Chapter 1

Overview and Introduction to Modeling and Simulation Support for System of Systems Engineering Applications

Larry B. Rainey[1] and Andreas Tolk[2]
[1] *Integrity Systems and Solutions, LLC, Colorado Springs, CO, USA*
[2] *SimIS Inc., Portsmouth, VA, USA*

1.1 MOTIVATION

A little longer than a decade ago, the community of systems engineers started to seriously deal with a category of challenges: system of systems (SoS).

Systems Engineering (SE) is now better understood since its official birth as a discipline in the middle of the last century. It is widely understood to control the total systems life cycle process: definition, development, deployment, and retirement of a system. SE ensures that solutions are reliable, maintainable, and cost-effective. But its solutions focus on a system made up of components born from a common set of user requirements. Interactions with other systems was always possible, but these other systems were external and beyond the central systems boundaries.

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In particular, the Internet showed the power of interconnectivity. Net-centric solutions were soon discussed that allowed the reuse of systems by loosely coupling them via information exchange. But this extended system was beyond traditional program, governance, and organization boundaries. New processes were needed to help synchronize activities, budgets, and schedules. Sage and Cuppan (2001) and Keating et al. (2003) contributed to the engineering managerial foundations to move toward System of Systems Engineering (SoSE) using the architecting principles identified by Maier (1998) only a couple of years earlier.

The technical challenges cannot be neglected. Designing interfaces and communications protocols to federate independently developed systems with each other without allowing for any significant redesign of the system is a huge challenge. However, the organizational challenges that had to be addressed by engineering managers were even bigger. For example, today's managers are not used to the task to bring systems together to fulfill a common task without having the power to establish common processes, a common administration, and a common governance.

In his work, which is actually summarized and continued in Chapter 2 of this handbook, Maier identified five criteria commonly recognized in SoSE literature:

1. *Operational independence of the individual systems*: An SoS is composed of systems that are independent and useful in their own right. If an SoS is disassembled into the component systems, these component systems are capable of independently performing useful operations independently of one another.
2. *Managerial independence of the systems*: The component systems not only can operate independently, but they generally do operate independently to achieve an intended purpose. The component systems are generally individually acquired and integrated, and they maintain a continuing operational existence that is independent of the SoS.
3. *Geographic distribution*: Geographic dispersion of component systems is often large. Often, these systems can readily exchange only information and knowledge with one another and not substantial quantities of physical mass or energy.
4. *Emergent behavior*: The SoS performs functions and carries out purposes that do not reside in any component system. These behaviors are emergent properties of the entire SoS and not the behavior of any component system. The principal purposes supporting engineering of these systems are fulfilled by these emergent behaviors.
5. *Evolutionary development*: An SoS is never fully formed or complete. Development of these systems is evolutionary over time and with structure, function, and purpose added, removed, and modified as experience with the system grows and evolves over time.

Modeling and simulation (M&S) in general and agent-directed simulation (ADS) in particular already support SE successfully. Yilmaz and Ören (2009) dedicated a whole book to the synergisms of ADS and SE. Simulated systems can be used to obtain, display, and evaluate operationally relevant data in agile contexts by executing models using operational data exploiting the full potential of M&S and producing numerical insight into the behavior of complex systems. ADS have been shown to

have the ability to support the development of robust, fault-tolerant, adaptive, self-optimizing, learning, social-capable, autonomous, and agile solutions. ADS also expose emergent behavior similar to SoS, so that they can be used to better understand and utilize this criterion and enforce positive emergence while avoiding negative emergence.

The experts in the field invited to contribute chapters to this handbook were asked to utilize the five criteria provided above as a common foundation. However, the community is still very diverse when it comes to using M&S in support of SoSE applications so this book can merely provide a map of the landscape of approaches.

1.2 OBJECTIVE

Jamshidi's books provided an overview on SoSE from the methodological perspective (Jamshidi, 2010) as well as from the application perspective (Jamshidi, 2011). He also invited experts to contribute chapters, but the focus was clearly on the SE processes.

This book has the objective to focus more on M&S support, providing the foundations for a better research agenda. This research agenda, however, cannot only focus on M&S support questions, but it needs to understand the SoSE application cases as well. As such, the objective of this book is to contribute to find answers—or identify required research to provide answers—to questions such as the following:

- What are the processes of SoSE?
- What steps in the processes are supported by M&S?
- What steps in the processes can be supported in the future by M&S, and what are the necessary constraints?
- How can M&S be used to better understand SoS?

The chapter of this book will start to address them and hopefully initiate more research to fill the gap in the body of knowledge.

1.3 STRUCTURE OF THE HANDBOOK

Despite the challenges mentioned in the last section, this text has the objective to demonstrate how M&S can provide academic augmentation to the relatively new term of SoS. To facilitate this discussion, this text is divided into four major sections. Section I is the "Overview and Introduction." Its purpose is to provide the taxonomy and academic foundation for the rest of the text. Section II is the "Theoretical or Methodological Considerations." The purpose of this section is to address, as the title implies, more theoretical or more generalized approaches to the subject. Section III is the "Theoretical or Methodological Considerations with Applications and Lessons Learned." The purpose of this section is to identify specific cases where definitive applications can be abstracted and lessons learned drawn from the specific application. The final section of the text, Section IV, provides a review of what has been presented previously and draws major conclusions across both the theoretical and application spectrums.

1.3.1 Overview and Introduction

The main thrust of Section I is Chapter 2 "The Role of Modeling and Simulation in System of Systems Development." This chapter is the cornerstone to this text. In this chapter, Mark Maier defines SoS and identifies important systems and various categories of systems that the reader should be cognizant of. He also discusses M&S within the specific SoS category. He then moves ahead to address architecture, architecture description, and development. He closes his chapter with a summary and conclusions.

1.3.2 Theoretical or Methodological Considerations

Section II has five chapters that have been categorized as purely theoretical or methodological in nature.

In Chapter 3, Mike Jones addresses the M&S subject of "Composability." He has taken the attributes of an SoS as defined by Mark Maier to lay a foundation for his chapter. He then examines the M&S topics of conceptual modeling separately and then composability, interoperability, and integratability as a unit. The levels of the Conceptual Interoperability Model are then addressed. Current standards and current research are then addressed from Maier's SoS perspective. Mike finishes with his conclusions.

In Chapter 4, Adam Ross and Donna Rhodes discuss "An Approach for System of Systems Tradespace Exploration (TE)." First, they provide the reader a background on the subject of TE. Then they identify SoS-specific considerations for TE. Next, a specific approach is provided for TE. Then, an illustrative case is considered. They close their discussion with a chapter summary.

Daniele Gianni, in Chapter 5, pursues "Data Policy Definition and Verification for SoS Governance." First, in his background, he addresses a methodology based upon the terminology and concepts from the Unified Modeling Language, enterprise architecture frameworks, SoS governance, and conceptual data modeling. In his next section, he identifies the role of data policy methodology in the context of SoS governance. Next, he addresses the topic of the design of the data policy method methodology. Finally, he provides an example application for the European Space Agency (ESA) space situational awareness preparatory program. Daniele completes his chapter with conclusions.

In Chapter 6, Stephen Johnson addresses the subject of "System Health Management (SHM)." He starts off by laying a foundation of definitions from which to draw upon later in his chapter. Then SHM is addressed for a system. He follows this topic with another that discusses SHM from the perspective of models, simulations, and their applications. Next, he draws a distinction between a system and an SoS. Finally, he illustrates how SHM would pertain to an SoS. He closes his chapter with a conclusion section.

In the last chapter of Section II, Chapter 7, R. William Maule describes a Model Methodology for a Department of Defense Architecture Design. This chapter is an examination of the Department of Defense Architecture Framework (DoDAF) as looked at through the lens of an SoS. The first few sections address a reference architecture, model tooling, and model workflow. The rest of the chapter addresses each individual view as currently portrayed in DoDAF. The chapter closes with a chapter conclusion.

1.3.3 Theoretical or Methodological Considerations with Applications and Lessons Learned

Section III constitutes the bulk of this text. It has 14 chapters assigned to it. These chapters are those that have been categorized as truly methodological consideration in nature as they have definitive applications from which lessons learned can be drawn.

The first in this section is Chapter 8 by Agostino Bruzzone, Marina Massei, Alfredo Garro, and Francesco Longo. It is entitled "An Agent-Oriented Perspective on System of Systems for Multiple Domains." In this chapter, the authors first address the spectrum that ranges from large-scale systems to SoS. Then they address M&S approaches for SoS. Next is an agent-oriented perspective for SoS. Then they turn the discussion to exploiting the agent-oriented perspective with application examples in multiple domains. They end their chapter with conclusions and future works.

Chapter 9 by Sanjay Jain, Charles Hutchings, and Y. Tina Lee is entitled "Building Analytical Support for Homeland Security." The authors address the relationship between homeland security and SoS. Then they identify the need for M&S and analysis for homeland security. This discussion is followed by providing a knowledge sharing framework. The last consideration in their chapter is that of a prototype for an SoS application. Their chapter is completed with a chapter summary.

Chapter 10 by William Crossley and Daniel DeLaurentis makes the case that the "Air Transportation System" provides many examples of SoS. The authors address theoretical considerations, methodology, applications and is finalized with lessons learned.

Chapter 11 is entitled "Systemigram Modeling for Contextualizing Complexity in System of Systems" and is written by Brian Sauser and John Boardman. These authors first address what is meant by SoS thinking. They then develop the "Boardman–Sauser Systems Methodology: A System of Systems Thinking Tool." There are seven steps that are enumerated and defined that constitute their thinking tool. They then provide case examples to illustrate their tool. Their chapter closes with conclusions.

Chapter 12 by Joachim Fuchs and Niklas Lindman is entitled "Using Modeling and Simulation for System of Systems Engineering Applications in the European Space Agency (ESA)." These authors first introduce the reader to ESA's background and context. Then they explain the complexity of problems that exists within the ESA. Next, the authors present what they refer to as the ESA Architecture Framework. They explain their framework via an overview, identify the process involved, discuss the supporting modeling tool that supports their framework, discuss various application cases in general, and then identify two specific ESA programs to which their framework would be applicable to and what the results are of making this application. Overall lessons learned are then addressed. The authors finalize their chapter with conclusions.

Chapter 13 addresses "System of Systems Modeling and Simulation for Microgrids Using a Dynamic Data-Driven Application System (DDDAS)" authored by Aristotelis E. Tanos, DeLante Moore, Xiaoran Shi, and Nurcin Celik. In this chapter, the authors first define a microgrid in the context of an SoS. Next, they introduce the DDDAS framework for a particular microgrid design. In their third section, they provide detailed experiments and results of the DDDAS framework as it applies to microgrids. They finalize their chapter with conclusions about the simulation technique used.

In Chapter 14, Clifford Whitcomb, Mikhail Auguston, and Kristin Giammarco address the subject of "Composition of Behavior Models for Systems Architecture." Within the scope of their chapter, they discuss a lineage of topics: common characteristics for architecture descriptions, the Monterey Phoenix (MP) approach to behavior modeling, modeling component behavior, modeling component interaction, merging schemas, comparison of MP with common SE notations, assertions and queries, and implementation prototypes. The authors then provide a chapter summary of their work.

"Joint training" is the subject of consideration in Chapter 15 by James Harrington, Laura Hinton, and Michael Wright. This chapter is another lineage of topics to be addressed by the authors to support the development of their selected subject. They begin with an introduction to Joint training then continue building their discussion with the following topics: SoS characterization for Army and Joint training M&S, complexity of layered M&S of SoS, Joint Land Component Constructive Training Capability (JLCCTC) overview, SoS characterization for JLCCTC, JLCCTC SoSE functions, JLCCTC SE key themes, and JLCCTC SE processes. Their chapter is completed with their conclusions.

The next chapter is 16, which explores the subject of "Human in the Loop in System of Systems (SoS) Modeling and Simulation: Applications to Live, Virtual, and Constructive (LVC) Distributed Mission Operations (DMO) Training." The authorship of this chapter has been undertaken by Saurabh Mittal, Margery J. Doyle, and Antoinette M. Portrey. They approach their subject first by providing a background and scope for the reader and then transition into the detailed topics to unveil their subject. This process starts with a discussion of a Model-Based Systems Engineering (MBSE) process applicable to LVC DMO training. This is followed by the topic of "Not-So-Grand-Challenge (NSGC) Phase I: Integrating Various Modeling Architectures with Air Force Research Laboratory Systems." In the second phase, the authors address environment abstraction (EA) for advanced situation awareness and semantic interoperability. Applying EA to next-generation intelligent combat (NGIC) systems is the next topic, which is followed by a presentation of conclusions and discussion of future work.

Chapter 17 is the next chapter and is entitled "On Analysis of Ballistic Missile Defense Architecture through Surrogate Modeling and Simulation" and has been written by Tommer R. Ender, Phillip D. West, W. Dale Blair, and Paul A. Miceli. These authors start with their proposed approach, address the associated results, and make recommendations for future work and practical application. They finish their chapter with a conclusion.

Chapter 18 is "Medical Enhancements to Sustain Life during Extreme Trauma Care" as written by L. Drew Pihera, Nathan Adams, and Tommer Ender. This chapter starts off with the topic of taming the problem through MBSE. The authors build on this foundation by a discussion of "MBSE and Extracorporeal Membrane Oxygenation (ECMO) Phase 1: Understanding the Problem." In turn, the follow-on topic is "MBSE and ECMO Phase 2: Refactoring the Models to Better Support Trade Studies." The last topic addressed is future work and conclusions.

Chapter 19 is coauthored by Tom Obrien and John Sarkesain and is entitled "Utility: Problem-Focused, Effects-Based Analysis." They start off their subject with the topic of the need for a cybersecurity framework. The discussion transitions to a definition of the problem to be solved. In turn, the application of SE and other disciplines is addressed. The chapter closes with a summary. It also provides the operational foundations for the

following chapter that goes into the details of building a framework to address the challenges describe here.

John Sarkesain and Tom Obrien have also coauthored Chapter 20 entitled "Framework for Cyber Command and Control/Battle Management Research and Development, Acquisition, and Operations." Based in the foundation provided in the foregoing chapter, they start their subject off by addressing the topic of "Information Assurance and Defense in Depth: A Failed Strategy." They then transition to a discussion of cyber command and control/battle management operational architecture. This topic is followed by addressing cyber command and control/battle management systems architecture. The last major topic covered in their chapter is the presentation of a cyber command and control/battle management and missile defense SoS use-case scenario. Their chapter is completed with their conclusions.

Chapter 21 is the last chapter of this text that supports methodological considerations that have definitive applications from which lessons learned can be drawn. This chapter is written by Bharat Madan and is entitled "System of Systems Security." The author begins his subject discussion with topics addressing SoS security requirements, SoS security challenges, and SoS security solutions. He then turns his attention to intrusion-tolerant SoS and modeling, simulation, and emulation SoS security. The chapter closes with his conclusions.

Chapter 22 summarizes the contributions and gives the conclusions of the editors for an ongoing research agenda for the M&S support for SoSE applications. Using examples of the book chapters as well as additional contributions in the public domain, the need for a better understanding of the interplay in SoS is shown.

A new category of engineers is needed to solve the challenges of SoSE. While old engineers build bridges over gap, such stationary solutions are no longer an option in the agile world we find ourselves in today. We have to admit that we do not provide too many answers in this book, but we hope that we at least raise the right questions to spawn new research in both communities—SE and M&S—that will collaboratively contribute to the scientific foundations for Modeling and Simulation Support for System of Systems Engineering Applications.

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