom Conroy for patiently reading through my amateur attempts at scholarly research and keeping me on point. I would also like to thank the Defense Acquisition University 2019-2020 Senior Service College Fellowship Cohort and Directors for providing a great learning environment and opportunity to grow professionally and personally. I can assure you that everyone I have encountered as part of the SSCF program has in some way added to my perspective and knowledge. I would also like to thank my wife, Martha, for putting up with a husband who was away on travel or had his face in a book for the last 10 months.

Finally, I would like to dedicate this work to my grandson Logan and all of my grandchildren to come. It is my hope that what I have contributed here, and will contribute going forward, will in some small way result in a better world for you to live in.