2005

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Original Publication Citation

Mun, J. H., Henrie, M., Correa, Y., Keating, C., & Sousa-Poza, A. (2005). *Development of a system of systems engineering method.* IIE Annual Conference and Exposition 2005, 14-18 May 2005, Atlanta, GA.

Development of A System of Systems Engineering Method

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Abstract

Systems engineers have been facing challenges with the design and analysis of multiple complex systems. System of Systems Engineering has emerged to assist in this challenge with the systemic analysis, design, and transformation of complex metasystems. This paper outlines a proposed method to overcome these challenges, which is grounded in System of Systems Engineering principles and methodology. An overview of System of Systems Engineering will be provided for understanding of its significance and the attempt to complement Systems Engineering efforts in dealing with the aforementioned challenges. Finally, discussion on the proposed method, with respect to complex system analysis, is provided.

Keywords

Complex systems, Systems Engineering, System of Systems Engineering

1. Introduction

The world we live in is a mesh of global economics, political interaction, social networks, technical innovation, and other factors that form dynamic complex systems [1] [2] [3]. It is a world that has been reported as "… facing a new set of problems and opportunities…" [1] with levels of complexity ever increasing [4]. In this changing global environment, one description of a complex system is "one whose properties are not fully explained by an understanding of its component parts" (p. x) [3]. Other descriptions include descriptive phrases such as emergence [5], diversity of agents interacting [2], and self-organization [6]. Regardless of how complexity is defined or described, the literature consistently indicates that the level of complexity is escalating.

This escalation of globally interrelated complex systems creates an environment that requires a new way of thinking. No longer can the government or corporation view a system or system-of-systems design as a discrete device operating within a well defined and controlled environment. The complex systems of today are about systems that must be designed, managed, and operated on the fine line between total order and total chaos. As complexity theorists point out:

> … all significant change takes place between too much and too little order. When there is too much order, systems are frozen and cannot change, and when there is too little order, systems disintegrate and can no longer function (p. 14) [4].

"System of System Engineering (SoSE) is an emerging discipline that is attempting to address design and analysis and understanding of complex metasystems, Systems of Systems (SoS). However, SoSE is in the embryonic stages of development and lacks consistent focus" (p. 36) [7]. As an emerging discipline the practicing Systems of Systems Engineer is faced with the need for methodologies and methods for systems of systems analysis and design.

The intent of this paper is to present an approach of SoSE that provides the practicing SoS engineer with a method of system analysis. The paper is arranged to provide a short background on the challenges faced by systems engineers. Following the Systems Engineering discussion, a short overview of SoSE is presented. These sections set the foundation for the proposed research method, which is then described. This paper contributes to the discussion on how SoS engineers can conduct a SoSE process and presents one method of SoSE analysis.

2. Challenges for Systems Engineering

Systems Engineering literature links "Systems engineering methodologies and practices [as beginning] to emerge from experience gained in the U.S. Department of Defense (DoD) acquisition programs of the later 1950s" (p. 1) [8].

It provides a "logical sequence of activities and decisions that transforms an operational need into a description of system performance parameters and a preferred system configuration" [9]. Also, there is a body of literature that discusses how Systems Engineering has been successfully applied to SoS [10]. Counter to this is the SoS literature that takes the position that Systems Engineering is not fully applicable to SoS analysis and engineering. Some of the proposed reasons, for this lack of applicability, included: Systems Engineering cannot be applied at the higher SoS level, SoS systemic complexity [3], tiered levels of discipline involved [11], misapplied applications [12], and due to SoS inherent context and environmental changes [13]. In general, the inherent complexity of SoS limits the applicability of Systems Engineering within this domain. The complexity of SoS is discussed in the next section.

3. Systems-of-Systems

System-of Systems has become a commonly used term whose origins date from the mid to early 1990s [14]. "The concept of System-of-Systems (SoS) has been extensively examined [15] [14] [16] and is broadly acknowledged as a challenging issue due to its high complexity" (p. 171) [13]. From these earlier scholarly efforts, a fairly consistent set of SoS literature themes, such as complex systems [11], complexity [14], emergence [5], and chaos [6], develops, that is, SoS is clearly linked with the concept of complexity and complexity theories and concepts. As a complex, interacting set of embedded systems, design and analysis of SoS design and analysis are difficult. This difficulty is driven by many factors, but as Keating et al. [7] state, for SoS "Optimization, in the sense of singular best configuration, does not exist for complex systems of systems. Optimal performance in a complex system of systems is an illusion that exists beyond our capacity to understand or develop" (p. 40).

Due to the inherent difficulty in SoS engineering and analysis, SoSE methodology has been evolving. SoSE methodology is a generalized framework that provides an orderly design, assessment, or transformation of a system of systems [7]. The next step in this evolutionary process is the development of the SoSE analysis methods. The next section presents a proposed SoSE analysis method based on a helical process. This helical process is intended to develop a new SoS worldview based on a holistic system perspective.

4. Proposed SoSE Analysis Method

SoSE methodology involves the "…rigorous inquiry that is as much about thinking and framing of problems, their context, and managing emergent conditions as it is about taking decisive action" [7]. This proposed method continues the evolutionary history of system engineering. As Bertalanffy [17] presented, "The system problem is essentially the problem of the limitations of analytical procedures in science" (p. 18). SoS literature articulates the issues with current SE analytical capabilities as applied to complex SoSs.

In this section, a method is introduced to address the difficulty in the analysis of complex SoS. The proposed SoSE method involves an interactive helical process of bottom-up and top-down, iterative, data gathering and analysis method. As the discussion unfolds an appearance of a linear and sequential process may be developed. This is an inadvertent function of presentation versus application. While the steps are outlined as discrete and linear, they are in fact interactive and iterative in nature and need. One should view this process through a mental picture of a helical process where bottom-up and top-down analyses interweave to create a new worldview based on the holistic SoSE worldview.

This analysis process involves the creation of several system views. Each of these views contributes to the overall SoS analysis. These various systems are highlighted in Table 1.

Table 1. SoS descriptions

System Name	Description
Idealized System - System 1	The ideal system which contains no constraints or barriers. This system is not achievable in reality
Normalized System – System 2	The perceived achievable ideal state. This system can not obtain System 1 status due to the existence of barriers
Target System – System 3	This system can consist of one or more transition state systems used to transform the current system state to the Normalized system state.

SoSE Current System – System 4	The stakeholder current state as modified by the SoSE worldview
Stakeholder Current System – System 5	The system as perceived by the stakeholders

Of the five systems, System 2 (Normalized System), System 3 (Target System) and System 4 (SoSE Current System) require analysis and design that are reliant on preceding efforts. System 3 requires the development of Systems 2 and 4, while System 4 is preceded by the development of System 5. Based on the iterative nature of this process, each of the systems can evolve as a result of subsequent system analysis.

For the bottom-up analysis, the primary data source is the stakeholders' views and information. Each of the stakeholders is interviewed and available documents are analyzed to determine how they perceive their system and its interactions with the metasystem, the SoS. This stakeholder system analysis may create the view that the SoS is a set of stand alone systems that, at some level, interact with each other and their environments, within a specific context. The intent of this analysis is to determine each stakeholder's view on how their system works, how each of their system interacts with the other systems, where the system boundaries appear to be, and what are the system barriers and constraints. The resulting analyses on the multiple and divergent perspectives of the stakeholders of their system are then integrated to develop the stakeholders' current worldview, System 5.

In the development of the 'stakeholders' current system worldview, it is not the intent to reconcile any apparent differences in system views. It is anticipated that each stakeholder will have a unique view of the SoS under analysis. These different views are based on the perceptions of the stakeholders, their contextual setting and unique understandings. These potentially divergent system views are fully congruent with systems thinking in that the system is a function of the view of the beholder [18] [19].

Evolving the stakeholders' current system view into a unified current view, SoSE Current View (System 4), involves the application of the SoSE worldview through training and facilitated dialogue. In this process, the SoSE assists the stakeholders in the creation of a common system view. The common system view includes the system context, constraints, barriers and environment, which are grounded in the SoSE methodology. Development of the unified SoSE view of the system will establish the system domain that assists in the development of the transformation system(s), System 3.

Prior to the development of transformation system, the normative system (System 2) must be defined. Development of System 2 evolves from interaction of the bottom-up process (understanding of the current system as perceived by the stakeholders), identification of system barriers, and from the top-down efforts of identifying the inherent purpose of the SoS. The top-down process begins with the development of the ideal system (System 1). This is a system that is not limited in its capabilities by any constraints or barriers. For this proposed method, constraints are those factors that impact the ability of the system to transform from its current state to the normative state. Constraints are items that the system can affect and change. Barriers also limit the system's abilities to affect a transformation. However, unlike constraints, barriers are those items that the system cannot modify, change or eliminate. They effectively inhibit the achievement of the ideal state, System 1. Figure 1 graphically depicts these relationships.

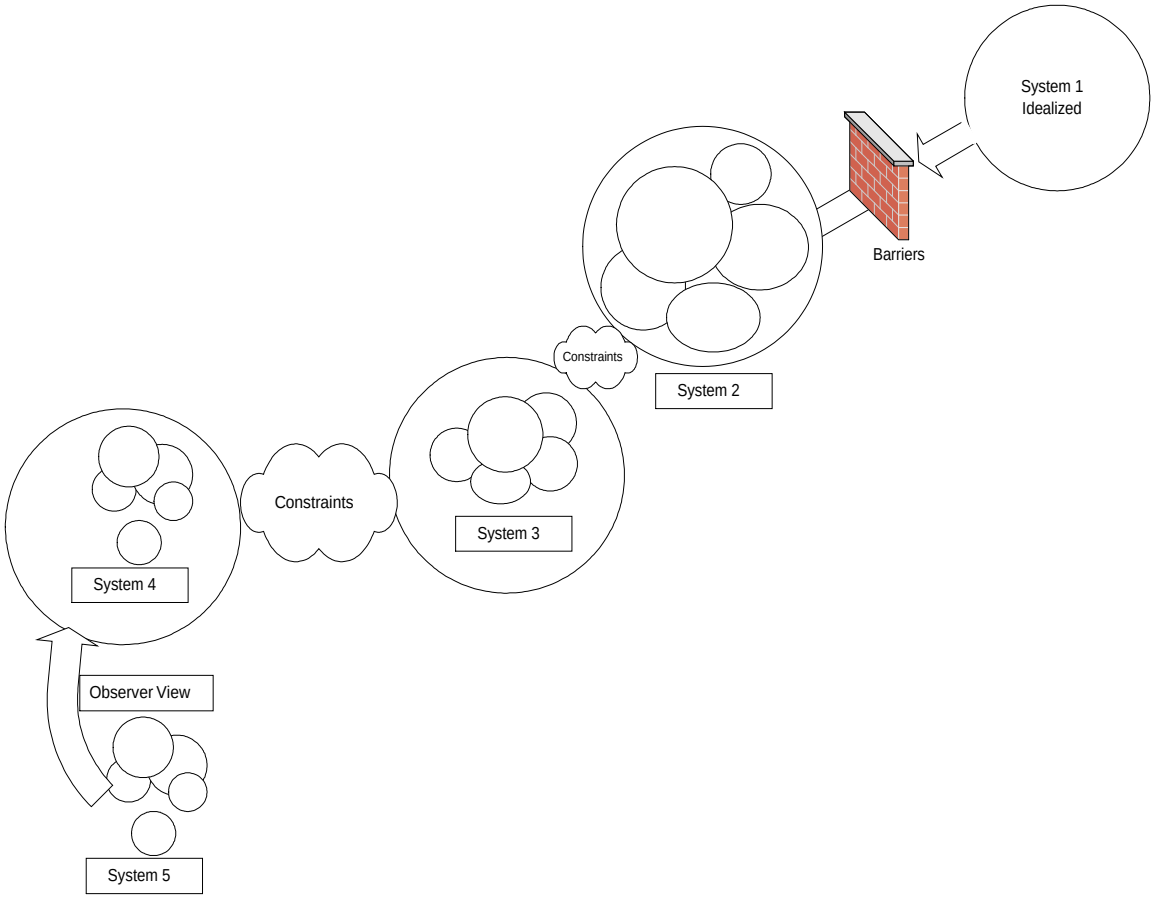

Figure 1. System of Systems

Development of the various SoSs involves many well known tools and techniques. During the helical SoSE analysis process, system data gathering and analysis the tools of interviewing, surveying and document review are applied.

5. Conclusion

SoSE has emerged as a result of the difficulty in designing and analyzing systems that are of increasing complexity. The current discipline of Systems Engineering and its application are inadequate in addressing the challenging and difficult aspects of design, operation, management, and transformation of the SoS. A method has been developed to analyze the current state of the SoS from divergent views of the stakeholders and to transform these views into a unified system through the lens of SoSE worldview. The proposed method provides a helical process of analyses through the use of bottom-up, top-down, and iterative approaches that will lessen the challenges imposed by the complex SoS.

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