Chapter 1

Introduction to System of Systems

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1.1 INTRODUCTION

Recently, there has been a growing interest in a class of complex systems whose constituents are themselves complex. Performance optimization, robustness, and reliability among an emerging group of heterogeneous systems in order to realize a common goal have become the focus of various applications including military, security, aerospace, space, manufacturing, service industry, environmental systems, and disaster management, to name a few (Crossley, 2004; Lopez, 2006; Wojcik and Hoffman, 2006). There is an increasing interest in achieving synergy between these independent systems to achieve the desired overall system performance (Azarnoosh et al., 2006). In the literature, researchers have addressed the issue of coordination and interoperability in a system of systems (SoS) (Abel and Sukkarieh, 2006; DiMario, 2006). SoS technology is believed to more effectively implement and analyze large, complex, independent, and *heterogeneous* systems working (or made to work) cooperatively (Abel and Sukkarieh, 2006). The main thrust behind the desire to view the systems as an SoS is to obtain higher capabilities and performance than would be possible with a traditional system view. The SoS concept presents a high-level viewpoint and explains the interactions between each of the independent systems. However, the SoS concept is still at its developing stages (Abbott, 2006; Meilich, 2006).

The next section will present some definitions out of many possible definitions of SoS. However, a practical definition may be that a system of systems is a "supersystem" comprised of other elements that themselves are independent complex

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operational systems and interact among themselves to achieve a common goal. Each element of an SoS achieves well-substantiated goals even if they are detached from the rest of the SoS. For example, a Boeing 747 airplane, as an element of an SoS, is not SoS, but an airport is an SoS, or a rover on Mars is not an SoS, but a robotic colony (or a robotic swarm) exploring the red planet, or any other place, is an SoS. As will be illustrated shortly, associated with SoS, there are numerous problems and open-ended issues that need a great deal of fundamental advances in theory and verifications. It is hoped that this volume will be a first effort toward bridging the gaps between an *idea* and a *practice*.

1.2 DEFINITIONS OF SYSTEM OF SYSTEMS

Based on the literature survey on system of systems, there are numerous definitions whose detailed discussion is beyond the space allotted to this chapter (Kotov, 1997; Luskasik, 1998; Pei, 2000; Carlock and Fenton, 2001; Sage and Cuppan, 2001; Jamshidi, 2005). Here we enumerate only six of many potential definitions:

Definition 1: Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development (Jamshidi, 2005).

Definition 2: Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems (Carlock and Fenton, 2001; Jamshidi, 2005).

Definition 3: Enterprise system of systems engineering is focused on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis (Carlock and Fenton, 2001).

Definition 4: System of systems integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios (Pei, 2000).

Definition 5: SoSE involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure (Luskasik, 1998).

Definition 6: In relation to joint warfighting, system of systems is concerned with interoperability and synergism of command, control, computers, communications, and information (C4I) and intelligence, surveillance, and reconnaissance (ISR) systems (Manthorpe, 1996).

Detailed literature survey and discussions on these definitions are given in Jamshidi (2005, 2008). Various definitions of SoS have their own merits, depending on their application. Favorite definition of this author and the volume's editor is *systems of systems are large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal*. The goal, as mentioned before, may be cost, performance, robustness, and so on.

1.3 CHALLENGING PROBLEMS IN SYSTEM OF SYSTEMS

In the realm of open problems in SoS, just about anywhere one touches, there is an unsolved problem and immense attention is needed by many engineers and scientists. No engineering field is more urgently needed in tackling SoS problems than system engineering (SE). On top of the list of engineering issues in SoS is the "engineering of SoS," leading to a new field of SoSE (see Chapter 3). How does one extend SE concepts such as analysis, control, estimation, design, modeling, controllability, observability, stability, filtering, simulation, and so on that can be applied to SoS? Among numerous open questions are how can one model and simulate such systems (see Chapter 5 by Mittal et al.). In almost all cases, a chapter in this volume will accommodate the topic raised.

1.3.1 Theoretical Problems

In this section, a number of urgent problems facing SoS and SoSE are discussed. The major issue here is that a merger between SoS and engineering needs to be made. In other words, SE needs to undergo a number of innovative changes to accommodate and encompass SoS.

1.3.1.1 Open Systems Approach to System of Systems Engineering Azani, in Chapter 2, discusses an open systems approach to SoSE. The author notes that SoS exists within a continuum that contains ad-hoc, short-lived, and relatively speaking simple SoS on one end, and long-lasting, continually evolving, and complex SoS on the other end of the continuum. Military operations and less sophisticated biotic systems (e.g., bacteria and ant colonies) are examples of ad-hoc, simple, and short-lived SoS, while galactic and more sophisticated biotic systems (e.g., ecosystem, human colonies) are examples of SoS at the opposite end of the SoS continuum. The engineering approaches utilized by galactic SoS are at best unknown and perhaps forever inconceivable. However, biotic SoS seem to follow, relatively speaking, less complicated engineering and development strategies allowing them to continually learn and adapt, grow and evolve, resolve emerging conflicts, and have more predictable behavior. Based on what the author already knows about biotic SoS, it is apparent that these systems employ robust reconfigurable architectures enabling them to effectively capitalize on open systems development principles and strategies such as modular design, standardized interfaces, emergence, natural selection, conservation, synergism, symbiosis, homeostasis, and self-organization. Chapter 2 provides further elaboration on open systems development strategies and principles utilized by biotic SoS, discusses their implications for engineering of man-made SoS, and introduces an integrated SoS development methodology for engineering and development of adaptable, sustainable, and interoperable SoS based on open systems principles and strategies.

1.3.1.2 Engineering of SoS Emerging needs for a comprehensive look at the applications of classical systems engineering issue in SoSE will be discussed in this volume. The thrust of the discussion will concern the reality that the technological, human, and organizational issues are each far different when considering a system of systems or federation of systems and that these needs are very significant when considering system of systems engineering and management.

As we have noted, today there is much interest in the engineering of systems that are comprised of other component systems, and where each of the component systems serves organizational and human purposes. These systems have several principal characteristics that make the system family designation appropriate: operational independence of the individual systems; managerial independence of the systems; often large geographic and temporal distribution of the individual systems; emergent behavior, in which the system family performs functions and carries out purposes that do not reside uniquely in any of the constituent systems but which evolve over time in an adaptive manner and where these behaviors arise as a consequence of the formation of the entire system family and are not the behavior of any constituent system. The principal purposes supporting engineering of these individual systems and the composite system family are fulfilled by these emergent behaviors. Thus, a system of systems is never fully formed or complete. Development of these systems is evolutionary and adaptive over time, and structures, functions, and purposes are added, removed, and modified as experience of the community with the individual systems and the composite system grows and evolves. The systems engineering and management of these systems families pose special challenges. This is especially the case with respect to the federated systems management principles that must be utilized to deal successfully with the multiple contractors and interests involved in these efforts. Please refer to the paper by Sage and Biemer (2007) and DeLaurentis et al. (2007) for the creation of a SoS Consortium (i.e., International Consortium on System of Systems (ICSoS)) of concerned individuals and organizations by the author of this chapter. Chapter 3 by Wells and Sage discusses the challenges of engineering of SoS.

1.3.1.3 Standards of SoS System of systems literature, definitions, and perspectives are marked with great variability in the engineering community. Viewed as an extension of systems engineering to a means of describing and managing social networks and organizations, the variations of perspectives lead to difficulty in advancing and understanding the discipline. Standards have been used to facilitate a common understanding and approach to align disparities of perspectives to drive a uniform agreement to definitions and approaches. By having the ICSoS (DeLaurentis et al., 2007) represent to the IEEE and INCoSE for support of technical committees to derive standards for system of systems will help unify and advance the discipline for engineering, healthcare, banking, space exploration, and all other disciplines that require interoperability among disparate systems.

1.3.1.4 System of Systems Architecting Dagli and Kilicay-Ergin in Chapter 4 provide a framework for SoS architectures. As the world is moving toward a networked society, the authors assert the business and government applications require integrated systems that exhibit intelligent behavior. The dynamically changing environmental and operational conditions necessitate a need for system architectures that will be effective for the duration of the mission but evolve to new system architectures as the mission changes. This new challenging demand has led to a new operational style: instead of designing or subcontracting systems from scratch, business or government gets the best systems the industry develops and focuses on becoming the lead system integrator to provide SoS. SoS is a set of interdependent systems that are related or connected to provide a common mission. In the SoS environment, architectural constraints imposed by existing systems have a major effect on the system capabilities, requirements, and behavior. This fact is important, as it complicates the systems architecting activities. Hence, architecture becomes a dominating but confusing concept in capability development. There is a need to push system architecting research to meet the challenges imposed by new demands of the SoS environment. This chapter focuses on system of systems architecting in terms of creating meta-architectures from collections of different systems. Several examples are provided to clarify system of systems architecting concept. Since the technology base, organizational needs, and human needs are changing, the system of systems architecting becomes an evolutionary process. Components and functions are added, removed, and modified as owners of the SoS experience and use the system. Therefore, in Chapter 4 evolutionary system architecting is described and the challenges are identified for this process. Finally, the authors discuss the possible use of artificial life tools for the design and architecting of SoS. Artificial life tools such as swarm intelligence, evolutionary computation, and multiagent systems have been successfully used for the analysis of complex adaptive systems. The potential use of these tools for SoS analysis and architecting is discussed, by the authors, using several domain application specific examples.

1.3.1.5 SoS Simulation Sahin et al. (2007) have presented an SoS architecture based on Extensible Markup Language (XML) in order to wrap data coming from different systems in a common way. The XML can be used to describe each component of the SoS and their data in a unifying way. If XML-based data architecture is used in an SoS, the only requirement for the SoS components is to understand/parse XML file received from the components of the SoS. In XML, data can be represented in addition to the properties of the data such as source name, data type, importance of the data, and so on. Thus, it does not only represent data but also gives useful information that can be used in the SoS to take better actions and to understand the situation better. The XML language has a hierarchical structure where an environment can be described with a standard and without a huge overhead. Each entity can be defined by the user in the XML in terms of its visualization and functionality. As a case study in this effort (see Chapter 5 by Mittal et al.), a master-scout rover combination represents an SoS where for the first time a sensor detects a fire in a field. The fire is detected by the master rover and commands the scout rover to verify the existence of the fire. It is important to note that such an architecture and simulation do not need any mathematical model for members of the systems.

1.3.1.6 SoS Integration Integration is probably the key viability of any SoS. Integration of SoS implies that each system can communicate and interact (control) with the SoS regardless of their hardware, software characteristics, or nature. This means that they need to have the ability to communicate with the SoS or a part of the SoS without compatibility issues such as operating systems, communication hardware, and so on. For this purpose, an SoS needs a common language the SoS's systems can speak. Without having a common language, the systems of any SoS cannot be fully functional and the SoS cannot be adaptive in the sense that new components cannot be integrated to it without major effort. Integration also implies the control aspects of the SoS because systems need to understand each other in order to take commands or signals from other SoS systems. See Chapter 6 by Cloutier et al. on network centric architecture of SoS.

1.3.1.7 Emergence in SoS Emergent behavior of an SoS resembles the slowdown of the traffic going through a tunnel, even in the absence of any lights, obstacles, or accident. A tunnel, automobiles, and the highway, as systems of an SoS, have an emergent behavior or property in slowing down (Morley, 2006). Fisher (2006) has noted that an SoS cannot achieve its goals depends on its emergent behaviors. The author *explores* "interdependencies among systems, emergence, and interoperation" and develops maxim-like findings such as these: (1) Because they cannot control one another, autonomous entities can achieve goals that are not local to themselves only by increasing their influence through cooperative interactions with others. (2) Emergent composition is often poorly understood and sometimes misunderstood because it has few analogies in traditional systems engineering. (3) Even in the absence of accidents, tight coupling can ensure that a system of systems is unable to satisfy its objectives. (4) If it is to remain scalable and affordable no matter how large it may become, a system's cost per constituent must grow less linearly with its size. (5) Delay is a critical aspect of systems of systems. Chapter 7 by Keating will provide a detailed perspective into emergence property of SoS.

1.3.1.8 SoS Management: The Governance of Paradox Sauser and Boardman, in Chapter 8, present an SoS approach to the management problem. They note that the study of SoS has moved many to support their understanding of these systems through the groundbreaking science of networks. The understanding of networks and how to manage them may give one the fingerprint that is independent of the specific systems that exemplify this complexity. The authors point out that it does not matter whether they are studying the synchronized flashing of fireflies, space stations, structure of the human brain, the internet, the flocking of birds, a future combat system, or the behavior of red harvester ants. The same emergent principles apply: large is really small, weak is really strong, significance is really obscure, little means a lot, simple is really complex, and complexity hides simplicity. The conceptual foundation of complexity is paradox, which leads us to a paradigm shift in the SE body of knowledge.

Paradox exists for a reason and there are reasons for systems engineers to appreciate paradox even though they may be unable to resolve them as they would a problem specification into a system solution. Hitherto paradoxes have confronted current logic only to yield at a later date to more refined thinking. The existence of paradox is always the inspirational source for seeking new wisdom, attempting new thought patterns, and ultimately building systems for the “flat world.” It is our ability to govern, not control, these paradoxes that will bring new knowledge to our understanding on how to manage the emerging complex systems called system of systems.

Chapter 8 establishes a foundation in what has been learnt about how one practices project management, establishes some key concepts and challenges that make the management of SoS different from our fundamental practices, presents an intellectual model for how they classify and manage an SoS, appraises this model with recognized SoS, and concludes with grand challenges for how they may move their understanding of SoS management beyond the foundation.

In the previous section, a brief introduction was presented for six theoretical issues of SoS, that is, integration, engineering, standards, open and other architectures, modeling, infrastructure, and simulation. These topics are discussed in great detail by a number of experts in the field in chapters in the book.

1.3.2 Implementation Problems

Besides from many theoretical and essential difficulties with SoS, there are many implementation challenges facing SoS. Here, some of these implementation problems are briefly discussed and references are made to some with their full coverage.

1.3.2.1 Systems Engineering for the Department of Defense System of Systems Dahmann and Baldwin, in Chapter 9, have addressed the national defense aspects of SoS. Military operations are the synchronized efforts of people and systems toward a common objective. In this way from an operational perspective, defense is essentially a “system of systems” enterprise. However, despite the fact that today almost every military system is operated as part of a system of systems, most of these systems were designed and developed without the benefit of systems engineering at the SoS level factoring the role the system will play in the broader system of systems context. With changes in operations and technology, the need for systems that work effectively together is increasingly visible. Chapter 9 outlines the changing situation in the defense department and the challenges it poses for systems engineering.

1.3.2.2 e-Enabling and SoS Aircraft Design Via SoSE A case of aeronautical application of SoS worth noting is that of e-enabling in aircraft design as a system of an SoS at Boeing Commercial Aircraft Division (Wilber, 2007). The project focused on developing a strategy and technical architecture to facilitate making the airplane (Boeing 787, see Fig. 1.1) network-aware and capable of leveraging computing and network advances in industry. The project grew to include many ground-based architectural components at the airlines and at the Boeing factory, as well as other key locations such as the airports, suppliers, and terrestrial Internet Service Suppliers (ISPs).

Wilber (2007) points out that the e-enabled project took on the task of defining a system of systems engineering solution to problem of interoperation and communication with the existing, numerous, and diverse elements that make up the airlines’

FIGURE 1.1 A photo of the new SoS e-enabled Boeing 787 (courtesy of Boeing Company, see also Chapter 10 by G.R. Wilber)

operational systems (flight operations and maintenance operations). The objective has been to find ways of leveraging network-centric operations, to reduce production, operations and maintenance costs for both Boeing and the airline customers.

> One of the key products of this effort is the "e-enabled architecture." The e-enabling architecture is defined at multiple levels of abstraction. There is a single top-level or "reference architecture" that is necessarily abstract and multiple "implementation architectures." The implementation architectures map directly to airplane and airline implementations and provide a family of physical solutions that all exhibit common attributes and are designed to work together and allow re-use of systems components. The implementation architectures allow for effective forward and retrofit installations addressing a wide range of market needs for narrow and wide-body aircraft.
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> The 787 "Open Data Network" is a key element of one implementation of this architecture. It enabled on-board and off-board elements to be networked in a fashion that is efficient, flexible, and secure. The fullest implementations are best depicted in Boeing's GoldCare Architecture and design.

Wilber, in Chapter 10, presents an architecture at the reference level and how it has been mapped into the 787 airplane implementation. *GoldCare* environment is described and is used as an example of the full potential of the current e-enabling.

1.3.2.3 A System of Systems Perspective on Infrastructures Thissen and Herder, in Chapter 11, touch upon a very important application in the service industry (see also Chapter 13 by Tien). Infrastructure systems (or infrasystems) providing services such as energy, transport, communications, and clean and safe water are vital to the functioning of modern society. Key societal challenges with respect to our present and future infrastructure systems relate to, among other things, safety and reliability, affordability, and transitions to sustainability. Infrasystem complexity precludes simple answers to these challenges. While each of the infrasystems can be seen as a complex system of systems in itself, increasing interdependency among these systems (both technologically and institutionally) adds a layer of complexity.

One approach to increased understanding of complex infrasystems that has received little attention in the engineering community thus far is to focus on the commonalities of the different sectors and to develop generic theories and approaches such that lessons from one sector could easily be applied to other sectors. The system of systems paradigm offers interesting perspectives in this respect. The authors present, as an initial step in this direction, a fairly simple three-level model distinguishing the physical/technological systems, the organization and management systems, and the systems and organizations providing infrastructure-related products and services. The authors use the model as a conceptual structure to identify a number of key commonalities and differences between the transport, energy, drinking water, and ICT sectors. Using two energy-related examples, the authors further illustrate some of the system of systems related complexities of analysis and design at a more operational level. The authors finally discuss a number of key research and engineering challenges related to infrastructure systems, with a focus on the potential contributions of systems of systems perspectives.

1.3.2.4 Sensor Networks The main purpose of sensor networks is to utilize the distributed sensing capability provided by tiny, low-powered, and low-cost devices. Multiple sensing devices can be used cooperatively and collaboratively to capture events or monitor space more effectively than a single sensing device (Sridhar et al., 2007). The realm of applications for sensor networks is quite diverse, which include military, aerospace, industrial, commercial, environmental, and health monitoring, to name a few. Applications include traffic monitoring of vehicles, cross-border infiltration detection and assessment, military reconnaissance and surveillance, target tracking, habitat monitoring and structure monitoring, and so on.

Communication capability of these small devices and often with heterogeneous attributes makes them good candidates for system of systems. Numerous issues with sensor networks such as data integrity, data fusion and compression, power consumption, multidecision making, and fault tolerance all make these SoS very challenging just like other SoS. It is thus necessary to devise a fault-tolerant mechanism with a low computation overhead to validate the integrity of the data obtained from the sensors (systems). Moreover, a robust diagnostics and decision-making process should aid in monitoring and control of critical parameters to efficiently manage the operational behavior of a deployed sensor network. Specifically, Chapter 12 by Sridhar et al. will focus on innovative approaches to deal with multivariable multispace problem domain as well as other issues, in wireless sensor networks within the framework of an SoS.

1.3.2.5 A System of Systems View of Services Tien, in Chapter 13, covers a very important applications of SoS in our today's global village — *service industry.* The services sector employs a large and growing proportion of workers in the industrialized nations, and it is increasingly dependent on information technology. While the interdependences, similarities, and complementarities of manufacturing and services are significant, there are considerable differences between goods and services, including the shift in focus from mass production to mass customization (whereby a service is produced and delivered in response to a customer's stated or imputed needs). In general, a service system can be considered to be a combination or recombination of three essential components — people (characterized by behaviors, attitudes, values, etc.), processes (characterized by collaboration, customization, etc.), and products (characterized by software, hardware, infrastructures, etc.). Furthermore, inasmuch as a service system is an integrated system, it is, in essence, a system of systems whose objectives are to enhance its efficiency (leading to greater interdependency), effectiveness (leading to greater usefulness), and adaptiveness (leading to greater responsiveness). The integrative methods include a component's design, interface, and interdependency; a decision's strategic, tactical, and operational orientation; and an organization's data, modelling, and cybernetic consideration. A number of insights are also provided, including an alternative system of systems view of services; the increasing complexity of systems (especially service systems), with all the attendant life cycle design, human interface, and system integration issues; the increasing need for real-time, adaptive decision making within such systems of systems; and the fact that modern systems are also becoming increasingly more human centered, if not human focused — thus, products and services are becoming more complex and more personalized or customized.

1.3.2.6 System of Systems Engineering in Space Exploration Jolly and Muirhead, in Chapter 14, cover SoSE topics that are largely unique for space exploration with the intent to provide the reader a discussion of the key issues, the major challenges of the twenty-first century in moving from systems engineering to SoSE, potential applications in the future, and the current state of the art. Specific emphasis is placed on how software and electronics are revolutionizing the way space missions are being designed, including both the capabilities and vulnerabilities introduced. The role of margins, risk management, and interface control is all critically important in current space mission design and execution, but in SoSE applications they become paramount. Similarly, SoSE space missions will have extremely large, complex, and intertwined command and control and data distribution ground networks, most of which will involve extensive parallel processing to produce tera-to-petabytes of products per day and distribute them worldwide.

1.3.2.7 Communication and Navigation in Space SoS Bhasin and Hayden, in Chapter 15, have taken upon the challenges in communication and navigation for space SoS. They indicate that communication and navigation networks provide critical services in the operation, system management, information transfer, and situation awareness to the space system of systems. In addition, space systems of systems are requiring system interoperability, enhanced reliability, common interfaces, dynamic operations, and autonomy in system management. New approaches to communications and navigation networks are required to enable the interoperability needed to satisfy the complex goals and dynamic operations and activities of the space system of systems. Historically, space systems had direct links to Earth ground communication systems, or they required a space communication satellite infrastructure to achieve higher coverage around the Earth. It is becoming increasingly apparent that many systems of systems may include communication networks that are also systems of systems. These communication and navigation networks must be as nearly ubiquitous as possible and accessible on the demand of the user, much like the cell phone link is available at any time to an Earth user in range of a cell tower. The new demands on communication and navigation networks will be met by space Internet technologies. It is important to bring Internet technologies, Internet Protocols (IP), routers, servers, software, and interfaces to space networks to enable as much autonomous operation of those networks as possible. These technologies provide extensive savings in reduced cost of operations. The more these networks can be made to run themselves, the less humans will have to schedule and control them. The Internet technologies also bring with them a very large repertoire of hardware and software solutions to communication and networking problems that would be very expensive to replicate under a different paradigm. Higher bandwidths are needed to support the expected voice, video, and data transfer traffic for the coordination of activities at each stage of an exploration mission.

Existing communications, navigation, and networking have grown in an independent fashion with experts in each field solving the problem just for that field. Radio engineers designed the payloads for today's "bent pipe" communication satellites. The Global Positioning Satellite (GPS) system design for providing precise Earth location determination is an extrapolation of the Long Range Navigation (LORAN) technique of the 1950s where precise time is correlated to precise position on the Earth. Other space navigation techniques use artifacts in the RF communication path (Doppler shift of the RF and transponder-reflected ranging signals in the RF) and time transfer techniques to determine the location and velocity of a spacecraft within the solar system. Networking in space today is point-to-point among ground terminals and spacecraft, requiring most communication paths to/from space to be scheduled such that communications is available only on an operational plan and is not easily adapted to handle multidirectional communications under dynamic conditions.

Chapter 15 begins with a brief history of the communications, navigation, and networks of the 1960s and 1970s in use by the first system of systems, the NASA Apollo missions; it is followed by short discussions of the communication and navigation networks and architectures that the DoD and NASA employed from the 1980s onward. Next is a synopsis of the emerging space system of systems that will require complex communication and navigation networks to meet their needs. Architecture approaches and processes being developed for communication and navigation networks in emerging space system and systems are also described. Several examples are given of the products generated in using the architecture development process for space exploration systems. The architecture addresses the capabilities to enable voice, video, and data interoperability needed among the explorers during exploration, while in habitat, and with Earth operations. Advanced technologies are then described that will allow space system of systems to operate autonomously or semiautonomously. Chapter 15 ends with a summary of the challenges and issues raised in implementing these new concepts.

1.3.2.8 Electric Power Systems Grids as SoS Hiskens and Korba, in Chapter 16, provide an overview of the systems of systems that are fundamental to the operation and control of electrical power systems. Perspectives are drawn from industry and academia, and reflect theoretical and practical challenges that are facing power systems in an era of energy markets and increasing utilization of renewable energy resources (see also Chapter 17 by Duffy et al.). Power systems cover extensive geographical regions and are composed of many diverse components. Accordingly, power systems are large-scale, complex, dynamical systems that must operate reliably to supply electrical energy to customers. Stable operation is achieved through extensive monitoring systems and a hierarchy of controls that together seek to ensure total generation matches consumption and voltages remain at acceptable levels. Safety margins play an important role in ensuring reliability, but tend to incur economic penalties. Significant effort is therefore being devoted to the development of demanding control and supervision strategies that enable reduction of these safety margins, with consequent improvements in transfer limits and profitability. Recent academic and industrial research in this field will also be addressed in Chapter 16.

1.3.2.9 SoS Approach for Renewable Energy Duffy et al., in Chapter 17, have provided the SoS approach to sustainable supply of energy. They note that over one half of the petroleum consumed in the United States is imported, and that percentage is expected to rise to 60% by 2025. America's transportation system of systems relies almost exclusively on refined petroleum products, accounting for over two thirds of the oil used. Each day, over 8 million barrels of oil are required to fuel over 225 million vehicles that constitute the United States light-duty transportation fleet. The gap between the United States oil production and transportation oil needs is projected to grow, and the increase in the number of light-duty vehicles will account for most of that growth. On a global scale, petroleum supplies will be in increasingly higher demand as highly populated developing countries expand their economies and become more energy intensive. Clean forms of energy are needed to support sustainable global economic growth while mitigating impacts on air quality and the potential effects of greenhouse gas emissions. Growing dependence of the united states on foreign sources of energy threatens her national security. As a nation, the authors assert that we must work to reduce our dependence on foreign sources of energy in a manner that is affordable and preserves environmental quality.

1.3.2.10 Sustainable Environmental Management from a System of Systems Engineering Perspective Hipel et al., in Chapter 18, provide a rich range of decision tools from the field of SE that are described for addressing complex environmental SoS problems in order to obtain sustainable, fair, and responsible solutions to satisfy as much as possible the value systems of stakeholders, including the natural environment and future generations who are not even present at the bargaining table. To better understand the environmental problem being investigated and thereby eventually reach more informed decisions, the insightful paradigm of a system of systems can be readily utilized. For example, when developing solutions to global warming problems, one can envision how societal systems, such as agricultural and industrial systems, interact with the atmospheric system of systems, especially at the tropospheric level. The great import of developing a comprehensive toolbox of decision methodologies and techniques is emphasized by pointing out many current pressing environmental issues, such as global warming and its potential adverse affects, and the widespread pollution of our land, water, and air systems of systems. To tackle these large-scale complex systems of systems problems, systems engineering decision techniques that can take into account multiple stakeholders having multiple objectives are explained according to their design and capabilities. To illustrate how systems decision tools can be employed in practice to assist in reaching better decisions for benefiting society, different decision tools are applied to three real-world systems of systems environmental problems. Specifically, the Graph Model for Conflict Resolution is applied to the international dispute over the utilization of water in the Aral Sea Basin; a large-scale optimization model founded upon concepts from cooperative game theory, economics, and hydrology is utilized for systematically investigating the fair allocation of scarce water resources among multiple users in the South Saskatchewan River Basin in Western Canada; and multiple criteria decision analysis methods are used to evaluate and compare solutions to handling fluctuating water levels in the five Great Lakes located along the border of Canada and the United States (Wang et al., 2007).

1.3.2.11 Robotic Swarms as an SoS As another application of SoS, a robotic swarm is considered by Sahin in Chapter 19. Here a robotic swarm based on ant colony optimization and artificial immune systems is considered. In the ant colony optimization, the author has developed a multiagent system model based on the food gathering behaviors of the ants. Similarly, a multiagent system model is developed based on the human immune system. These multiagent system models, are then tested on the mine detection problem. A modular microrobot is designed to perform to emulate the mine detection problem in a basketball court. The software and hardware components of the modular robot are designed to be modular so that robots can be assembled using hot swappable components. An adaptive TDMA communication protocol is developed in order to control connectivity among the swarm robots without the user intervention. Details are given in Chapter 19.

1.3.2.12 Transportation Systems The National Transportation System (NTS) can be viewed as a collection of layered networks composed by heterogeneous systems for which the Air Transportation System (ATS) and its National Airspace System (NAS) is one part. At present, research on each sector of the NTS is generally conducted independently, with infrequent and/or incomplete consideration of scope dimensions (e.g., multimodal impacts and policy, societal, and business enterprise influences) and network interactions (e.g., layered dynamics within a scope category). This isolated treatment does not capture the higher level interactions seen at the NTS or ATS architecture level; thus, modifying the transportation system based on limited observations and analyses may not necessarily have the intended effect or impact. A systematic method for modeling these interactions with a system of systems (SoS) approach is essential to the formation of a more complete model and understanding of the ATS, which would ultimately lead to better outcomes from high-consequence decisions in technological, socioeconomic, operational, and political policy-making context (DeLaurentis, 2005). This is especially vital as decision makers in both the public and the private sector, for example, at the interagency Joint Planning and Development Office (JPDO), which is charged with transformation of air transportation, are facing problems of increasing complexity and uncertainty in attempting to encourage the evolution of superior transportation architectures (DeLaurentis and Callaway, 2006). Chapter 20 by DeLaurentis will be addressing this application.

1.3.2.13 Healthcare Systems Under a 2004 Presidential Order, the U.S. Secretary of Health has initiated the development of a National Healthcare Information Network (NHIN), with the goal of creating a nationwide information system that can build and maintain Electronic Health Records (EHRs) for all citizens by 2014. The NHIN system architecture currently under development will provide a near-real-time heterogeneous integration of disaggregated hospital, departmental, and physician patient care data and will assemble and present a complete current EHR to any physician or hospital a patient consults (Sloane, 2006). The NHIN will rely on a network of independent Regional Healthcare Information Organizations (RHIOs) that are being developed and deployed to transform and communicate data from the hundreds of thousands of legacy medical information systems presently used in hospital departments, physician offices, and telemedicine sites into NHIN-specified metaformats that can be securely relayed and reliably interpreted anywhere in the country. The NHIN "network of networks" will clearly be a very complex SoS, and the performance of the NHIN and RHIOs will directly affect the safety, efficacy, and efficiency of healthcare in the United States. Simulation, modeling, and other appropriate SoSE tools are under development to help ensure reliable, cost-effective planning, configuration, deployment, and management of the heterogeneous, life-critical NHIN and RHIO systems and subsystems (Sloane et al., 2007). ICSoS represents an invaluable opportunity to access and leverage SoSE expertise already under development in other industry and academic sectors. ICSoS also represents an opportunity to discuss the positive and negative emergent behaviors that can significantly affect personal and public health status and the costs of healthcare in the United States (DeLaurentis et al., 2007). See Chapter 21 by Chalasani et al.

1.3.2.14 Global Earth Observation System of Systems GEOSS is a global project consisting of over 60 nations whose purpose is to address the need for timely, quality, long-term, global information as a basis for sound decision making (Butterfield et al., 2006). Its objectives are: (i) improved coordination of strategies and systems for Earth observations to achieve a comprehensive, coordinated, and sustained Earth observation system or systems; (ii) a coordinated effort to involve and assist developing countries in improving and sustaining their contributions to observing systems, their effective utilization of observations, and the related technologies; and (iii) the exchange of observations recorded from *in situ*, air full and open manner with minimum time delay and cost. In GEOSS, the "SoSE process provides a complete, detailed, and systematic development approach for engineering systems of systems

Boeing's new architecture-centric, model-based systems engineering process emphasizes concurrent development of the system architecture model and system specifications. The process is applicable to all phases of a system's life cycle. The SoSE process is a unified approach for system architecture development that integrates the views of each of a program's participating engineering disciplines into a single system architecture model supporting civil and military domain applications" (Pearlman, 2006). ICSoS will be another platform for all concerned around the globe to bring the progress and principles of GEOSS to formal discussions and examination on an annual basis. Chapter 22 by Shibasaki and Pearlman will be addressing GEOSS application. Figure 1.2 shows a number of systems in GEOSS .

1.3.2.15 Deepwater Coastguard Program One of the earliest realization of an SoS in the United States is the so-called Deepwater Coastguard Program shown in Fig. 1.3. As seen here, the program takes advantage of all the necessary assets at their disposal, for example, helicopters, aircrafts, cutters, satellite (GPS), ground station, human, computers, and so on — all systems of the SoS integrated together to react to unforeseen circumstances to secure the coastal borders of the southeastern United States, for example, Florida Coast. The Deepwater program is making progress in the development and delivery of mission effective command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) equipment (Keeter, 2007). The SoS approach, the report goes on, has "improved the operational capabilities of legacy cutters and aircraft, and will provide even more functionality when the next generation of surface and air platforms arrives in service." The key

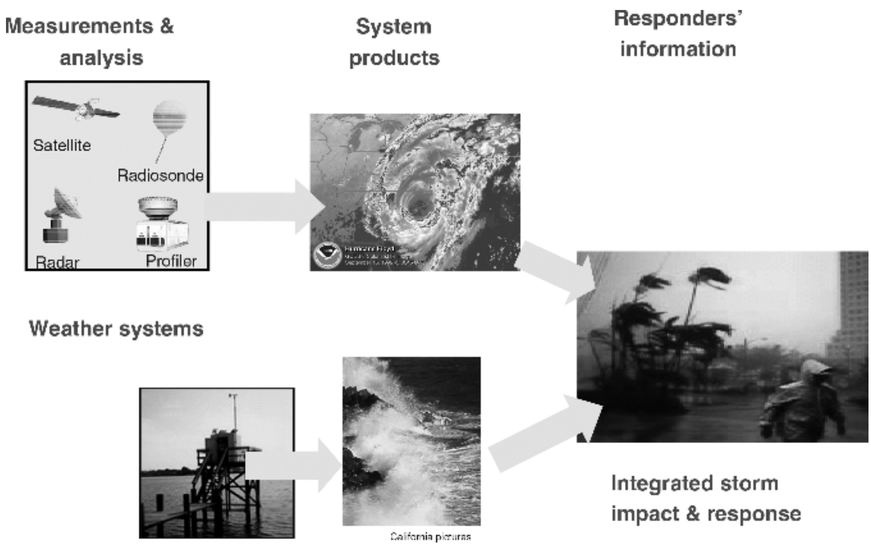

FIGURE 1.2 SoS of the GEOSS project (courtesy, Jay Pearlman, Boeing Company, see also Chapter 22 by Shibasaki and Pearlman)

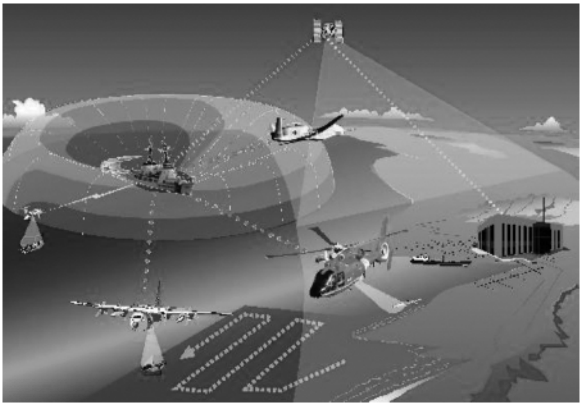

FIGURE 1.3 A security example of an SoS — deepwater coastguard configuration in United States

feature of the system is its ability to interoperate among all Coast Guard mission assets and capabilities with those of appropriate authorities at both local and federal levels.

1.3.2.16 Future Combat Missions Another national security or defense application of SoS is the future combat mission (FCM). Figure 1.4 shows one of the numerous possible configurations of an FCM. The FCM system is "envisioned to be an ensemble of manned and potentially unmanned combat systems, designed to ensure that the future force is strategically responsive and dominant at every point on the spectrum of operations from nonlethal to full-scale conflict. FCM will provide a rapidly deployable capability for mounted tactical operations by conducting direct combat, delivering both line-of-sight and beyond-line-of-sight precision munitions, providing variable lethal effect (nonlethal to lethal), performing reconnaissance, and

FIGURE 1.4 A defense example of a SoS (courtesy, Don Walker, Aerospace Corporation)

transporting troops. Significant capability enhancements will be achieved by developing multifunctional, multimission, and modular features for system and component commonality that will allow for multiple state-of-the-art technology options for mission tailoring and performance enhancements. The FCM force will incorporate and exploit information dominance to develop a common, relevant operating picture and achieve battle space situational understanding" (Global Security Organization, 2007). See also Chapter 9 by Dahmann and Baldwin for insights in this and other defense applications.

1.3.2.17 National Security Perhaps one of the most talked-about application areas of SoSE is national security. After many years of discussion of the goals, merits, and attributes of SoS, very few tangible results or solutions have appeared in this or other areas of this technology. It is commonly believed that "systems engineering tools, methods, and processes are becoming inadequate to perform the tasks needed to realize the systems of systems envisioned for future human endeavors. This is especially becoming evident in evolving national security capabilities realizations for large-scale, complex space, and terrestrial military endeavors. Therefore, the development of systems of systems engineering tools, methods, and processes is imperative to enable the realization of future national security capabilities" (Walker, 2007). In most SoSE applications, heterogeneous systems (or communities) are brought together to cooperate for a common good and enhanced robustness and performance. "These communities range in focus from architectures, to lasers, to complex systems, and will eventually cover each area involved in aerospace-related national security endeavors. These communities are not developed in isolation in that cross-community interactions on terminology, methods, and processes are done" (Walker, 2007). The key is to have these communities work together to guarantee the common goal of making our world a safer place for all. See Chapter 9 by Dahmann and Baldwin for insights in this and other security applications.

1.3.2.18 Critical Infrastructure and Air Transportation Security Air transportation networks consist of concourses, runways, parking, airlines, cargo terminal operators, fuel depots, retail, cleaning, catering, and many interacting people including travelers, service providers, and visitors. The facilities are distributed and fall under multiple legal jurisdictions in regard to occupational health and safety, customs, quarantine, and security.

Currently decision making in this domain space is focused on individual systems. The challenge of delivering improved nationwide air transportation security, while maintaining performance and continuing growth, demands a new approach. In addition, information flow and data management are a critical issue, where trust plays a key role in defining interactions of organizations.

SoS methodologies are required to rapidly model, analyze, and optimize air transportation systems (Nahavandi, 2007). In any critical real-world system there is and must be a compromise between increased risk and increased flexibility and productivity. By approaching such problem spaces from an SoS perspective the authors are in the best position to find the right balance (DeLaurentis et al., 2007).

1.4 CONCLUSIONS

This chapter is written to serve as an introduction to the book. The subject matter of this book is an unsettled topic in engineering in general and in systems engineering in particular. Attempt has been made to cover as many open questions in both theory and applications of SoS and SoSE. It is our intention that this book would be the beginning of much debate and challenges among and by the readers of this book. The book is equally intended to benefit industry, academia, or government. A sister volume, by the author, on the subject is under press at the present time and can give readers further insight into SoS (Jamshidi, 2008).

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