
SYSTEMS ENGINEERING AND THE WORLD OF MODERN SYSTEMS

1.1 WHAT IS SYSTEMS ENGINEERING?

There are many ways in which to define systems engineering. We will use the following definition:

The function of systems engineering is to **guide** the **engineering and development** of **complex systems**.

To **guide** is defined as “to lead, manage, or direct, usually based on the superior experience in pursuing a given course” and “to show the way.” This characterization emphasizes the process of selecting the path for others to follow from among many possible courses – a primary function of systems engineering. A dictionary definition of **engineering** is “the application of scientific principles to practical ends; as the design, construction and operation of efficient and economical structures, equipment, and systems.” In this definition, the terms “efficient” and “economical” are particular contributions of good systems engineering. “Development” includes the identification, coordination, and management of diverse field of expertise in many domain applications.

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The word “system,” as is the case with most common English words, has a very broad meaning. A frequently used definition of a system is “**a set of interrelated components working together** toward some **common** objective.” This definition implies a multiplicity of interacting parts that collectively perform a significant function. The term **complex** restricts this definition to systems in which the elements are diverse and have intricate relationships with one another. Thus, a home appliance such as a washing machine would not be considered sufficiently diverse and complex to require systems engineering, even though it may have some modern automated attachments. On the other hand, the context of an **engineered** system excludes such complex systems as living organisms and ecosystems. The restriction of the term “system” to one that is **complex and engineered** makes it more clearly applicable to the function of systems engineering as it is commonly understood.

The above definitions of “systems engineering” and “system” are not represented as being unique or superior to those used in other textbooks, each of which defines them somewhat differently. In order to avoid any potential misunderstanding, the meaning of these terms **as used in this book** is defined at the very outset, before going on to the more important subjects of the responsibilities, problems, activities, and tools of systems engineering.

Systems Engineering and Traditional Engineering Disciplines

From the above definition, it can be seen that systems engineering differs from mechanical, electrical, and other engineering disciplines in several important ways.

1. Systems engineering is focused on the system as a whole; it emphasizes its total operation. It looks at the system from the outside, that is, at its interactions with other systems and the environment, as well as from the inside. It is concerned not only with the engineering design of the system but also with external factors, which can significantly constrain the design. These include the identification of customer needs, the system operational environment, interfacing systems, logistic support requirements, the capabilities of operating personnel, and such other factors as must be correctly reflected in system requirements documents and accommodated in the system design.
2. While the primary purpose of systems engineering is to **guide**, this does not mean that systems engineers do not themselves play a key role in system design. On the contrary, they are responsible for leading the formative (Concept Development) stage of a new system development, which culminates in the functional design of the system reflecting the needs of the user. Important design decisions at this stage cannot be based entirely on quantitative knowledge, as they are for the traditional engineering disciplines, but rather must often rely on qualitative judgments balancing a variety of incommensurate quantities and utilizing experience in a variety of disciplines, especially when dealing with new technology.
3. Systems engineering **bridges** the traditional engineering disciplines. The diversity of the elements in a complex system requires different engineering disciplines to

be involved in their design and development. For the system to perform correctly, each system element must function properly in combination with one or more other system elements. Implementation of these interrelated functions is dependent on a complex set of physical and functional interactions between separately designed elements. Thus, the various elements cannot be engineered independently of one another and then simply assembled to produce a working system. Rather, systems engineers must guide and coordinate the design of each individual element as necessary to assure that the interactions and interfaces between system elements are compatible and mutually supporting. Such coordination is especially important when individual system elements are designed, tested, and supplied by different organizations.

Systems Engineering and Project Management

The engineering of a new complex system usually begins with an exploratory stage in which a new system concept is evolved to meet a recognized need or exploit a technological opportunity. When the decision is made to engineer the new concept into an operational system, the resulting effort is inherently a major enterprise, which typically requires many people, with diverse skills, to devote years of effort to bring the system from concept to operational use.

The magnitude and complexity of the effort to engineer a new system requires a dedicated team to lead and coordinate its execution. Such an enterprise is called a “project” and is directed by a project manager aided by a staff. Systems engineering is an inherent part of project management – the part that is concerned with guiding the engineering effort itself – setting its objectives, guiding its execution, evaluating its results, and prescribing necessary corrective actions to keep it on course. The management of the planning and control aspects of the project fiscal, contractual, and customer relations is supported by systems engineering, but is usually not considered to be part of the systems engineering function. This subject is described in more detail in Chapter 4.

Recognition of the importance of systems engineering by every participant in a system development project is essential for its effective implementation. To accomplish this, it is often useful to formally assign the leader of the systems engineering team to a recognized position of technical responsibility and authority within the project.

1.2 THE SYSTEMS ENGINEERING LANDSCAPE

Systems engineering principles have been practiced at some level since the building of the pyramids and probably before. The recognition of systems engineering as a distinct activity is often associated with the effects of World War II. More generally, the recognition of systems engineering as a unique activity evolved as a necessary corollary to

the rapid growth of technology, and its application to major defense and commercial operations during the second half of the twentieth century.

World War II provided a tremendous spur to the advancement of technology. The development of high-performance aircraft, military radar, the proximity fuse, missiles, and especially the atomic bomb required revolutionary advances in the application of energy, materials, and information. These systems were complex, combining multiple technical disciplines, and their development posed engineering challenges significantly beyond those that had been presented by their more conventional predecessors. Moreover, the compressed development time schedules imposed by wartime imperatives necessitated a level of organization and efficiency that required new approaches in program planning, technical coordination, and engineering management. Systems engineering developed to meet these challenges.

During the late 1900s, defense requirements continued to drive the growth of technology in jet propulsion, control systems, and materials. However, another development, that of solid-state electronics, has had perhaps a more profound effect on technological growth. This to a large extent made possible the “information age,” in which computing, global networks, and communications are extending the power and reach of systems far beyond their previous limits. Particularly significant in this connection is the development of the digital computer and the associated software technology driving it, which increasingly leads to the replacement of human control of systems by automation. Computer control and complex human–computer interfaces are qualitatively increasing the complexity of systems, and is a particularly important concern of systems engineering.

In the current century, processing power and global networks have led to instantaneous transfer of information and hence social concerns and systems security drive continuing developments to expand and protect the ubiquitous presence of digital components and the software associated with them. Systems engineering designs will continue to focus on monitoring, surveillance, and control of autonomous systems interconnected and vulnerable to attack. Sensor technology coupled with miniaturization is producing innovation at an increasing pace, leading to many new products and services.

Future Systems

Global innovation across a wide range of domain applications will continue to drive systems solutions requiring increased collaboration and improved systems tools and dedicated, educated systems engineers. Systems will be more complex, network intensive, autonomous capable, intelligent, adaptable, robust, and secure. Economic drivers will be felt much more strongly as competition and government policies provide outlines for commercial development.

In addition to systems application to traditional engineering domains, systems engineering will continue to expand in social, medical, cyber, virtual, environmental, and natural systems. These domains increasingly influence the needs, requirements, and usability of modern systems. Human interests, disease control, healthcare, entertainment, communication, urban design, and commercialization, among other factors, profoundly affect the design, life cycle, and domain applications for complex systems.

The International Council on Systems Engineering (INCOSE) provides the assessment, guidance, and policies for professional systems engineers. The INCOSE systems engineering vision for 2025 is an excellent reference to describe future systems and systems challenges.

Risks

The explosive growth of technology has been the single largest factor in the emergence of systems engineering as an essential ingredient in the engineering of complex systems. Advancing technology has not only greatly extended the capabilities of earlier systems, such as aircraft, telecommunications, and power plants, but has also created entirely new systems such as those based on jet propulsion, satellite communications and navigation, global networks, and a host of computer-based systems for manufacturing, finance, transportation, entertainment, healthcare, and other products and services. Advances in technology have not only affected the nature of products, but have also fundamentally changed the way they are engineered, produced, and operated. These are particularly important in early phases of systems development, as described in Needs Analysis, in Chapter 5.

Modern technology has had a profound effect on the very approach to engineering. Traditionally, engineering applies known principles to practical ends. Innovation, however, produces new materials, devices, and processes, whose characteristics are not yet fully measured or understood. The application of these to the engineering of new systems thus increases the risk of encountering unexpected properties and effects that might impact system performance and require costly changes and program delays.

However, failure to apply the latest technology to system development also carries risks. These are the risks of producing an inferior system; one that could become prematurely obsolete. If a competitor succeeds in overcoming such problems as may be encountered in using advanced technology, the competing approach is likely to be superior. The successful entrepreneurial organization will thus assume carefully selected technological risks, and surmount them by skillful design, systems engineering, and program management.

Software continues to be a growing engineering medium, whose power and versatility have resulted in its use in preference to hardware for the implementation of a growing fraction of system functions. Thus, the performance of modern systems increasingly depends on the proper design and maintenance of software components. As a result, more and more of the systems engineering effort has to be directed to the control of software design and its application.

The increase in automation has had an enormous impact on people who operate systems, decreasing their number but often requiring higher skills and therefore special training. Human–machine interfaces and other people–system interactions are particular concerns of systems engineering.

Risks, some known and others as yet unknown, will entail a significant development effort to bring each new design approach to maturity and later to validate the use of these designs in system components. Selecting the most promising technological

approaches, assessing the associated risks, rejecting those for which the risks outweigh the potential payoff, planning critical experiments, and deciding on potential fallbacks are all primary responsibilities of systems engineering.

Interfaces

A complex system that performs a number of different functions must of necessity be configured in such a way that each major function is embodied in a separate component capable of being specified, developed, built, and tested as an individual entity. Such a subdivision takes advantage of the expertise of organizations specializing in particular types of products and hence capable of engineering and producing components of highest quality at lowest cost. Chapter 3 describes the kind of functional and physical building blocks that make up most modern systems.

The immensity and diversity of engineering knowledge, which are still growing, have made it necessary to divide the education and practice of engineering into a number of specialties, such as mechanical, electrical, aeronautical, and so on. To acquire the necessary depth of knowledge in any one of these fields, further specialization is needed, into such subfields as robotics, digital design, and fluid dynamics. Thus, engineering specialization is a predominant condition in the field of engineering and manufacturing and must be recognized as a basic condition in the system development process.

Each engineering specialty has developed a set of specialized tools and facilities to aid in the design and manufacture of its associated products. Large and small companies have organized around one or several engineering groups to develop and manufacture devices to meet the needs of the commercial market or of system-oriented industry.

The convenience of subdividing complex systems into individual components or subsystems requires integrating these disparate parts into an efficient, smoothly operating system. Integration means that each component fits perfectly with its neighbors accomplished at inter-component boundaries called **interfaces**. The functional relationships are called **interactions**. The task of analyzing, specifying, and validating the component interfaces with each other and with the external environment is beyond the expertise of the individual design specialists and is the province of the systems engineer. Chapter 3 discusses further the importance and nature of this responsibility.

An essential goal of systems engineering is to achieve a high degree of modularity to make interfaces and interactions as simple as possible for efficient manufacture, system integration, test, operational maintenance, reliability, and ease of in-service upgrading. The process of subdividing a system into modular building blocks is called “functional allocation” and is another basic tool of systems engineering.

Agile Systems Engineering

New products and systems with creative new innovations are designed and introduced into the market place at a rapid pace. Systems engineers need to develop systems that thrive in uncertain and unpredictably evolving environments – that is, they need to be

agile. Quite often there exists uncertainty in future user needs and operating environments. There should be agility in the systems engineering process itself, carefully exploring design alternatives and delaying manufacturing and deployment as long as possible as new information becomes available during product development. Systems modules would be able to perform effectively with operational environments that are risky, variable, and evolving. This would be considered **agile systems-engineering**.

In addition, there should be agility in the resulting system. In other words, systems need to be resilient, providing the ability to repair or replace lost capability over time. Some have described such systems as having reusable, reconfigurable, and scalable design principles. An agile system is hence flexible with the ability to change from one state or operating condition to another rapidly, without large costs or increases in system complexity. They are systems that can respond to changed requirements after initial fielding of the system. This would be considered **agile-systems engineering**.

Model-Based Systems Engineering

“Model Based Systems Engineering (MBSE) is an emerging new paradigm for improving the efficiency and effectiveness of systems engineering through the pervasive use of integrated descriptive representations of the system to capture knowledge about the system for the benefit of all stakeholders” (Noguchi 2016). Discussed in Chapter 10, MBSE is the application of purpose-built modeling languages and tools to improve the effectiveness of systems engineering by allowing system concepts, architectures, requirements, and parametrics to be represented and queried. This permits unprecedented levels of insights and alleviates the cognitive burden imposed by document-intensive systems engineering (DISE). Instead of being forced to sift or search through document-based representations of systems information, systems engineers can develop rich queries that return relevant information in compact, meaningful forms. In addition, it permits adjacent analyses and simulations to draw information from (and return information to) the system model without “air gaps” or human translation.

1.3 SYSTEMS ENGINEERING VIEWPOINT

The emergence of complex systems and the prevailing conditions of advancing technology, competitive pressures, and specialization of engineering disciplines and organizations required the development of a new profession: systems engineering. This profession did not, until much later, bring with it a new academic discipline, but rather it was initially filled by engineers and scientists who acquired through experience the ability to lead successfully complex system development programs. To do so, they had to acquire a greater breadth of technical knowledge and, more importantly, develop a different way of thinking about engineering, which has been called “the systems engineering viewpoint.”

The essence of the systems engineering viewpoint is exactly what it implies – making the central objective the system as a whole and the success of its mission. This, in turn,

means the subordination of individual goals and attributes in favor of those of the overall system. The systems engineer is always the advocate of the total system in any contest with a subordinate objective.

Successful Systems

The principal focus of systems engineering, from the very start of a system development, is the success of the system – in meeting its requirements and development objectives, its successful operation in the field, and a long useful operating life. The systems engineering viewpoint encompasses all of these objectives. It seeks to look beyond the obvious and the immediate, to understand the user's problems and the environmental conditions that the system will be subjected to during its operation. It aims at the establishment of a technical approach that will both facilitate the system's operational maintenance and accommodate the eventual upgrading that will likely be required at some point in the future. It attempts to anticipate developmental problems and to resolve them as early as possible in the development cycle; where this is not practicable, it establishes contingency plans for later implementation as required.

Successful system development requires the use of a consistent well-understood systems engineering approach within the organization, which involves the exercise of systematic and disciplined direction, with extensive planning, analysis, reviews, and documentation. Just as important, however, is a side of systems engineering that is often overlooked, namely, innovation. For a new complex system to compete successfully in a climate of rapid technological change and to retain its edge for many years of useful life, its key components must use some of the latest technological advances.

Total Systems View

In characterizing the systems engineering viewpoint, two oft-stated maxims are “the best is the enemy of the good enough” and “systems engineering is the art of the good enough.” The popular maxims use the terms “best” and “good enough” to refer to system performance, whereas systems engineering views performance as only one of several critical attributes; equally important ones are affordability, timely availability to the user, ease of maintenance, and adherence to an agreed-upon development completion schedule. Thus, the systems engineer seeks the **best balance** of the critical system attributes from the standpoint of the success of the development program and of the value of the system to the user.

One of the dictionary definitions of the word “balance” that is especially appropriate to system design is “a harmonious or satisfying arrangement or proportion of parts or elements, as in a design or a composition.” An essential function of systems engineering is to bring about a balance among the various components of the system, which, it was noted earlier, are designed by engineering specialists, with each intent on optimizing the characteristics of a particular component. This is often a daunting task, as illustrated in Figure 1.1. The figure is an artist's conception of what a guided missile

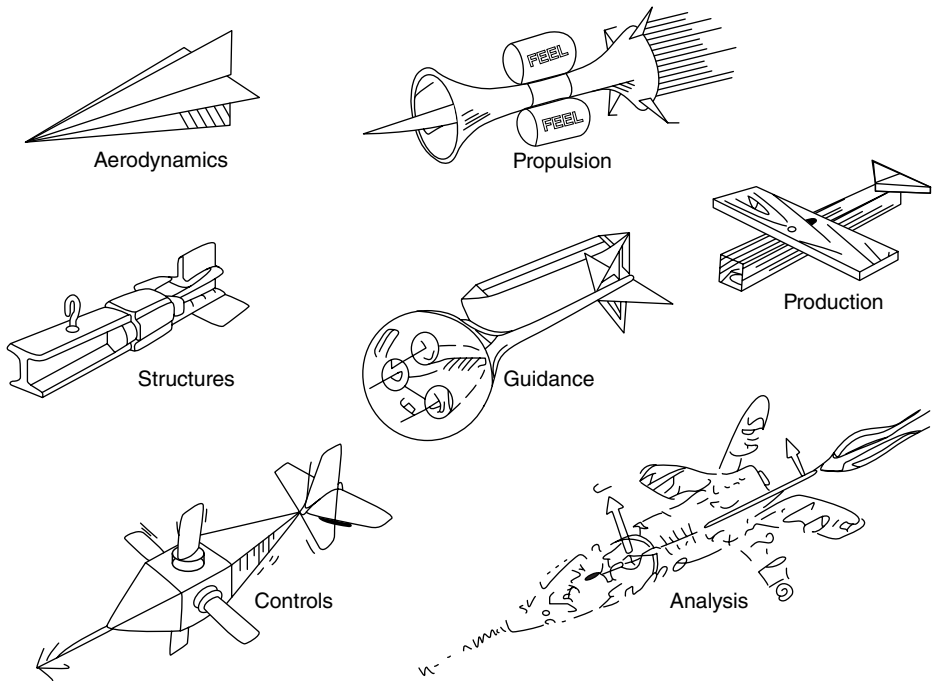


Figure 1.1. The ideal missile design from the viewpoint of various specialists.

might look like if it were designed by a specialist in one or another guided missile component technology. While the cartoons may seem fanciful, they reflect a basic truth, that is, that design specialists will seek to optimize the particular aspect of a system that they best understand and appreciate. In general, it is to be expected that, while the design specialist does understand that the system is a group of components that in combination provide a specific set of capabilities, during system development, the specialist's attention is necessarily focused on those issues that most directly affect his or her own area of technical expertise and assigned responsibilities.

Conversely, the systems engineer must always **focus on the system as a whole**, while addressing design specialty issues only in so far as they may affect overall system performance, developmental risk, cost, or long-term system viability. In short, it is the responsibility of the systems engineer to guide the development so that each of the components receives the proper balance of attention and resources, while achieving the capabilities that are optimal for the best overall system behavior. This often involves serving as an “honest technical broker” who guides the establishment of technical design compromises in order to achieve a workable interface between key system elements.

The viewpoint of the systems engineer calls for a different combination of skills and areas of knowledge than those of a design specialist or a manager. The design specialist may have limited managerial skills but has a deep understanding in one or a few

related areas of technology. Similarly, a project manager needs to have a little depth in any particular technical discipline, but must have considerable breadth and capability to manage people and technical effort. A systems engineer, on the other hand, requires significant capabilities in all components, representing the balance needed to span the needs of a total system effort.

1.4 PERSPECTIVES OF SYSTEMS ENGINEERING

While the field of systems engineering has matured rapidly in the past few decades, there will continue to exist a variety of differing perspectives as more is learned about the potential and the utility of systems approaches to solve the increasing complex problems around the world. The growth of systems engineering is evidenced in the number of academic programs and graduates in the area. Systems engineering is a favored and potentially excellent career path. Employers in all sectors, private and government, seek experienced systems engineering candidates. Experts in workforce development look for ways to encourage more secondary school and college students to pursue degrees in science, technology, engineering, and mathematics (STEM). With experience and additional knowledge, these students can mature into capable systems engineers.

Think Like a Systems Engineer

Since it often requires professional experience in addition to education to tackle the most complex and challenging problems, developing a systems mindset – to “think like a systems engineer” – is a high priority at any stage of life. Systems thinking sees everything as holistic, with all parts interconnected and interdependent. Systems thinking is the method of achieving and maintaining a system design in which every requirement is carefully monitored and carefully controlled, including the human factor. A perspective that relates a progression in the maturity of thinking includes concepts of systems thinking, systems engineering, and engineering systems. See Table 1.1. An approach to understanding the environment, process, and policies of a systems problem requires one to use systems thinking. This approach to a problem examines the domain and scope of the problem and defines it in quantitative terms. One looks at the parameters that help define the problem, and then through research and surveys develops observations about the environment the problem exists in and finally generates options that could address the problem. This approach would be appropriate for use in secondary schools to have young students gain an appreciation of the “big picture” as they learn fundamental science and engineering skills.

The systems engineering approach discussed in this book focuses on the products and solutions of a problem, with intent to develop or build a system to address the problem. The approach tends to be more technical, seeking from potential future users and developers of the solution system, what are the top-level needs, requirements, and concepts of operations, before and then conducting a functional and physical design,

TABLE 1.1. Comparison of Systems Perspectives

Systems thinking	Systems engineering	Engineering systems
Focus on process	Focus on whole product	Focus on both process and product
Consideration of issues	Solve complex technical problems	Solve complex interdisciplinary technical, social, and management issues
Evaluation of multiple factors and influences	Develop and test tangible system solutions	Influence policy, processes, and use systems engineering to develop systems solutions
Inclusion of patterns, relationships, and common understanding	Need to meet requirements, measure outcomes, and solve problems	Integrate human and technical domain dynamics and approaches

development of design specifications, production, and testing of a system solution for the problem. Attention is given to the subsystem interfaces and the need for viable and tangible results. The approach and practical end could be applied to many degrees of complexity, but there is an expectation of a successful field operation of a product.

A broader and robust perspective to systems approaches to solve very extensive complex engineering problems by integrating engineering, management, and social sciences approaches using advanced modeling methodologies is termed “engineering systems.” The intent is to tackle some of society’s grandest challenges with significant global impact by investigating ways in which engineering systems behave and interact with one another including social, economic, and environmental factors. This approach encompasses engineering, social sciences, and management processes without the implied rigidity of systems engineering. Hence, applications to critical infrastructure, healthcare, energy, environment, information security, and other global issues are likely areas of attention.

Much like the proverbial blind men examining the elephant, the field of systems engineering can be considered in terms of various domains and application areas where it is applied. Based on the background of the individuals and on the needs of the systems problems to be solved, the systems environment can be discussed in terms of the fields and technologies that are used in the solution sets. Another perspective can be taken from the methodologies and approaches taken to solve problems and develop complex systems. In any mature discipline, there exist for systems engineering a number of processes, standards, guidelines, and software tools to organize and enhance the effectiveness of the systems engineering professional. The INCOSE maintains current information and reviews in these areas. These perspectives will be discussed in the following sections.

Systems Engineering Principles and Practice

The scope of systems engineering is very broad and multidimensional. As more practitioners and organizations understand the importance and engage in systems engineering, new approaches and applications are developed. As shown in Figure 1.2,

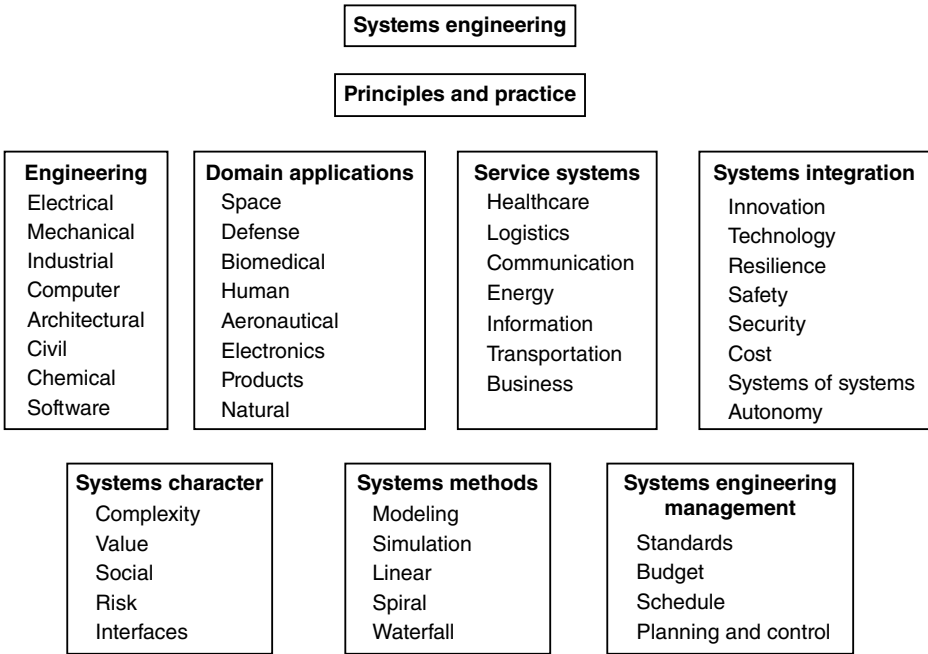


Figure 1.2. Systems engineering principles and practice.

systems engineering principles and practice require a perspective that is encompassing and complex. This broadening landscape illustrates the importance of systems engineering in nearly every product, professional, social, and human endeavor.

Systems Domains

With a broad view of systems development, it can be seen that the traditional approach to systems now encompasses a growing domain breadth. And much like a Rubik’s Cube, the domain faces are now completely integrated into the systems engineer’s perspective of the “big (but complex) picture.” The systems domain faces shown in Figure 1.3 include not only the engineering, technical, and management domains but also social, political/legal, and human domains. These latter dimensions require additional attention and research to fully understand their impact and utility in systems development, especially as we move to areas at the enterprise and global family of systems levels of complexity.

Particularly interesting domains are those that involve scale, such as nano and microsystems, or systems that operate (often autonomously) in extreme environments, such as deep undersea or outer space. Much like physical laws change with scale, does the systems engineering approach need to change? Should systems engineering practices evolve to address the needs for submersibles, planetary explorers, or intravascular robotic systems? Additionally, interesting are the increasing complexities introduced

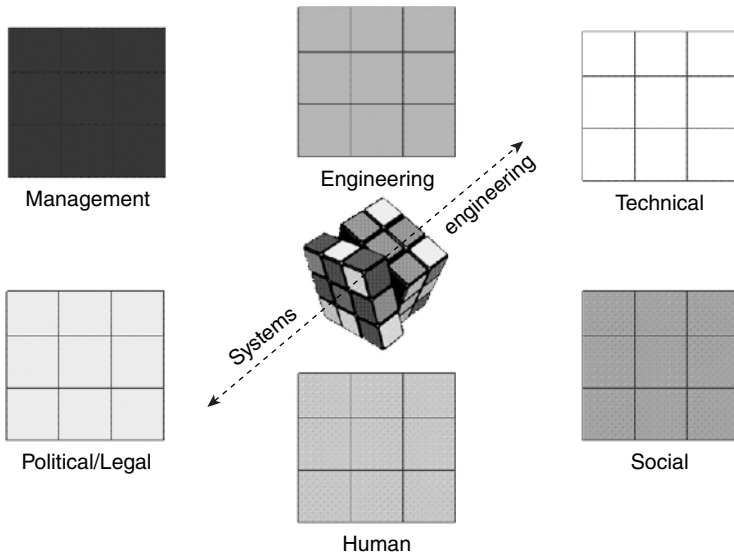


Figure 1.3. Systems engineering.

with rapid mobile communications, autonomous vehicles, and social networks, which confound the human, legal, and political elements.

Systems Engineering Components

Since systems engineering has a strong connection bridging the traditional engineering disciplines like electrical, mechanical, aerodynamic, and civil engineering among others, it should be expected that engineering specialists look at systems engineering with a perspective more strongly from their engineering discipline. Similarly, since systems engineering is a guide to design of systems often exercised in the context of a project or program, then functional, project, and senior managers will consider the management elements of planning and control to be key aspects of systems development. The management support functions that are vital to systems engineering success such as quality management, human resource management, and financial management can all claim an integral role and perspective to the systems development.

These perceptions are illustrated in Figure 1.4 and additional fields are also shown that represent a few of the traditional areas associated with and influence systems engineering methods and practices. An example is the area of operations research whose view of systems engineering includes provision of a structure that will lead to quantitative analysis of alternatives and optimal decisions. The design of systems also has a contingency of professionals who focus on the structures and architectures. In diverse areas such as manufacturing to autonomous systems, another interpretation of systems engineering comes from engineers who develop control systems who lean heavily on

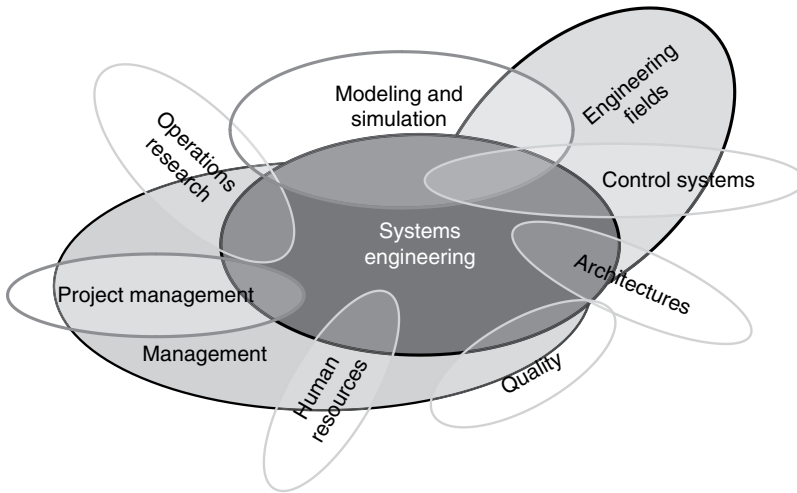


Figure 1.4. Examples of systems engineering components.

the systems engineering principles that focus on management of interfaces and feedback systems. Finally, the overlap of elements of modeling and simulation with systems engineering provides a perspective that is integral to cost-effective examination of systems options to meet the requirements and needs of the users. As systems engineering matures, there will be an increasing number of perspectives from varying fields that adopt it as their own.

Systems Engineering Methods

Systems engineering can also be viewed in terms of the depictions of the sequence of processes and methodologies used in execution of design, development, integration, and testing of a system. See Figure 1.5 for examples. Early graphics were linear in the process flow with sequences of steps that are often iterative to show the logical means to achieve consistency and viability. Small variations are shown in the waterfall charts that provide added means to illustrate interfaces and broader interactions. Many of the steps are repeated and dependent on each other leading to the spiral or loop conceptual diagrams. The popular systems engineering “V” diagram provides a view of life cycle development with explicit relationships shown between requirements and systems definition and the developed and validated product.

1.5 EXAMPLES OF SYSTEMS REQUIRING SYSTEMS ENGINEERING

As noted at the beginning of this chapter, the generic definition of a system as a **set of interrelated components** working **together** as an integrated whole to achieve some common objective would fit most familiar home appliances. A washing machine

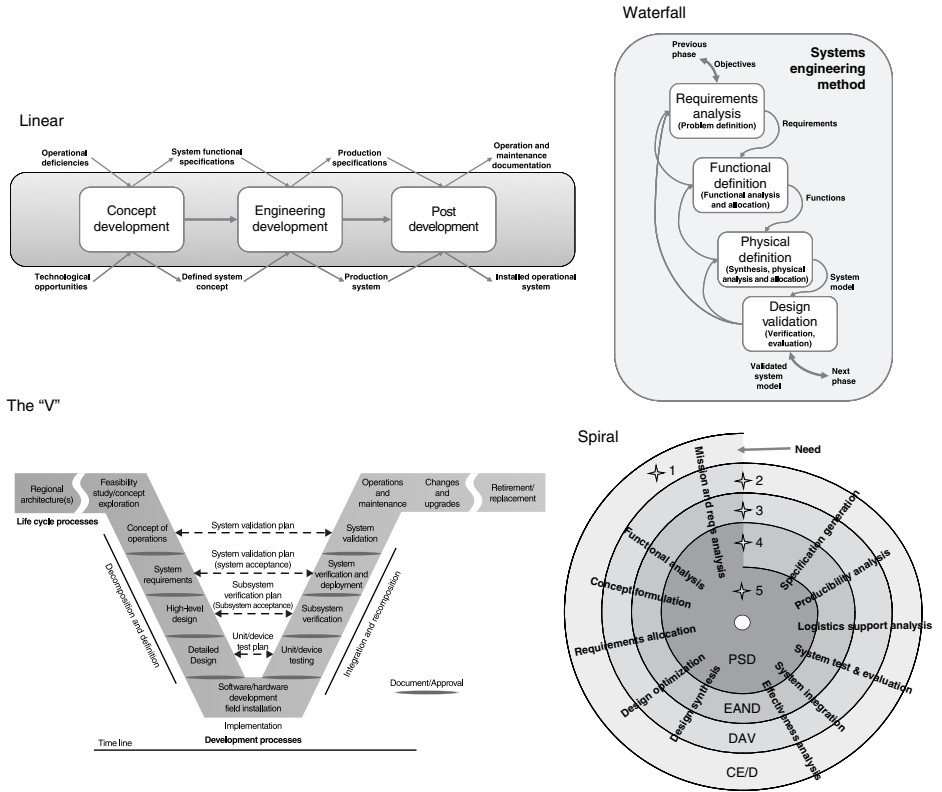


Figure 1.5. Examples of systems engineering approaches.

consists of a main clothes tub, an electric motor, an agitator, a pump, a timer, an inner spinning tub, and various valves, sensors, and controls. It performs a sequence of timed operations and auxiliary functions based on a schedule and operation mode set by the operator. A refrigerator, microwave oven, dishwasher, vacuum cleaner, and radio all perform a number of useful operations in a systematic manner. However, these appliances involve only one or two engineering disciplines, and their design is based on well-established technology. Thus, they fail the criterion of being **complex** and we would not consider the development of a new washer or refrigerator to involve much systems engineering as we understand the term, although it would certainly require a high order of reliability and cost engineering. Of course, home appliances increasingly include clever automatic devices that use newly available microchips, but these are usually self-contained add-ons and are not necessary to the main function of the appliance.

Since the development of new modern systems is strongly driven by technological change, we shall add one more characteristic to a system requiring systems engineering, namely, that some of its **key elements use advanced technology**. The characteristics

of a system whose development, test, and application require the practice of systems engineering are that the system

- Is an engineered product and hence satisfies a specified need.
- Consists of diverse components that have intricate relationships with one another and hence is multidisciplinary and relatively complex.
- Uses advanced technology in ways that are central to the performance of its primary functions and hence involves development risk and often relatively high cost.

Henceforth, references in this text to an **engineered** or **complex** system (or in the proper context, just **system**) will mean the type which has the three attributes noted above; that is, is an engineered product, contains diverse components, and uses advanced technology. These attributes are, of course, in addition to the generic definition stated earlier, and serve to identify the systems of concern to the systems engineer as those that require system design, development, integration, test, and evaluation.

Complex Engineered Systems

To illustrate the types of systems that fit within the above definition, Tables 1.2 and 1.3 list 10 modern systems and their principal inputs, processes, and outputs.

It has been noted that a system consists of a multiplicity of elements, some of which may well themselves be complex and deserve to be considered a system in their own right. For example, a telephone-switching substation can well be considered as a system, with the telephone network considered as a “system of systems.” Such issues will be discussed more fully in future chapters, to the extent necessary for the understanding of systems engineering.

TABLE 1.2. Examples of Engineered Complex Systems: Signal and Data Systems

System	Inputs	Process	Outputs
Weather satellite	Images	<ul style="list-style-type: none"> • Data storage • Transmission 	Encoded images
Terminal air traffic control system	Aircraft beacon responses	<ul style="list-style-type: none"> • Identification • Tracking 	<ul style="list-style-type: none"> • Identity • Air tracks • Communications
Track location system	Cargo routing requests	<ul style="list-style-type: none"> • Map tracing • Communication 	<ul style="list-style-type: none"> • Routing info. • Delivered cargo
Airline reservation system	Travel requests	Data management	<ul style="list-style-type: none"> • Reservations • Tickets
Clinical information system	<ul style="list-style-type: none"> • Patient ID • Test records • Diagnosis 	Information management	<ul style="list-style-type: none"> • Patient status • History • Treatment

TABLE 1.3. Examples of Engineered Complex Systems: Material and Energy Systems

System	Inputs	Process	Outputs
Passenger aircraft	<ul style="list-style-type: none"> • Passengers • Fuel 	<ul style="list-style-type: none"> • Combustion • Thrust • Lift 	Transported passengers
Modern harvester combine	<ul style="list-style-type: none"> • Grain field • Fuel 	<ul style="list-style-type: none"> • Cutting • Threshing 	Harvested grain
Oil refinery	<ul style="list-style-type: none"> • Crude oil • Catalysts • Energy 	<ul style="list-style-type: none"> • Cracking • Separation • Blending 	<ul style="list-style-type: none"> • Gasoline • Oil products • Chemicals
Auto assembly plant	<ul style="list-style-type: none"> • Auto parts • Energy 	<ul style="list-style-type: none"> • Manipulation • Joining • Finishing 	Assembled auto
Electric power plant	<ul style="list-style-type: none"> • Fuel • Air 	<ul style="list-style-type: none"> • Power generation • Regulation 	<ul style="list-style-type: none"> • Electric AC power • Waste products

Example: A Modern Automobile. A more simple and familiar system, which still meets the criteria for an engineered system, is a fully equipped passenger automobile. It can be considered as a lower limit to more complex vehicular systems. It is made up of a large number of diverse components requiring the combination of several different disciplines. To operate properly, the components must work together accurately and efficiently. Whereas the operating principles of automobiles are well established, modern autos must be designed to operate efficiently, while at the same time maintaining very close control of engine emissions, which requires sophisticated sensors and computer-controlled mechanisms for injecting fuel and air. Anti-lock brakes are another example of a finely tuned automatic automobile subsystem. Advanced materials and computer technology are used to an increasing degree in passenger protection, cruise control, automated navigation, and autonomous driving and parking. The stringent requirements on cost, reliability, performance, comfort, safety, and a dozen other parameters present a number of substantive systems engineering problems. Accordingly, an automobile meets the definition established earlier for a system requiring the application of systems engineering.

An automobile (without future autonomous capability) is also an example of a large class of systems that require active interaction (control) by a human operator. To some degree, all systems require such interaction, but in this case, continuous control is required. In a very real sense, the operator (driver) functions as an integral part of the overall automobile system, serving as the steering feedback element that detects and corrects deviations of the car's path on the road. The design must therefore address as a critical constraint the inherent sensing and reaction capabilities of the operator, in addition to a range of associated human-machine interfaces such as the design and placement of controls and displays, seat position, and so on. Also, while the passengers may not function as integral elements of the auto steering system, their associated

interfaces (e.g. weight, seating and viewing comfort, safety) must be carefully addressed as part of the design process.

1.6 SYSTEMS ENGINEERING ACTIVITIES AND PRODUCTS

Sometimes followed as a roadmap, the life cycle development of a system can be associated with a number of systems engineering and project management products or outputs that are listed in Table 1.4. The variety and breadth of these products reflect the challenges early professional have in understanding the full utility of engaging in systems engineering. Throughout this book, these products will be introduced and discussed in some detail to help guide the systems engineer in product development.

1.7 SYSTEMS ENGINEERING AS A PROFESSION

With the increasing prevalence of complex systems in modern society, and the essential role of systems engineering in the development of systems, systems engineering as a profession has become widely recognized. Its primary recognition has come in companies specializing in the development of large systems. A number of these have established departments of systems engineering, and have classified those engaging in the process as systems engineers. In addition, global challenges in healthcare, communications, environment, and many more complex areas require engineering systems methods to develop viable solutions.

Engineering disciplines are built on quantitative relationships, obeying established physical laws, and measured properties of materials, energy, or information. Systems engineering, on the other hand, deals mainly with problems for which there is incomplete

TABLE 1.4. Systems Engineering Activities and Documents

Context diagrams	Opportunity assessments	Prototype integration
Problem definition	Candidate concepts	Prototype test and evaluation
User/owner identification	Risk analysis/management plan	Production/operations plan
User needs	Systems functions	Operational tests
Concept of operations	Physical allocation	Verification and validation
Scenarios	Component interfaces	Field support/maintenance
Use cases	Traceability	System/product effectiveness
Requirements	Trade studies	Upgrade/revise
Technology readiness	Component development and test	Disposal/reuse

knowledge, whose variables do not obey known equations, and where a balance must be made among conflicting objectives involving incommensurate attributes. The absence of a quantitative knowledge base previously inhibited the establishment of systems engineering as a unique discipline.

Despite those obstacles, the recognized need for systems engineering in industry and government has spurred the establishment worldwide of a number of academic programs offering master's degrees and doctoral degrees in system(s) engineering. An increasing number of universities are offering undergraduate degrees in systems engineering as well.

The recognition of systems engineering as a profession led in the formation of a professional society, the INCOSE, one of whose primary objectives is the promotion of systems engineering, and the recognition of systems engineering as a professional career.

Career Choices

Systems engineers are highly sought after because their skills complement those in other fields and often serve as the “glue” to bring new ideas to fruition. However, career choices and the related educational needs for those choices are complex, especially when the role and responsibilities of a systems engineer are poorly understood.

Four potential career directions are shown in Figure 1.6: financial, management, technical, and systems engineering. There are varying degrees of overlap between them despite the symmetry shown in the figure. The systems engineer focuses on the whole system product leading and working with many diverse technical team members, following the systems engineering development cycle, conducting studies of alternatives, and managing the system interfaces. The systems engineer generally matures in the field after a technical undergraduate degree with work experience and a master of science degree in systems engineering, with increasing responsibility of successively larger projects, eventually serving as the chief or lead systems engineer for a major systems, or systems-of-systems development. Note the overlap and need to understand the content and roles of the technical specialists and coordinate with the program manager (PM).

The project manager often with a technical or business background, is responsible for interfacing with the customer and defining the work, developing the plans, monitoring and controlling the project progress, and delivering the finished output to the customer. The project manager often learns on the job from experience with projects of increasing size and importance, enhancing the toolset available with a master of science degree in technical/program management. While not exclusively true, the chief executive officer frequently originates from the ranks of the organization's project managers.

The financial or business career path that ultimately could lead to a chief financial officer position usually includes business undergraduate and master in business administration (MBA) degrees. Individuals progress through their careers with various horizontal and vertical moves, often with specialization in the field. There is overlap in skill and knowledge with the PM in areas of contract and finance management.

Many early careers start with a technical undergraduate degree in engineering, science, or information technology. The technical specialist makes contributions as part

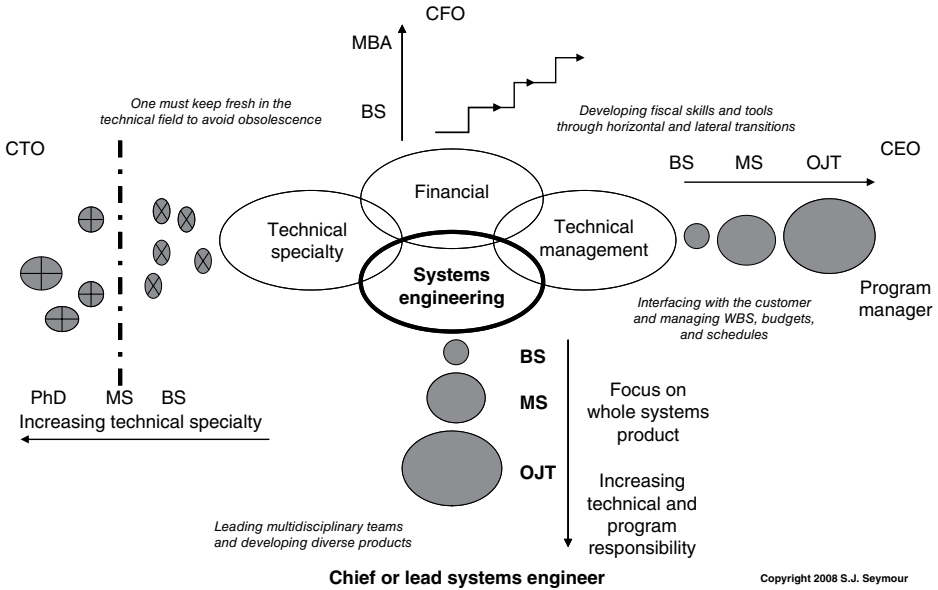


Figure 1.6. Career opportunities and growth.

of a team in the area of their primary knowledge, honing skills and experience to develop and test individual components or algorithms that are part of a larger system. Contributions are made project-to-project over time and recognition is gained from innovative, timely, and quality workmanship. Technical specialists need to continue to learn about their field, and stay current in order to be employable compared with the next generation of college graduates. Often advanced degrees (MS and PhDs) are acquired to enhance knowledge, capability, and recognition, and job responsibilities can lead to positions such as lead engineer, lead scientist, or chief technology officer in an organization. The broader minded or experienced specialist often considers a career in systems engineering.

The Challenge of Systems Engineering

An inhibiting factor in becoming a professional systems engineer is that it represents a deviation from a chosen established discipline to a more diverse, complicated professional practice. It requires the investment of time and effort to gain experience and extensive broadening of the engineering base, as well as learning communication and management skills.

For the above reasons, an engineer considering a career in systems engineering may come to the conclusion that the road is difficult. It is clear that a great deal must be learned and that the educational experience in a traditional engineering discipline is

necessary and will be of only limited direct use; that is, there are few tools and few quantitative relationships to help make decisions. Instead, the issues are ambiguous and abstract, defying definitive solutions. There may appear to be little opportunity for individual accomplishment and even less for individual recognition. For a systems engineer, success is measured by the accomplishment of the development team, not necessarily the system team leader.

What Then Is the Attraction of Systems Engineering?

The answer may lie in the challenges of systems engineering rather than its direct rewards. Systems engineers deal with the most important issues in the system development process. They design the overall system architecture and the technical approach and lead others in designing the components. They prioritize the system requirements in conjunction with the customer, to ensure that the different system attributes are appropriately weighted when balancing the various technical efforts. They decide which risks are worth undertaking and which are not, and how the former should be hedged to ensure program success.

It is the systems engineers who map out the course of the development program that prescribes the type and timing of tests and simulations to be performed along the way. They are the ultimate authorities on how the system performance and system affordability goals may be achieved at the same time.

When unanticipated problems arise in the development program, as they always do, it is the systems engineers who decide how they may be solved. They determine whether an entirely new approach to the problem is necessary, whether more intense effort will accomplish the purpose, whether an entirely different part of the system can be modified to compensate for the problem, or whether the requirement at issue can best be scaled back to relieve the problem.

Systems engineers derive their ability to guide the system development not from their position in the organization, but from their superior knowledge of the system as a whole, its operational objectives, how all its parts work together, and all the technical factors that go into its development, as well as from their proven experience in steering complex programs through a maze of difficulties to a successful conclusion.

Attributes and Motivations of Systems Engineers

In order to identify candidates for systems engineering careers, it is useful to examine the characteristics that may be useful to distinguish people with a talent for systems engineering from those who are not likely to be interested or successful in that discipline. Those likely to become talented systems engineers would be expected to have done well in mathematics and science in college.

A systems engineer will be required to work in a multidisciplinary environment and grasp the essentials of related disciplines. It is here that an aptitude for science and engineering helps a great deal, because it makes it much easier and less threatening for

individuals to learn the essentials of new disciplines. It is not so much that they require in-depth knowledge of higher mathematics, but rather those who have a limited mathematical background tend to lack confidence in their ability to grasp subjects that inherently contain mathematical concepts.

A systems engineer should have a creative bent and must like to solve practical problems. Interest in the job should be greater than interest in career advancement. Systems engineering is more of a challenge than a quick way to the top.

The following characteristics are commonly found in successful systems engineers. They

1. Enjoy learning new things and solving problems.
2. Like a challenge.
3. Are skeptical of unproven assertions.
4. Are open-minded to new ideas.
5. Have a solid background in science and engineering.
6. Have demonstrated technical achievement in a specialty area.
7. Are knowledgeable in several engineering areas.
8. Pick up new ideas and information quickly.
9. Have good interpersonal and communication skills.

1.8 SYSTEMS ENGINEER CAREER DEVELOPMENT MODEL

When one has the characteristics noted above and is attracted to become a systems engineer, there are four more elements that need to be present in the work environment. As shown in Figure 1.7, one should seek assignments to problems and tasks that are very challenging and likely to expand technical domain knowledge and creative juices. Whatever the work assignment, understanding the context of the work and understanding the big picture is also essential. Systems engineers are expected to manage many activities at the same time, being able to have broad perspectives, but able to delve deeply in to many subjects at once. This ability to multiplex is one that takes time to develop. Finally, the systems engineer should not be intimidated by complex problems since this is the expected work environment. It is clear these elements are not part of an educational program and must be gained through extended professional work experience. This becomes the foundation for the systems engineering career growth model.

Employers seeking to develop systems engineers to competitively address more challenging problems should provide key staff with relevant systems engineering work experience, activities that require mature systems thinking, and opportunities for systems engineering education and training. In Figure 1.8, it can be seen that the experience can be achieved not only with challenging problems, but with experienced mentors and real, practical exercises. While using systems thinking to explore complex

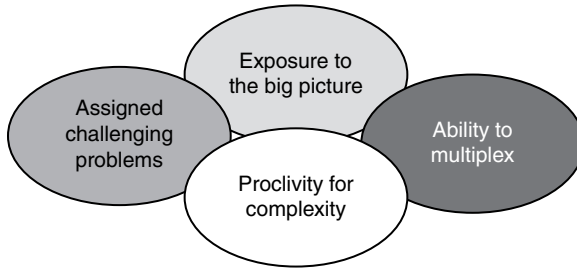


Figure 1.7. Systems engineering career elements derived from quality work experiences.

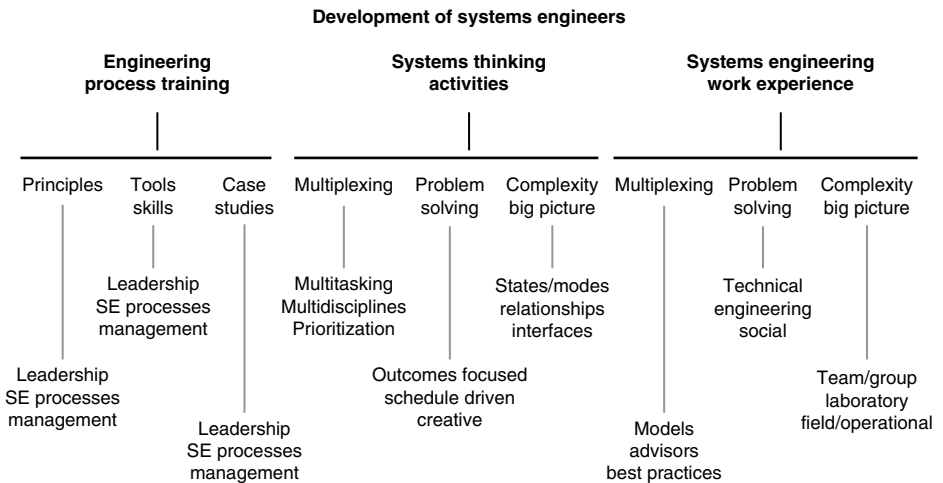


Figure 1.8. Components of employer development of systems engineers.

problem domains, staff should be encouraged to think creatively and out of the box. Often, technically trained people rigidly follow the same processes and tired ineffective solutions. Using lessons learned from past programs and case studies creates opportunities for improvements. Formal training and use of systems engineering tools further enhance employer preparation for tackling complex issues.

Interests, attributes, and training, along with an appropriate environment, provide the opportunity for individuals to mature into successful systems engineers. The combination of these factors is captured in the “T” model for systems engineer career development illustrated in Figure 1.9. In the vertical part, from bottom to top is the time progression in a professional’s career path. After completion of a technical undergraduate degree, shown along the bottom of the chart, an individual generally enters professional life as a technical contributor to a larger effort. The effort is part of a project or program that falls in a particular domain such as aerodynamics, biomedicine, combat

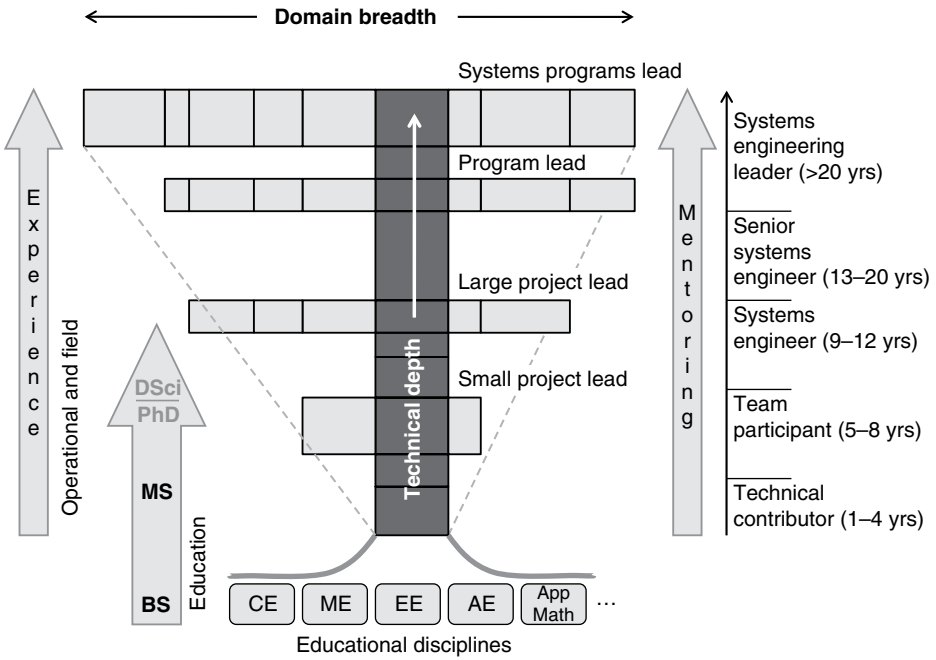


Figure 1.9. "T" model for systems engineer career development.

systems, information systems, or space exploration. Within a domain, there are several technical competencies that are fundamental for systems to operate or be developed.

The "T" is formed by snapshots during a professional's career that illustrates in the horizontal part of the "T" the technical competencies at the time that were learned and used to meet the responsibilities assigned at that point in their career. After initial experience in one or two technical domains as technical contributor, one progresses to increasing responsibilities in a team setting and eventually to leading small technical groups. After eight or more years, the professional has acquired both sufficient technical depth and technical domain depth to be considered a systems engineer. Additional assignments lead to project and program systems engineering leadership and eventually to being the senior systems engineer for a major development program that exercises the full range of the technical competencies for the domain.

In parallel with broadening and deepening technical experience and competencies, the successful career path is augmented by assignments that involve operational field experiences, advanced education and training, and a strong mentoring program. In order to obtain a good understanding of the environment where the system under development will operate and to obtain firsthand knowledge of the system requirements, it is essential the early systems engineer professional visit the "field site" and operational location. That approach is important to continue throughout one's career. A wide variety of

systems engineering educational opportunities are available in both classroom and online formats. As in most engineering disciplines where the student is not planning on an academic career, the master of science is the terminal degree. Courses are usually a combination of systems engineering and domain or concentration centric focused with a thesis or capstone project for the student to demonstrate their knowledge and skills on a practical systems problem. Large commercial companies also provide training in systems engineering and systems architecting with examples and tools that are specific to their organization and products. Finally, the pairing of a young professional with an experienced systems engineer will enhance the learning process.

1.9 SUMMARY

What Is Systems Engineering?

The function of systems engineering is to guide the engineering of complex systems. And a system is defined as a set of interrelated components working together toward a common objective. Furthermore, a complex engineered system is (i) composed of a multiplicity of intricately interrelated diverse elements and (ii) requires systems engineering to lead its development.

Systems engineering differs from traditional disciplines in that it (i) is focused on the system as a whole; (ii) is concerned with customer needs and operational environment; (iii) leads system conceptual design; and (iv) bridges traditional engineering disciplines and gaps between specialties. Moreover, systems engineering is an integral part of project management in that it plans and guides the engineering effort.

Systems Engineering Landscape

Systems will be more complex, network intensive, autonomous capable, intelligent, adaptable, robust, and secure. Drivers will include economics, risks – both known and unknown – from advancing technology and innovation, increased complexity and interfaces, expanded systems applications and social impacts, new autonomy, and expected agility.

Systems Engineering Viewpoint

The systems engineering viewpoint is focused on producing a successful system that meets requirements and development objectives, is successful in its operation in the field, and achieves its desired operating life. In order to achieve this definition of success, the systems engineer must balance superior performance with affordability and schedule constraints. In fact, many aspects of systems engineering involve achieving a balance among conflicting objectives. For example, the systems engineering typically must apply new technology to the development of a new system while managing the inherent risks that new technology poses.

Throughout the development period, the systems engineering focuses on the total system, making decisions based on the impacts and capabilities of the system as a whole. Often, this is accomplished by bridging multiple disciplines and components to ensure a total solution. Specialized design is one-dimensional, in that it has great technical depth, but little technical breadth and little management expertise. Planning and control is two-dimensional: it has great management expertise, but moderate technical breadth and small technical depth. But systems engineering is three-dimensional: it has great technical breadth, as well as moderate technical depth and management expertise.

Perspectives of Systems Engineering

A spectrum of views exist in understanding systems engineering, from a general systems thinking approach to problems, to the developmental process approach for systems engineering, to the broad perspective of engineering systems. Systems thinking is the method of achieving and maintaining a system design, in which every requirement is carefully monitored and carefully controlled, including the human factor.

The engineering systems view encompasses not only traditional engineering disciplines, but technical, and management domains, social, political/legal, and human domains. Scales at the extremes are of particular interest due to their complexity.

As the field of systems engineering matures and is used for many applications, several process models have been developed including the linear, the “V,” spiral, and waterfall.

Examples of Systems Requiring Systems Engineering

Examples of engineered complex systems include:

- Weather satellites
- Terminal air traffic control
- Truck location systems
- Airline navigation systems
- Clinical information systems
- Passenger aircraft
- Modern harvester combines
- Oil refineries
- Auto assembly plants
- Electric power plants

Systems Engineering Activities and Products

A full systems life cycle view illustrates the close relationship with the management process and leads to a large diverse set of activities and products.

Systems Engineering as a Profession

Systems engineering is now recognized as a profession, and has an increasing role in government and industry. In fact, numerous graduate (and some undergraduate) degree programs are now available across the country. And a formal, recognized organization exists for systems engineering professionals: the INCOSE.

Technical professionals have specific technical orientations – technical graduates tend to be highly specialized. Only a few become interested in interdisciplinary problems – it is these individuals who often become systems engineers.

Systems Engineer Career Development Model

The systems engineering profession is difficult but rewarding. A career in systems engineering typically features technical satisfaction – finding the solution of abstract and ambiguous problems – and recognition in the form of a pivotal program role. Consequently, a successful systems engineer has the following traits and attributes:

- A good problem solver and should welcome challenges.
- Well-grounded technically, with broad interests.
- Analytical and systematic, but also creative.
- A superior communicator, with leadership skills.

The “T” model represents the proper convergence of experience, education, mentoring, and technical depth necessary to become a successful and influential systems engineer.

PROBLEMS

- 1.1 Explain what is meant by the statement “Systems engineering is focused on the system as a whole.” State what characteristics of a system you think this statement implies, and how they apply to systems engineering.
- 1.2 Discuss the difference between engineered complex systems and complex systems that are not engineered. Give three examples of the latter. Can you think of systems engineering principles that can also be applied to non-engineered complex systems?
- 1.3 For each of the following areas, list and explain how at least two major technological advances/breakthroughs occurring since 2010 that have radically changed them. In each case, explain how the change was effected.
 - (a) Transportation
 - (b) Communication
 - (c) Financial management

- (d) Manufacturing
 - (e) Distribution and sales
 - (f) Entertainment
 - (g) Medical care
- 1.4 What characteristics of an airplane would you attribute to the system as a whole rather than to a collection of its parts? Explain why.
 - 1.5 List four pros and cons (two of each) of incorporating some of the latest technology into the development of a new complex system. Give a specific example of each.
 - 1.6 Systems engineers have been described as being an advocate for the whole system. Given this statement, which stakeholders should the systems engineer advocate the most? Obviously, there are many stakeholders and the systems engineer must be concerned with most, if not all, of them. Therefore, rank your answer in priority order – which stakeholder is the most important to the systems engineer; which is second; which is third?
 - 1.7 Explain the advantages and disadvantages of introducing systems concepts to secondary students in order to encourage them to pursue STEM careers.
 - 1.8 Select a very large complex system of system example and explain how the engineering systems approach could provide useful solutions that would have wide acceptance across many communities.
 - 1.9 Discuss the use of difference systems engineering process models in terms of their optimal use for various systems developments. Is one model significantly better than another?

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