Part II

Systems Engineering

Chapter 6

Introduction to Systems Engineering

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> Science determines what IS ... Component engineering determines what CAN BE ... Systems engineering determines what SHOULD BE and Engineering managers determine what WILL BE.
>
> —Modified from Arunski et al. [1]

6.1 INTRODUCTION

This chapter introduces systems engineering. We begin by reviewing our definition of a system. We provide a brief history of the relatively new discipline of systems engineering. Then we identify the major trends in systems that provide challenges for systems engineers. Next, we review our definition of systems engineering and use it to identify the three fundamental tasks of systems engineers. Then we discuss the relationship of systems engineers to other engineering disciplines. Finally, we conclude with discussion of the education and training of systems engineers.

6.2 DEFINITION OF SYSTEM AND SYSTEMS THINKING

Understanding systems and using systems thinking are foundational for systems engineering. Recall our definitions of systems and systems thinking from Chapter 1.

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A system is “an integrated set of elements that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements” [2].

Systems thinking is a holistic mental framework and world view that recognizes a system as an entity first, as a whole, with its fit and relationship with its environment being primary concerns.

6.3 BRIEF HISTORY OF SYSTEMS ENGINEERING

Systems engineering is a relatively new discipline. Of course, people have engineered large, complex systems since the Egyptians built the pyramids, Romans built their aqueducts, and fifteenth-century sea captains prepared their sailing ships to go around the world. However, until about a hundred years ago, system integration was generally in the hands of a craft specialist with a lifetime of experience in his craft, working mainly from a huge store of painfully learned rules of thumb. The need for disciplined and multidisciplinary engineering at the systems level was first widely recognized in the telephone industry in the 1920s and 1930s, where the approach became fairly common. Systems thinking and mathematical modeling got a further boost during World War II with the success of operations research, which used the scientific method and mathematical modeling to improve military operations. After the war, the military services discovered that systems engineering was essential to developing the complex weapon systems of the computer and missile age. The private sector followed this lead, using systems engineering for such projects as commercial aircraft, nuclear power plants, and petroleum refineries. The first book on systems engineering was published in 1957 [3]; and by the 1960s, degree programs in the discipline became widely available. The professional organization for systems engineers, now known as the International Council on Systems Engineering (INCOSE) [4], was founded in 1990.

The INCOSE mission is to enhance the state-of-the-art and practice of systems engineering in industry, academia, and government by promoting interdisciplinary, scalable approaches to produce technologically appropriate solutions to meet societal needs [4].

6.4 SYSTEMS TRENDS THAT CHALLENGE SYSTEMS ENGINEERS

There are several important systems trends that create significant systems engineering challenges. First, systems have become increasingly more complex, more dynamic, and more interconnected, involve more stakeholders than in the past, and face increasing security, and privacy challenges.

Increasing Complexity. Systems are more complex. Today's systems involve many science and engineering disciplines. New technologies (including information, biotechnology, and nanotechnology) create new opportunities and challenges. Interfaces are increasingly more complex and system integration is more difficult. To emphasize this complexity new terms have been used; for example, systems of systems, system architectures, and enterprise systems.

More Dynamic. Systems interact with their environment and the needs of stakeholders evolve in concert with this interaction. Rapid changes in the environment require systems to be dynamic to continue to provide value to consumers of products and services.

Increasing Interconnectedness. The Internet and advances in information technology have led to business-to-business collaboration and a global economy enabled by pervasive interconnectedness. Anyone can start a global business by establishing a website. We now have an international supply chain for electronic components; and, increasingly, hardware development, software development, component production, and services are being done globally.

Many Stakeholders. The increasing complexity and interconnectedness contribute to the increase in the number of stakeholders involved in the system life cycle. In addition to considering the perspectives of scientists, engineers, and engineering managers, system engineers must consider the perspectives of functional managers (production, sales, marketing, finance, etc.), regulators, professional organizations, legal, environmentalists, government, community groups, and international groups to name just a few of the many stakeholders with vested interests in the system.

Increasing Security Concerns. Many systems face increasing security challenges due to threats from malicious adversaries ranging from hackers to terrorists. Information assurance, which is the activity of protecting data and its flow across communication networks, is a major concern of system developers and users. In a similar fashion, physical security is an important design criteria for many systems as well.

Increasing Privacy Concerns. As systems become more complex, more interconnected, and face more security challenges the potential for privacy violations increases. The protection of personal information in systems is now a major system challenge.

Complexity is a challenging concept when it comes to systems decision problems. Table 6.1 illustrates a modified and expanded spectrum of complexity for low, medium, and high complexity problems across 10 problem dimensions of systems decision problems based on the complexity research of Clemens [5]. The third category, called a "Wicked Problem," is a recently characterized phenomenon typifying a growing number of systems in existence today. These descriptions are particularly helpful for the Problem Definition phase of the SDP during which the systems

TABLE 6.1 Dimensions of Problem Complexity [6]

Problem Dimension	Low (Technical Problem)	Medium (Complex Problem)	High (Wicked Problem)
Boundary	Isolated, defined	Interconnected, defined	No defined boundary
Type	Similar to solved problems	Several unique features and new constraints will occur over time	Unique or unprecedented
Stakeholders	Few homogeneous stakeholders	Multiple with different and/or conflicting views and interests	Hostile or alienated stakeholders with mutually exclusive interests
Challenges	Technology application and natural environment requirements	New technology development, natural environment, adaptive adversaries	No known technology, hostile natural environment, constant threats
Parameters	Stable and predictable	Parameter prediction difficult or unknown	Unstable or unpredictable
Use of Experiments	Multiple low-risk experiments possible	Modeling and simulation can be used to perform experiments	Multiple experiments not possible
Alternative Solutions	Limited set	Large number are possible	No bounded set
Solutions	Single optimal and testable solution	Good solutions can be identified and evaluated objectively and subjectively	No optimal or objectively testable solution
Resources	Reasonable and predictable	Large and dynamic	Not sustainable within existing constraints
End State	Optimal solution clearly defined	Good solutions can be implemented but additional needs arise from dynamic needs	No clear stopping point

team is dedicated to identifying the structure, characteristics, and challenges of the system under study.

Second, the risks associated with systems have increased dramatically. As systems become more complex, dynamic, and interconnected and face security challenges from determined adversaries, the consequences of system failures increase dramatically. System failures can become system catastrophes. Examples of system catastrophes include the Exxon Valdez oil spills, the terrorist attacks on 11 September 2001, the loss of the Challenger space shuttle, the loss of the Columbia space shuttle, Hurricane Katrina the financial crisis that began in 2007, and the British Petroleum (BP) Gulf oil spill of 2010. These catastrophic events have resulted in significant direct and indirect consequences including loss of life, economic, social, environmental, and political consequences, precisely the type of events that the risk management approach introduced in Chapter 3 is intended to address. Each of these events fall into at least one of the risk categories identified: environmental risk (hurricanes), technical risk (space shuttles), operational risk (deep water oil drilling), organizational risk (space shuttles), and systemic risk (financial crisis of 2007).

6.5 THREE FUNDAMENTAL TASKS OF SYSTEMS ENGINEERS

In Part I, we identified the need for systems thinking and introduced a host of tools for applying systems thinking to systems decision problems. All participants in the system life cycle should use systems thinking. However, systems engineers are the primary system thinkers. We define systems engineering using the INCOSE definition [2]:

> Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

From this definition, we can derive the three most fundamental tasks of systems engineers and the key questions that systems engineers must answer for each task.

Task 1: Use an interdisciplinary systems thinking approach to consider the complete problem in every systems decision in every stage of the system life cycle.

The problems change in each stage of the life cycle. The initial problem statement from one decision maker or stakeholder is never the total problem. In each stage, an interdisciplinary approach to systems thinking and problem definition is required by the system trends described in the previous section.

As they perform the first fundamental task, they must answer the following key questions modified from [7]:

- What is the system under consideration?
- What is the system boundary?
- What is the actual problem we are trying to solve?
- Who are the decision makers and stakeholders?
- What are the influencing factors and constraints of the system environment?
- How will we know when we have adequately defined the problem?
- What value can the system provide to decision makers and stakeholders including clients, system owners, system users, and consumers of products and services?
- How much time do we have to solve the problem?

Chapter 10 describes the first phase in our systems decision process (SDP), including some useful techniques for problem definition based on research and stakeholder analysis.

Task 2: Convert customer needs to system functions, requirements, and performance measures.

The opening quote of this chapter clearly defined the difference between scientists, component (discipline) engineers, systems engineers, and engineering managers. Systems engineers determine what should be. One of the most surprising facts of systems engineering is that it is not always easy to identify the future users or consumers of the system that will be designed as a solution to a problem. Many times the organization funding the system is not the user or the consumer of the product or service. This is especially true when the users do not directly pay for the service or product the system provides. This happens in many government systems engineering efforts. Working with customers and users to determine the functions that the system must perform is a daunting task when dealing with complex, dynamic, interdependent systems involving many stakeholders and facing significant security and privacy challenges. Once the functions have been determined, the system requirements must be specified and assigned to system elements (components) so the component engineers can begin design.

The following are some of the key questions for this task:

- Who are the stakeholders (clients, system owners, system users, and consumers of product and services) holding a vested interest in the system?
- What is our methodology for implementing the systems engineering process to define system functions and requirements?
- How do we involve decision makers and stakeholders in our systems engineering process?
- What are the functions the system needs to perform to create value for stakeholders?
- What are the design objectives for each function?
- How will we measure the ability of a design solution to meet the design objectives?
- What are the requirements for each function?
- How will we allocate system functions to system elements?
- How, when, and why do system elements interact?
- What are the design, operational, and maintenance constraints?
- How will we verify that elements meet their requirements and interfaces?

Chapter 10 describes the tasks and some useful techniques for functional and requirements analyses and value modeling. The screening criteria (the requirements that any potential solution must be able to meet) and the value model (which defines the minimum acceptable levels on each value measures) define the major system requirements.

Task 3: Lead the requirements analysis, design synthesis, and system validation to achieve successful system realization.

After identifying system functions, requirements, and performance measures, the systems engineer must lead the requirements analysis and design synthesis and validate that the design solution solves the defined problem. The basis for system design and validation is usually an iterative sequence of functional and requirements analyses modeling, simulation, development, test, production, and evaluation. For complex systems, a spiral development approach may be used to develop system prototypes with increasing capabilities until the system requirements and feasibility are established. Once the system design is validated, the systems engineer must continue to work on the successful system realization.

One of the most essential systems engineering tasks is to lead the resolution of requirements, configuration control, design integration, interface management, and test issues that will occur during the life cycle stages. The chief (or lead) systems engineer creates a technical environment that encourages the early identification, multidisciplinary assessment, creative solution development, timely decision making, and integrated resolution of engineering issues. To achieve the value the system was designed to obtain, the following are some of the key questions for this task:

- How will we know when we have adequately solved the problem?
- How do we ensure that the design will meet the requirements?
- How do we resolve conflicting requirements, interfaces or design issues?
- How can we allocate system performance to system elements?
- How can we identify and validate component and system interfaces?
- Can we trade off one performance measure versus another measure?
- How will we verify that system performance has been achieved?
- How do we identify, assess, and manage risk during the system life cycle?
- How do we trade off system performance with life cycle cost to ensure affordability?

Several chapters of this book provide information on performance measurement:

- Chapters 4 and 8 provide mathematical techniques for modeling system performance and system suitability.
- Cost is almost always a critical systems performance measure. Chapter 5 provides techniques for life cycle costing.
- Chapter 10 describes the multiple objective decision analysis value model that identifies the value measures (often system performance measures) for the objectives of each system function. The value model captures the value added for each increment of the range of the value measures. It also captures the relative importance of the value measure range to the system design.
- Chapter 4 describes modeling and simulation techniques to assess system performance, screen alternatives, and enhance candidate solutions.

- Chapter 12 describes the use of multiple objective decision analysis to assess the value of candidate solutions, improve the value of candidate solutions with Value-Focused Thinking (Chapter 9), and perform tradeoff analysis among value measures and between system value and system cost.

Systems thinking is critical to each of the three fundamental systems engineering tasks. Systems engineer must help everyone think about the problem and the solution that is being designed for the problem. Systems engineers must continue to be the consumer and user advocates as they help convert owner, user, and consumer needs to systems functions, requirements, and value measures. In addition, they must define, validate, and test the element interfaces. These three fundamental tasks are made more challenging by the increasing system complexity, dynamic changes, interconnectedness, number of stakeholders, and increasing security and privacy concerns.

6.6 RELATIONSHIP OF SYSTEMS ENGINEERS TO OTHER ENGINEERING DISCIPLINES

As noted in our opening quote of this chapter, systems engineering is not the only engineering discipline involved in the system life cycle. Section 1.6, Table 1.1 provides a comparison of systems engineering and other engineering disciplines' views on several dimensions. Scientists play a critical role by developing the fundamental theory that supports each of the engineering disciplines. Component (or discipline) engineers develop the technology that determines what can be. By performing the tasks described above, systems engineers determine what should be. Finally, engineering managers determine what will be. The manager approves all the products developed by the systems engineers and obtains the organizational approvals and resources to design, produce, and operate the system.

Systems engineers help provide design synthesis. To do this job, they need to understand the system component engineering disciplines, work effectively with their engineering colleagues, and know when to bring interdisciplinary teams together to solve requirement, design, test, or operational problems.

6.7 EDUCATION, TRAINING, AND KNOWLEDGE OF SYSTEMS ENGINEERS

The education and training of systems engineers includes undergraduate, graduate, and continuing education, and certification programs. Most of these education programs introduce and reinforce the systems thinking and systems engineering tools needed to prepare systems engineers for work throughout the system life cycle of modern systems. Training programs are sometimes tailored to a stage in the system life cycle and the roles of the systems engineer in that stage.

Since it is a relatively new discipline, systems engineering programs are still being developed at several colleges and universities. Systems engineering programs are accredited by ABET Inc., which accredits all engineering disciplines [8]. INCOSE is currently working with ABET to become the professional society to establish systems engineering centric accrediting standards for systems engineering programs [8]. In addition to undergraduate systems engineering degree programs, several universities offer masters and Ph.D. programs in systems engineering. These programs have different names. Some of the common names are systems engineering, industrial and systems engineering, and information and systems engineering. A list of these programs can be found at [9]. Many engineers, including the editors, have undergraduate degrees in another engineering discipline before obtaining a graduate degree in systems engineering.

There are also several systems engineering continuing education programs offered. INCOSE established a systems engineering certification program in 2004 which has continued to expand [10].

As an evolving and growing field, systems engineering knowledge is available from many sources including textbooks and technical books. Specific series have been established by various publishers to highlight a select offering of references considered foundational to understanding the principles and practices of systems engineering. Two examples are the Wiley Series in Systems Engineering and Management [11] and the CRC Press Complex and Enterprise Systems Engineering series [12]. For a broader list of systems engineering books, readers can refer to Wikipedia. A second source of useful reference material is contained in primers, handbooks, and bodies of knowledge. INCOSE versions of these type of reference materials are available on their website. A third source of systems engineering knowledge is found in published standards. And in this, INCOSE committees continue to work to develop and improve worldwide SE standards [13].

6.7.1 Next Two Chapters

This completes our brief introduction to systems engineering. The next two chapters provide more information on roles and tools of systems engineers. Chapter 7 discusses systems engineering in professional practice. Key topics include the roles of systems engineering, the tasks and responsibilities of systems engineers in each stage of the system life cycle, and how they relate to other professionals in the system life cycle. Two of the key responsibilities of systems engineers are to assess system effectiveness and system risk. Chapter 8 discusses analysis techniques used by systems engineers to model systems effectiveness and systems suitability. Key topics include reliability modeling, maintenance modeling, and availability modeling.

6.8 EXERCISES

6.1. Write a simple one sentence definition of systems engineering that you can use to define your major and/or department to family and friends.

6.2. Who were the first system engineers? What were the factors that caused the discipline of systems engineering to be established?

6.3. What is the name of the professional society for systems engineering? Visit the website and find the purpose of the society. What resources are available on the website that might be useful to you in your academic program or professional career?

6.4. List and describe some system trends that create challenges for systems engineers. Illustrate each of these trends using the events of 9/11.

6.5. List and describe the three fundamental tasks of systems engineers.

6.6. Explain why an interdisciplinary approach is needed for systems engineering.

6.7. Explain why system performance measurement is important. Who develops performance measures and what are they used for? List three system performance measures for an automobile.

6.8. What is the difference between a system function and a system requirement? How are the functions and requirements identified for a new system? What is the role of the systems engineer?

6.9. What is the difference among the following three programs: an undergraduate systems engineer, a graduate systems engineer, and a systems engineering certification program?

6.10. Find an ABET accredited undergraduate systems engineering program at another college or university. How does their program compare to your program? What are the similarities and differences?

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