Pearson New International Edition

Systems Engineering and Analysis

Blanchard Fabrycky

Fifth Edition

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Systems Science and Engineering

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Systems Science and Engineering

Systems are as pervasive as the universe in which they exist. They are as grand as the universe itself or as infinitesimal as the atom. Systems appeared first in natural forms, but with the advent of human beings, a variety of human-made systems have come into existence. In recent decades, we have begun to understand the underlying structure and characteristics of natural and human-made systems in a scientific way.

In this chapter, some system definitions and systems science concepts are presented to provide a basis for the study of systems engineering and analysis. They include definitions of system characteristics, a classification of systems into various types, consideration of the current state of systems science, and a discussion of the transition to the Systems Age. Finally, the chapter presents technology and the nature and role of engineering in the Systems Age and ends with a number of commonly accepted definitions of systems engineering.

Upon completion of this chapter, the reader will have obtained essential insight into systems and systems thinking, with an orientation toward systems engineering and analysis. The system definitions, classifications, and concepts presented in this chapter are intended to impart a general understanding about the following:

- System classifications, similarities, and dissimilarities;
- The fundamental distinction between natural and human-made systems;
- The elements of a system and the position of the system in the hierarchy of systems;
- The domain of systems science, with consideration of cybernetics, general systems theory, and systemology;
- Technology as the progenitor for the creation of technical systems, recognizing its impact on the natural world;
- The transition from the machine or industrial age to the Systems Age, with recognition of its impact upon people and society;
- System complexity and scope and the demands these factors make on engineering in the Systems Age; and
- The range of contemporary definitions of systems engineering used within the profession.

The final section of this chapter provides a summary of the key concepts and ideas pertaining to systems science and engineering. It is augmented with selected references and website addresses recommended for further inquiry.

1 SYSTEM DEFINITIONS AND ELEMENTS

A *system* is an assemblage or combination of functionally related elements or parts forming a unitary whole, such as a river system or a transportation system. Not every set of items, facts, methods, or procedures is a system. A random group of items in a room would constitute a set with definite relationships between the items, but it would not qualify as a system because of the absence of functional relationships. This text deals primarily with systems that include physical elements and have useful purposes, including systems associated with all kinds of products, structures, and services, as well as those that consist of a coordinated body of methods or a complex scheme or plan of procedure.[1]

1.1 The Elements of a System

Systems are composed of components, attributes, and relationships. These are described as follows:

1. *Components* are the parts of a system.
2. *Attributes* are the properties (characteristics, configuration, qualities, powers, constraints, and state) of the components and of the system as a whole.
3. *Relationships* between pairs of linked components are the result of engineering the attributes of both components so that the pair operates together effectively in contributing to the system's purpose(s).

The state is the situation (condition and location) at a point in time of the system, or of a system component, with regard to its attributes and relationships. The situation of a system may change over time in only certain ways, as in the *on* or *off* state of an electrical switching system. A connected series of changes in the state over time comprise a *behavior*. The set of all behaviors with their relative sequence and timing comprise the *process*. The process of a component may control the process of another component.

A system is a set of interrelated components functioning together toward some common objective(s) or purpose(s). The set of components meets the following requirements:

1. The properties and behavior of each component of the set have an effect on the properties and behavior of the set as a whole.
2. The properties and behavior of each component of the set depend on the properties and behavior of at least one other component in the set.
3. Each possible subset of components meets the two requirements listed above; the components cannot be divided into independent subsets.

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[1] This definition-like description was influenced by the *Random House Webster's Unabridged Dictionary*, 2nd ed. (New York: Random House, Inc., 2001).

The previous requirements ensure that the set of components constituting a system always has some property, or behavior pattern, that cannot be exhibited by any of its subsets acting alone. A system is more than the sum of its component parts. However, the components of a system may themselves be systems, and every system may be part of a larger system in a hierarchy.

When designing a system, the objective(s) or purpose(s) of the system must be explicitly defined and understood so that system components may be engineered to provide the desired function(s), such as a desired output for each given set of inputs. Once defined, the objective(s) or purpose(s) make possible the derivation of measures of effectiveness indicating how well the system performs. Achieving the intended purpose(s) of a human-made system and defining its measures of effectiveness are usually challenging tasks.

The purposeful action performed by a system is its *function*. A common system function is that of altering material, energy, or information. This alteration embraces input, process, and output. Some examples are the materials processing in a manufacturing system or a digestive system, the conversion of coal to electricity in a power plant system, and the information processing in a computer system or a customer service system.

Systems that alter material, energy, or information are composed of structural components, operating components, and flow components. *Structural components* are the static parts; *operating components* are the parts that perform the processing; and *flow components* are the material, energy, or information being altered. A motive force must be present to provide the alteration within the restrictions set by structural and operating components.

System components have *attributes* that determine the component's contribution to the system's function. Examples of component attributes include the color of an automobile (a characteristic), the strength of a steel beam (a quality), the number and arrangement of bridge piers (a configuration), the capacitance of an electrical circuit (a power), the maximum speed permitted by the governor of a turbine (a constraint), and whether or not a person is talking on the telephone (a state). An example of a system-level attribute is the length of runway required by an aircraft for takeoff and landing. The runway length requirement is determined by the attributes and relationships of the aircraft as a component and by the configuration attributes of the air transportation system.

A single relationship exists between two and only two components based on their attributes. The two components are directly connected in some way, though they are not necessarily physically adjacent. In a system with more than two components, at least one of the components in the relationship also has at least one relationship with some other component. Each component in a relationship provides something that the other component needs so that it can contribute to the system's function. In order to form a relationship of maximum effectiveness, the attributes of each component must be engineered so that the collaborative functioning of the two components is optimized.

Relationships that are functionally necessary to both components may be characterized as *first order*. An example is symbiosis, the association of two unlike organisms for the benefit of each other. *Second-order* relationships, called *synergistic*, are those that are complementary and add to system performance. *Redundancy* in a system exists when duplicate components are present for the purpose of assuring continuation of the system function in case of component failure.

1.2 Systems and Subsystems

The definition of a system is not complete without consideration of its position in the hierarchy of systems. Every system is made up of *components*, and many components can be broken down into smaller components. If two hierarchical levels are involved in a given system, the lower is conveniently called a *subsystem*. For example, in an air transportation system, the aircraft, control tower, and terminals are subsystems. Equipment, people, and software are components. The designation of system, subsystem, and component are relative, because the system at one level in the hierarchy is the subsystem or component at another.

In any particular situation, it is important to define the system under consideration by specifying its limits, boundaries, or scope. Everything that remains outside the boundaries of the system is considered to be the *environment*. However, no system is completely isolated from its environment. Material, energy, and/or information must often pass through the boundaries as *inputs* to the system. In reverse, material, energy, and/or information that pass from the system to the environment are called *outputs*. That which enters the system in one form and leaves the system in another form is usually called *throughput*.

The total system, at whatever level in the hierarchy, consists of all components, attributes, and relationships needed to accomplish one or more objectives. Each system has objective(s) providing purpose(s) for which all system components, attributes, and relationships have been organized. Constraints placed on the system limit its operation and define the boundary within which it is intended to operate. Similarly, the system places boundaries and constraints on its subsystems.

An example of a total system is a fire department. The subsystems of this "fire control system" are the building, the fire engines, the firefighters with personal equipment, the communication equipment, and maintenance facilities. Each of these subsystems has several contributing components. At each level in the hierarchy, the description must include all components, all attributes, and all relationships.

Systems thinking and the systems viewpoint looks at a system from the top down rather than from the bottom up. Attention is first directed to the system as a black box that interacts with its environment. Next, attention is focused on how the smaller black boxes (subsystems) combine to achieve the system objective(s). The lowest level of concern is then with individual components.

The process of bringing systems into being and of improving systems already in existence, in a holistic way, is receiving increasing attention. By bounding the total system for study purposes, the systems engineer or analyst will be more likely to obtain a satisfactory result. The focus on systems, subsystems, and components in a hierarchy forces consideration of the pertinent functional relationships. Components and attributes are important, but only to the end that the purpose of the whole system is achieved through the functional relationships linking them.

2 A CLASSIFICATION OF SYSTEMS

Systems may be classified for convenience and to provide insight into their wide range. In this section, classification will be accomplished by several dichotomies conceptually contrasting system similarities and dissimilarities. Descriptions are given of natural and human-made systems, physical and conceptual systems, static and dynamic systems, and closed and open systems.[2]

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[2] The classifications in this section are only some of those that could be presented. All system types have embedded information flow components and, therefore, information systems are not included as a separate classification.

2.1 Natural and Human-Made Systems

The origin of systems gives the most important classification opportunity. *Natural systems* are those that came into being by natural processes. *Human-made systems* are those in which human beings have intervened through components, attributes, and relationships. A *human-modified system* is a natural system into which a human-made system has been integrated as a subsystem.

All human-made systems, when brought into being, are embedded into the natural world. Important interfaces often exist between human-made systems and natural systems. Each affects the other in some way. The effect of human-made systems on the natural world has only recently become a keen subject for study by concerned people, especially in those instances where the effect is undesirable. In some cases, this study is facilitated by analyzing the natural system as a human-modified system.

When designing a human-made system, undesirable effects can be minimized—and the natural system can sometimes be improved—by engineering the larger human-modified system instead of engineering only the human-made system. If analysis, evaluation, and validation of the human-modified system are appropriate, then the boundary of the environmental system—drawn to include the human-made system—should be considered the boundary of the human-modified system.

Natural systems exhibit a high degree of order and equilibrium. This is evidenced in the seasons, the food chain, the water cycle, and so on. Organisms and plant life adapt themselves to maintain equilibrium with the environment. Every event in nature is accompanied by an appropriate adaptation, one of the most important being that material flows are cyclic. In the natural environment there are no dead ends, no wastes, only continual recirculation and regeneration.

Only recently have significant human-made systems appeared. These systems make up the human-made world, their chief engineer being human. The rapid evolution of human beings is not adequately understood, but their arrival has significantly affected the natural world, often in undesirable ways. Primitive beings had little impact on the natural world, for they had not yet developed potent and pervasive technologies.

An example of the impact of human-made systems on natural systems is the set of problems that arose from building the Aswan Dam on the Nile River. Construction of this massive dam ensures that the Nile will never flood again, solving an age-old problem. However, several new problems arose. The food chain was broken in the eastern Mediterranean, thereby reducing the fishing industry. Rapid erosion of the Nile Delta took place, introducing soil salinity into Upper Egypt. No longer limited by periodic dryness, the population of bilharzia (a waterborne snail parasite) has produced an epidemic of disease along the Nile. These side effects were not adequately anticipated by those responsible for the project. A systems view encompassing both natural and human-made elements, as a human-modified system, might have led to a better solution to the problem of flooding.

2.2 Physical and Conceptual Systems

Physical systems are those that manifest themselves in physical form. They are composed of real components and may be contrasted with *conceptual systems*, where symbols represent the attributes of components. Ideas, plans, concepts, and hypotheses are examples of conceptual systems.

A physical system consumes physical space, whereas conceptual systems are organizations of ideas. One type of conceptual system is the set of plans and specifications for a physical system before it is actually brought into being. A proposed physical system may be simulated in the abstract by a mathematical or other conceptual model. Conceptual systems often play an essential role in the operation of physical systems in the real world.

The totality of elements encompassed by all components, attributes, and relationships focused on a given result employ a process that determines the state changes (behaviors) of a system. A process may be mental (thinking, planning, and learning), mental-motor (writing, drawing, and testing), or mechanical (operating, functioning, and producing). Processes exist in both physical and conceptual systems.

Process occurs at many different levels within systems. The subordinate process essential for the operation of a total system is provided by the subsystem. The subsystem may, in turn, depend on more detailed subsystems. System complexity is the feature that defines the number of subsystems present and, consequently, the number of processes involved. A system may be bounded for the purpose of study at any process or subsystem level. Also, related systems that are normally analyzed individually may be studied as a group, and the group is often called a *system-of-systems* (SOS).

2.3 Static and Dynamic Systems

Another system dichotomy is the distinction of static and dynamic types. A *static system* is one whose states do not change because it has structural components but no operating or flow components, as exemplified by a bridge. A *dynamic system* exhibits behaviors because it combines structural components with operating and/or flow components. An example is a school, combining a building, students, teachers, books, curricula, and knowledge.

A dynamic conception of the universe has become a necessity. Yet, a general definition of a system as an ongoing process is incomplete. Many systems would not be included under this broad definition because they lack operating and flow components. A highway system is static, yet it contains the system elements of components, attributes, and functional relationships.

A system is static only in a limited frame of reference. A bridge system is constructed, maintained, and altered over a period of time. This is a dynamic process conducted by a construction subsystem operating on a flow of construction materials. A structural engineer must view the bridge's members as operating components that expand and contract as they experience temperature changes.

A static system serves a useful purpose only as a component or subsystem of a dynamic system. For example, a static bridge is part of a dynamic system with an overpass operating component processing a traffic flow component and with an underpass component handling water or traffic flow.

Systems may be characterized as having random properties. In almost all systems in both the natural and human-made categories, the inputs, process, and output can only be described in statistical terms. Uncertainty often occurs in both the number of inputs and the distribution of these inputs over time. For example, it is difficult to predict exactly the number of passengers who will check in for a flight, or the exact time each will arrive at the airport. However, because these factors can be described in terms of probability distributions, system operation may be considered *probabilistic* in its behavior.

For centuries, humans viewed the universe of phenomena as immutable and unchanging. People habitually thought in terms of certainties and constants. The substitution of a process-oriented description for the static description of the universe, and the idea that almost anything can be improved, distinguishes modern science and engineering from earlier thinking.

2.4 Closed and Open Systems

A *closed system* is one that does not interact significantly with its environment. The environment provides only a context for the system. Closed systems usually exhibit the characteristic of equilibrium resulting from internal rigidity that maintains the system in spite of influences from the environment. An example is the chemical equilibrium eventually reached in a closed vessel when various reactants are mixed together, provided that the reaction does not increase pressure to the point that the vessel explodes. The reaction and pressure can be predicted from a set of initial conditions. Closed systems involve deterministic interactions, with a one-to-one correspondence between initial and final states. There are relatively few closed systems in the natural and the human-made world.

An *open system* allows information, energy, and matter to cross its boundaries. Open systems interact with their environment, examples being plants, ecological systems, and business organizations. They exhibit the characteristics of *steady state*, wherein a dynamic interaction of system elements adjusts to changes in the environment. Because of this steady state, open systems are self-regulatory and often self-adaptive.

It is not always easy to classify a system as either open or closed. Open systems are typical of those that have come into being by natural processes. Human-made systems have both open and closed characteristics. They may reproduce natural conditions not manageable in the natural world. They are closed when designed for invariant input and statistically predictable output, as in the case of a spacecraft in flight.

Both closed and open systems exhibit the property of entropy. *Entropy* is defined here as the degree of disorganization in a system and is analogous to the use of the term in thermodynamics. In the thermodynamic usage, entropy is the energy unavailable for work resulting from energy transformation from one form to another.

In systems, increased entropy means increased disorganization. A decrease in entropy occurs as order occurs. Life represents a transition from disorder to order. Atoms of carbon, hydrogen, oxygen, and other elements become arranged in a complex and orderly fashion to produce a living organism. A conscious decrease in entropy must occur to create a human-made system. All human-made systems, from the most primitive to the most complex, consume entropy because they involve the creation of more orderly states from less orderly states.

3 SCIENCE AND SYSTEMS SCIENCE

The significant accumulation of scientific knowledge, which began in the eighteenth century and rapidly expanded in the twentieth, made it necessary to classify what was discovered into scientific disciplines. Science began its separation from philosophy almost two centuries ago. It then proliferated into more than 100 distinct disciplines. A relatively recent unifying development is the idea that systems have general characteristics, independent of the area of science to which they belong. In this section, the evolution of a science of systems is presented through an examination of cybernetics, general systems theory, and systemology.

3.1 Cybernetics

The word *cybernetics* was first used in 1947 by Norbert Wiener, but it is not explicitly defined in his classical book.[3] Cybernetics comes from the Greek word meaning “steersman” and is a cognate of “governor.” In its narrow view, cybernetics is equivalent to servo theory in

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[3] N. Wiener, *Cybernetics* (New York: John Wiley & Sons, Inc., 1948). Also see H. S. Tsien, *Engineering Cybernetics* (New York: McGrew Hill Book Co., 1954).

engineering. In its broad view, it may encompass much of natural science. Cybernetics has to do with self-regulation, whether mechanical, electromechanical, electrical, or biological.

The concept of feedback is central to cybernetic theory. All goal-seeking behavior is controlled by the feedback of corrective information about deviation from a desired state. The best known and most easily explained illustration of feedback is the action of a thermostat. The thermometer component of a thermostat senses temperature. When the actual temperature falls below that set into the thermostat, an internal contact is made, activating the heating system. When the temperature rises above that set into the thermostat, the contact is broken, shutting off the heating system.

Biological organisms are endowed with the capacity for self-regulation, called *homeostasis*. The biological organism and the physical world are both very complex. And, analogies exist between them and human-made systems. Through these analogies humans have learned some things about their properties that might have not been learned from the study of natural systems alone. As people develop even more complex systems, we will gain a better understanding of how to control them and our environment.

The science of cybernetics has made three important contributions to the area of regulation and control. First, it stresses the concept of information flow as a distinct system component and clarifies the distinction between the activating power and the information signal. Second, it recognizes that similarities in the action of control mechanisms involve principles that are fundamentally identical. Third, the basic principles of feedback control are subject to mathematical treatment.

A practical application of cybernetics has been the remarkable development of automatic equipment and automated processes, most controlled by microprocessors. However, its significance is greater than this technological contribution. The science of cybernetics is important not only for the control engineer but also for the purest of scientists. Cybernetics is the science of purposeful and optimal control found in complex natural processes and applicable in society as well as commercial enterprises.

3.2 General Systems Theory

An even broader unifying concept than cybernetics evolved during the late 1940s. It was the idea that basic principles common to all systems could be found that go beyond the concept of control and self-regulation. A unifying principle for science and a common ground for interdisciplinary relationships needed in the study of complex systems were being sought. Ludwig von Bertalanffy used the phrase *general systems theory* around 1950 to describe this endeavor.[4] A related contribution was made by Kenneth Boulding.[5]

General systems theory is concerned with developing a systematic framework for describing general relationships in the natural and the human-made world. The need for a general theory of systems arises out of the problem of communication among various disciplines. Although the scientific method brings similarity between the methods of approach, the results are often difficult to communicate across disciplinary boundaries. Concepts and hypotheses formulated in one area seldom carry over to another, where they could lead to significant forward progress.

One approach to an orderly framework is the structuring of a hierarchy of levels of complexity for individual systems studied in the various fields of inquiry. A *hierarchy of levels*

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[4] L. von Bertalanffy, "General System Theory: A New Approach to Unity of Science," *Human Biology*, December 1951.

[5] K. Boulding, "General Systems Theory: The Skeleton of Science," *Management Science*, April 1956.

can lead to a systematic approach to systems that has broad application. Boulding suggested such a hierarchy. It begins with the simplest level and proceeds to increasingly complex levels that usually incorporate the capabilities of all the previous levels, summarized approximately as follows:

1. The level of static structure or *frameworks*, ranging from the pattern of the atom to the anatomy of an animal to a map of the earth to the geography of the universe.
2. The level of the simple dynamic system, or *clockworks*, adding predetermined, necessary motions, such as the pulley, the steam engine, and the solar system.
3. The level of the *thermostat* or cybernetic system, adding the transmission and interpretation of information.
4. The level of the *cell*, the open system where life begins to be evident, adding self-maintenance of structure in the midst of a throughput of material.
5. The level of the *plant*, adding a genetic-societal structure with differentiated and mutually dependent parts, "blueprinted" growth, and primitive information receptors.
6. The level of the *animal*, adding mobility, teleological behavior, and self-awareness using specialized information receptors, a nervous system, and a brain with a knowledge structure.
7. The level of the *human*, adding self-consciousness; the ability to produce, absorb, and interpret symbols; and understanding of time, relationship, and history.
8. The level of *social organization*, adding roles, communication channels, the content and meaning of messages, value systems, transcription of images into historical record, art, music, poetry, and complex human emotion.
9. The level of the *transcendental system*, adding the ultimates and absolutes and unknowables.

The first level in Boulding's hierarchy is the most pervasive. Static systems are everywhere, and this category provides a basis for analysis and synthesis of systems at higher levels. Dynamic systems with predetermined outcomes are predominant in the natural sciences. At higher levels, cybernetic models are available, mostly in closed-loop form. Open systems are currently receiving scientific attention, but modeling difficulties arise regarding their self-regulating properties. Beyond this level, there is little systematic knowledge available. However, general systems theory provides science with a useful framework within which each specialized discipline may contribute. It allows scientists to compare concepts and similar findings, with its greatest benefit being that of communication across disciplines.

3.3 Systemology and Synthesis

The science of systems or their formation is called *systemology*. Problems and problem complexes faced by humankind are not organized along disciplinary lines. A new organization of scientific and professional effort based on the common attributes and characteristics of problems will likely accelerate beneficial progress. As systems science is promulgated by the formation and acceptance of interdisciplines, humankind will benefit from systemology and systems thinking.

Disciplines in science and the humanities developed largely by what society permitted scientists and humanists to investigate. Areas that provided the least challenge to cultural, social, and moral beliefs were given priority. The survival of science was also of concern in the progress of certain disciplines. However, recent developments have added to the acceptance of a scientific approach in most areas. Much credit for this can be given to the recent respectability of interdisciplinary inquiry. One of the most important contributions of systemology is that it offers a single vocabulary and a unified set of concepts applicable to many types of systems.

During the 1940s, scientists of established reputation in their respective fields accepted the challenge of attempting to understand a number of common processes in military operations. Their team effort was called *operations research*, and the focus of their attention was the optimization of operational military systems. After the war, this interdisciplinary area began to take on the attributes of a discipline and a profession. Today a body of systematic knowledge exists for both military and commercial operations. But operations research is not the only science of systems available today. Cybernetics, general systems research, organizational and policy sciences, management science, and the information sciences are others.

Formation of interdisciplines began in the middle of the last century and has brought about an evolutionary synthesis of knowledge. This has occurred not only within science but also between science and technology and between science and the humanities. The forward progress of systemology in the study of large-scale complex systems requires a synthesis of science and the humanities as well as a synthesis of science and technology. Synthesis, sometimes referred to as an interdisciplinary discipline, is the central activity of people often considered to be *synthesists*.

4 TECHNOLOGY AND TECHNICAL SYSTEMS

Technology is broadly defined as the branch of knowledge that deals with the mechanical and industrial arts, applied science, and engineering, or the sum of the ways in which social groups provide themselves with the material objects and the services of their civilization.[6] A key attribute of a civilization is the inherent ability and the knowledge to maintain its store of technology. Modern civilizations possess pervasive and potent technology that makes possible needed systems manifested as products, which include structures and services.

4.1 Technology and Society

Human society is characterized by its culture. Each human culture manifests itself through the media of technology. In turn, the manifestation of culture is an important indicator of the degree to which a society is technologically advanced.

The entire history of humankind is closely related to the progress of technology. But, technological progress is often stressful on people and their cultures alike. This need not be. The challenge should be to find ways for humans to live better lives as a result of new technological capability and social organizational structure.

In general, the complexity of systems desired by societies is increasing. As new technologies become available, the pull of “want” is augmented by a push to incorporate these new capabilities into both new and existing systems. The desire for better systems produces an ever-changing set of requirements. The identification of the “true” need in answer to a problem and the elicitation of “real” requirements is, in itself, a technological challenge.

Transition from the past to present and future technological states is not a one-step process. Continuing technical advances become available to society as time unfolds. Societal

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[6] This definition was adapted from the *Random House Webster’s Unabridged Dictionary*, 2nd ed. (New York: Random House, Inc., 2001).

response is often to make one transition and then to adopt a static pattern of behavior. A better response would be to seek new and well-thought-out possibilities for continuous advancement.

Improvement in technological literacy should increase the population of individuals capable of participating in this desirable activity. One key to imparting this literacy is the communication technologies now expanding at a rapid pace. Thus, technology in this sphere may act favorably to aid the understanding and subsequent evaluation by society of technologies in other spheres.

4.2 Technical Systems[7]

Science and technology is a phrase used often. Translated into its systems counterpart, this phrase prompts consideration of the link between systems science and technical systems. Technical or engineered systems have their foundation in both the natural and the systems sciences. They are a prominent and pervasive sector of the human-made world.

The phrase *technical system* may be used to represent all types of human-made artifacts, including technical products and processes. Accordingly, the technical system is the subject of the collection of activities that are performed by engineers within the processes of engineering design, including generating, retrieving, processing, and transmitting product information. It is also the subject of production processes, including work preparation and planning. It is also the subject of many economic considerations, both within enterprises and in society.

In museums, thousands of technical objects are on display, and they are recognized as products of technology. Their variety of functions, form, size, and so forth tends to obscure common properties and features. But vast variety also exists in nature, and in those circumstances clearly defined kingdoms of natural objects have been defined for study in the natural sciences. Likewise, attempts have been made to define terms that conceptually describe classes of technical objects.

Technical objects can be referred to simply as objects, entities, things, machines, implements, products, documents, or technical works. The results of a manufacturing activity, as the conceptual content of technology, can be termed *artifacts* or *instrumentum*. Such definitions are meant to include all manner of machines, appliances, implements, structures, weapons, and vessels that represent the technical means by which humans achieve their ends. But, to be complete, this definition must recognize the hierarchical nature of systems and the interactions that occur between levels in the hierarchy. For example, the "system" of interest may be a transportation system, an airline system within the transportation system, or an aircraft system contained within the airline system.

Little difficulty exists in the classification of systems as either natural, technical (human-made), or human-modified. But it is difficult to classify technical systems accurately. One approach is to classify in accordance with the well-established subdivisions of technology in industry, for example, civil engineering, electrical engineering, and mechanical engineering. However, from a practical and organizational viewpoint, this does not permit a precise definition of a mechanical system or electrical system because no firm boundary can be established by describing these systems as outcomes of mechanical or electrical engineering.

Modern developments of technical systems have generally blurred the boundaries. Electronic and computer products, especially software, are increasingly used together with mechanical and human interfaces. Each acts as a subsystem to a system of greater complexity and purpose. Most systems in use today are hybrids of the simple systems of the past.

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[7] This section was adapted from V. Hubka and W. E. Eder, *Theory of Technical Systems* (Berlin: Springer-Verlag, 1988).

4.3 Technological Growth and Change

Technological growth and change is occurring continuously and is initiated by attempts to respond to unmet deficiencies and by attempts to perform ongoing activities in a more effective and efficient manner. In addition, changes are being stimulated by political objectives, social factors, and ecological concerns.

In general, people are not satisfied with the impact of the human-made or technical systems on the natural world and on humankind. Because engineering and the applied sciences are largely responsible for bringing technical systems into being, it is not surprising that there is some dissatisfaction with these fields of endeavor. Accordingly, technical and economic feasibility can no longer be the sole determinants of what engineers do. Ecological, political, social, cultural, and even psychological influences are equally important considerations. The number of factors in any given engineering project has multiplied. Because of the shifts in social attitudes toward moral responsibility, the ethics of personal decisions are becoming a major professional concern. Engineering is not alone in facing up to these newer considerations.

As examples, environmental concerns have resulted in recent legislation and regulations requiring new methods for crop protection from insects, new means for the disposal of medical waste, and new methods for treating solid waste. Concern for shortages of fossil fuel sources as well as ecological impacts brought about a great focus on energy conservation and alternative energy sources. These and other comparable situations were created through both properly planned programs and as a result of panic situations. A common outcome is that all have stimulated beneficial technological innovation.

The world is increasing in complexity because of human intervention. Through the advent of advanced technologies, transportation times have been greatly reduced, and vastly more efficient means of communication have been introduced. Every aspect of human existence has become more intimate and interactive. The need for integration of ideas and conflict resolution becomes more important. At the same time, increasing populations and the desire for larger and better systems is leading to the accelerated exploitation of resources and increased environmental impact. A variety of technically literate specialists, if properly organized and incentivized, can meet most needs that arise from technological advancement and change.

5 TRANSITION TO THE SYSTEMS AGE[8]

Evidence suggests that the advanced nations of the world are leaving one technological age and entering another. It appears that this transition is bringing about a change in the conception of the world in which we live. This conception is both a realization of the complexity of natural and human-made systems and a basis for improvement in humankind's management of these systems. Long-term sustainability of both human-made systems and the natural world is becoming a common desideratum.

5.1 The Machine Age

Two ideas have been dominant in the way people seek to understand the world in which we live. The first is called *reductionism*. It consists of the belief that everything can be reduced, decomposed, or disassembled to simple indivisible parts. These were taken to be atoms in

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[8] The first part of this section was adapted from R. L. Ackoff, *Redesigning the Future* (New York: John Wiley & Sons, Inc., 1974).

physics; simple substances in chemistry; cells in biology; and monads, instincts, drives, motives, and needs in psychology.

Reductionism gives rise to an analytical way of thinking about the world, a way of seeking explanations and understanding. Analysis consists, first, of taking apart what is to be explained, disassembling it, if possible, down to the independent and indivisible parts of which it is composed; second, of explaining the behavior of these parts; and, finally, of aggregating these partial explanations into an explanation of the whole. For example, the analysis of a problem consists of breaking it down into a set of as simple problems as possible, solving each, and assembling their solutions into a solution of the whole. If the analyst succeeds in decomposing a problem into simpler problems that are independent of each other, aggregating the partial solutions is not required because the solution to the whole is simply the sum of the solutions to its independent parts. In the industrial or *Machine Age*, understanding the world was taken to be the sum, or result, of an understanding of its parts, which were conceptualized as independently of each other as was possible.

The second basic idea was that of *mechanism*. All phenomena were believed to be explainable by using only one ultimately simple relation, cause and effect. One thing or event was taken to be the *cause* of another (its *effect*) if it was both necessary and sufficient for the other. Because a cause was taken to be sufficient for its effect, nothing was required to explain the effect other than the cause. Consequently, the search for causes was environment free. It employed what is now called "closed-system" thinking. Laws such as that of freely falling bodies were formulated so as to exclude environmental effects. Specially designed environments, called *laboratories*, were used so as to exclude environmental effects on phenomena under study.

Causal-based laws permit no exceptions. Effects are completely determined by causes. Hence, the prevailing view of the world was deterministic. It was also mechanistic because science found no need for teleological concepts (such as functions, goals, purposes, choice, and free will) in explaining any natural phenomenon. They considered such concepts to be unnecessary, illusory, or meaningless. The commitment to causal thinking yielded a conception of the world as a machine; it was taken to be like a hermetically sealed clock—a self-contained mechanism whose behavior was completely determined by its own structure.

The *Industrial Revolution* brought about *mechanization*, the substitution of machines for people as a source of physical work. This process affected the nature of work left for people to do. They no longer did all the things necessary to make a product; they repeatedly performed a simple operation in the production process. Consequently, the more machines were used as a substitute for people at work, the more workers were made to behave like machines. The dehumanization of work was an irony of the Industrial Revolution and the Machine Age.

5.2 The Systems Age

Although eras do not have precise beginnings and endings, the 1940s can be said to have contained the beginning of the end of the Machine Age and the beginning of the *Systems Age*. This new age is the result of a new intellectual framework in which the doctrines of reductionism and mechanism and the analytical mode of thought are being supplemented by the doctrines of expansionism, teleology, and a new synthetic (or systems) mode of thought.

Expansionism is a doctrine that considers all objects and events, and all experiences of them, as parts of larger wholes. It does not deny that they have parts, but it focuses on the wholes of which they are part. It provides another way of viewing things, a way that is different from, but compatible with, reductionism. It turns attention from ultimate elements to a whole with interrelated parts—to systems.

Preoccupation with systems brings with it the synthetic mode of thought. In the *analytic* mode, an explanation of the whole was derived from explanations of its parts. In *synthetic* thinking, something to be explained is viewed as part of a larger system and is explained in terms of its role in that larger system. The Systems Age is more interested in putting things together than in taking them apart.

Analytic thinking is outside-in thinking; synthetic thinking is inside-out thinking. Neither negates the value of the other, but by synthetic thinking one can gain understanding that cannot be obtained through analysis, particularly of collective phenomena.

The synthetic mode of thought, when applied to systems problems, is called *systems thinking* or the *systems approach*. This approach is based on the observation that when each part of a system performs as well as possible, the system as a whole may not perform as well as possible. This follows from the fact that the sum of the functioning of the parts is seldom equal to the functioning of the whole. Accordingly, the synthetic mode seeks to overcome the often observed predisposition to perfect details and ignore system outcomes.

Because the Systems Age is *teleologically oriented*, it is preoccupied with systems that are goal seeking or purposeful; that is, systems that offer the choice of either means or ends, or both. It is interested in purely mechanical systems only insofar as they can be used as enablers for purposeful systems. Furthermore, the Systems Age is largely concerned with purposeful systems, some of whose parts are purposeful; in the human domain, these are called *social groups*. The most important class of social groups is the one containing systems whose parts perform different functions that have a division of functional labor; these are called *organizations*.

In the Systems Age, attention is focused on groups and on organizations as parts of larger purposeful societal systems. Participative management, collaboration, group decision making, and total quality management are new working arrangements within the organization. Among organizations is now found a keen concern for social and environmental factors, with economic competition continuing to increase worldwide.

5.3 Engineering in the Systems Age

Engineering activities of analysis and design are not ends in themselves, but are a means for satisfying human wants. Thus, modern engineering has two aspects. One aspect concerns itself with the materials and forces of nature; the other is concerned with the needs of people.

In the Systems Age, successful accomplishment of engineering objectives usually requires a combination of technical specialties and expertise. Engineering in the Systems Age must be a team activity where various individuals involved are cognizant of the important relationships between specialties and between economic factors, ecological factors, political factors, and societal factors. The engineering decisions of today require consideration of these factors in the early stage of system design and development, and the results of such decisions have a definite impact on these factors. Conversely, these factors usually impose constraints on the design process. Thus, technical expertise must include not only the basic knowledge of individual specialty fields of engineering but also knowledge of the context of the system being brought into being.

Although relatively small products, such as a wireless communication device, an electrical household appliance, or even an automobile, may employ a limited number of direct engineering personnel and supporting resources, there are many large-scale systems that require the combined input of specialists representing a wide variety of engineering and related disciplines. An example is that of a ground-based mass-transit system.

Civil engineers are required for the layout and/or design of the railway, tunnels, bridges, and facilities. Electrical engineers are involved in the design and provision of automatic controls, traction power, substations for power distribution, automatic fare collection, digital data systems, and so on. Mechanical engineers are necessary in the design of passenger vehicles and related mechanical equipment. Architectural engineers provide design support for the construction of passenger terminals. Reliability and maintainability engineers are involved in the design for system availability and the incorporation of supportability characteristics. Industrial engineers deal with the production and utilization aspects of passenger vehicles and human components. Test engineers evaluate the system to ensure that all performance, effectiveness, and system support requirements are met. Engineers in the planning and marketing areas are required to keep the public informed, to explain the technical aspects of the system, and to gather and incorporate public input. General systems engineers are required to ensure that all aspects of the system are properly integrated and function together as a single entity.

Although the preceding example is not all-inclusive, it is evident that many different disciplines are needed. In fact, there are some large projects, such as the development of a new aircraft, where the number of engineers needed to perform engineering functions is in the thousands. In addition, the different engineering types often range in the hundreds. These engineers, forming a part of a large organization, must not only be able to communicate with each other but must also be conversant with such interface areas as purchasing, accounting, personnel, and legal.

Another major factor associated with large projects is that considerable system development, production, evaluation, and support are often accomplished at supplier (sometimes known as *subcontractor*) facilities located throughout the world. Often there is a prime producer or contractor who is ultimately responsible for the development and production of the total system as an entity, and there are numerous suppliers providing different system components. Thus, much of the project work and many of the associated engineering functions may be accomplished at dispersed locations, often worldwide.

5.4 Engineering Education for the Systems Age

Engineering education has been subjected to in-depth study every decade or so, beginning with the Mann Report in 1918.[9] The most recent and authoritative study was conducted by the National Academy of Engineering (NAE) and published in 2005 under the title *Educating the Engineer of 2020.*[10]

Although acknowledging that certain basics of engineering will not change, this NAE report concluded that the explosion of knowledge, the global economy, and the way engineers will work will reflect an ongoing evolution that began to gain momentum at the end of the twentieth century. The report gives three overarching trends to be reckoned with by engineering educators, interacting with engineering leaders in government and industry:

1. The economy in which we work will be strongly influenced by the global marketplace for engineering services, evidenced by the outsourcing of engineering jobs, a growing need for interdisciplinary and system-based approaches, demands for new paradigms of customization, and an increasingly international talent pool.

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[9] C. R. Mann, "A Study of Engineering Education," Bulletin No. 11, The Carnegie Foundation for the Advancement of Teaching, 1918.

[10] National Academy of Engineering, *Educating the Engineer of 2020* (Washington, DC: National Academies Press, 2005).

2. The steady integration of technology in our public infrastructures and lives will call for more involvement by engineers in the setting of public policy and for participation in the civic arena.
3. The external forces in society, the economy, and the professional environment will all challenge the stability of the engineering workforce and affect our ability to attract the most talented individuals to an engineering career.

Continuing technological advances have created an increasing demand for engineers in most fields. But certain engineering and technical specialties will be merged or become obsolete with time. There will always be a demand for engineers who can synthesize and adapt to changes. The astute engineer should be able to detect trends and plan for satisfactory transitions by acquiring knowledge to broaden his or her capability.

6 SYSTEMS ENGINEERING

To this day, there is no commonly accepted definition of systems engineering in the literature. Almost a half-century ago, Hendrick W. Bode, writing on "The Systems Approach" in *Applied Science-Technological Progress*, said that "It seems natural to begin the discussion with an immediate formal definition of systems engineering. However, systems engineering is an amorphous, slippery subject that does not lend itself to such formal, didactic treatment. One does much better with a broader, more loose-jointed approach. Some writers have, in fact, sidestepped the issue entirely by simply saying that 'systems engineering is what systems engineers do.'"[11]

The definition of systems engineering and the systems approach is usually based on the background and experience of the individual or the performing organization. The variations are evident from the following five published definitions:

1. "An interdisciplinary approach and means to enable the realization of successful systems."[12]
2. "An interdisciplinary approach encompassing the entire technical effort to evolve into and verify an integrated and life-cycle balanced set of system people, product, and process solutions that satisfy customer needs. Systems engineering encompasses (a) the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for, system products and processes; (b) the definition and management of the system configuration; (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making."[13]
3. "The application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of

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[11] H. Bode, Report to the Committee on Science and Astronautics, U.S. House of Representatives, Washington, DC, 1967.

[12] International Council on Systems Engineering (INCOSE), 7670 Opportunity Road, Suite 220, San Diego, CA, USA.

[13] EIA/IS 632, "Systems Engineering," Electronic Industries Alliance, 2500 Wilson Boulevard, Arlington, VA, 1994.

all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and (c) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into the total engineering effort to meet cost, schedule, supportability, and technical performance objectives."[14]
4. "An interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability."[15]
5. "An approach to translate operational needs and requirements into operationally suitable blocks of systems. The approach shall consist of a top-down, iterative process of requirements analysis, functional analysis and allocation, design synthesis and verification, and system analysis and control. Systems engineering shall permeate design, manufacturing, test and evaluation, and support of the product. Systems engineering principles shall influence the balance between performance, risk, cost, and schedule."[16]

Although the definitions vary, there are some common threads. Basically, systems engineering is good engineering with special areas of emphasis. Some of these are the following:

1. A *top-down* approach that views the system as a whole. Although engineering activities in the past have adequately covered the design of various system components (representing a bottom-up approach), the necessary overview and understanding of how these components effectively perform together is frequently overlooked.
2. A *life-cycle* orientation that addresses all phases to include system design and development, production and/or construction, distribution, operation, maintenance and support, retirement, phase-out, and disposal. Emphasis in the past has been placed primarily on design and system acquisition activities, with little (if any) consideration given to their impact on production, operations, maintenance, support, and disposal. If one is to adequately identify risks associated with the up-front decision-making process, then such decisions must be based on life-cycle considerations.
3. A better and more complete effort is required regarding the initial *definition of system requirements*, relating these requirements to specific design criteria, and the follow-on analysis effort to ensure the effectiveness of early decision making in the design process. The true system requirements need to be well defined and specified and the traceability of these requirements from the system level downward needs to be visible. In the past, the early "front-end" analysis as applied to many new systems has been minimal. The lack of defining an early "baseline" has resulted in greater individual design efforts downstream.
4. An *interdisciplinary* or team approach throughout the system design and development process to ensure that all design objectives are addressed in an effective and efficient manner. This requires a complete understanding of many different design disciplines and their interrelationships, together with the methods, techniques, and tools that can be applied to facilitate implementation of the system engineering process.

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[14] DSMC, *Systems Engineering Management Guide*, Defense Systems Management College, Superintendent of Documents, U.S. Government Printing Office, Washington, DC, 1990.

[15] IEEE P1220, "Standard for Application and Management of the Systems Engineering Process," Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, NY, 1994.

[16] Enclosure 12 on *Systems Engineering* in DOD Instruction 5000.02, "Operation of the Defense Acquisition System," December 8, 2008.

Systems engineering is not a traditional engineering discipline in the same sense as civil engineering, electrical engineering, industrial engineering, mechanical engineering, reliability engineering, or any of the other engineering specialties. It should not be organized in a similar manner, nor does the implementation of systems engineering (or its methods) require extensive resources. However, a well-planned and highly disciplined approach must be followed. The systems engineering process involves the use of appropriate technologies and management principles in a synergetic manner. Its application requires synthesis and a focus on process, along with a new "thought process" that is compatible with the needs of the Systems Age.

7 SUMMARY AND EXTENSIONS

This chapter is devoted to helping the reader gain essential insight into systems in general, and *systems thinking* in particular, with orientation toward the engineering and analysis of technical systems.

System definitions, a discussion of system elements, and a high-level classification of systems provide an opening panorama. It is here that a consideration of the origin of systems provides an orientation to natural and human-made domains as an overarching dichotomy. The importance of this dichotomy cannot be overemphasized in the study and application of systems engineering and analysis. It is the suggested frame of reference for considering and understanding the interface and impact of the human-made world on the natural world and on humans.

Individuals interested in obtaining an in-depth appreciation for this interface and the mitigation of environmental impacts are encouraged to read T. E. Graedel and B. R. Allenby, *Industrial Ecology*, 2nd ed., Prentice Hall, 2003. Also of contemporary interest is the issue of sustainability treated as part of an integrated approach to sustainable engineering by P. Stasinopoulos, M. H. Smith, K. Hargroves, and C. Desha, *Whole System Design*, Earthscan Publishing, 2009. These works are recommended as an extension to this chapter, because they illuminate and address the sensitive interface between the natural and the human-made.

This chapter is also anchored by the domains of *systems science* and *systems engineering*, beginning with the former and ending with the latter. Accordingly, it is important to recognize that at least one professional organization exists for each domain. For systems science, there is the International Society for the System Sciences (ISSS), originally named the "Society for General Systems Research." ISSS was established at the 1956 meeting of the American Association for the Advancement of Science under the leadership of biologist Ludwig von Bertalanffy, economist Kenneth Boulding, mathematician–biologist Anatol Rapoport, neurophysiologist Ralph Gerard, psychologist James Miller, and anthropologist Margaret Mead.

The founders of the International Society for the System Sciences felt strongly that the *systematic* (*holistic*) aspect of reality was being overlooked or downgraded by the conventional disciplines, which emphasize specialization and *reductionist* approaches to science. They stressed the need for more general principles and theories and sought to create a professional organization that would transcend the tendency toward fragmentation in the scientific enterprise. The reader interested in exploring the field of systems science and learning more about the work of the International Society for System Sciences, may visit the ISSS website at *http://www.isss.org*.

Technology, human-made, and human-modified systems comprise the core of this chapter, with science and systems science as the foundation. Accordingly, an in-depth understanding of the engineered system (through a focused definition and description) is not part of this chapter. The purpose is to clarify the distinction between systems that are engineered and systems that exist naturally.

Transition to the Systems Age spawned the systems sciences and, driven by potent technologies, established a compelling need for systems engineering. Accordingly, selected definitions of systems engineering are given at the end of this chapter. Many others exist, but are not included herein. However, systems engineering may be described as a *technologically-based interdisciplinary process* for bringing systems into being. Systems engineering is an *engineering interdiscipline* in its own right, with important engineering domain manifestations.

The most prominent professional organization for systems engineering is the International Council on Systems Engineering (INCOSE). Originally named the "National Council on Systems Engineering," NCOSE was chartered in 1991 in the United States; it has now expanded worldwide to become the leading society to develop, nurture, and enhance the interdisciplinary approach and means to enable the realization of successful systems. INCOSE has strong and enduring ties with industry, academia, and government to achieve the following goals: (1) to provide a focal point for the dissemination of systems engineering knowledge; (2) to promote collaboration in systems engineering education and research; (3) to assure the establishment of professional standards for integrity in the practice of systems engineering; (4) to improve the professional status of persons engaged in the practice of systems engineering; and (5) to encourage governmental and industrial support for research and educational programs that will improve the systems engineering process and its practice. An expanded view of systems engineering, as promulgated through the International Council on Systems Engineering, as well as a window into a wealth of information about this relatively new engineering interdiscipline may be obtained at *http://www.incose.org*.

Most scientific and professional societies in the United States interact and collaborate with cognizant but independent honor societies. The cognizant honor society for systems engineering is the Omega Alpha Association (OAA), emerging under the motto "Think About the End Before the Beginning." Chartered in 2006 as an international honor association, OAA has the overarching objective of advancing the systems engineering process and its professional practice in service to humankind. Among subordinate objectives are opportunities to (1) inculcate a greater appreciation within the engineering profession that every human design decision shapes the human-made world and determines its impact upon the natural world and upon people; (2) advance system design and development morphology through a better comprehension and adaptation of the da Vinci philosophy of thinking about the end before the beginning; that is, determining what designed entities are intended to do before specifying what the entities are and concentrating on the provision of functionality, capability, or a solution before designing the entities per se; and (3) encourage excellence in systems engineering education and research through collaboration with academic institutions and professional societies to evolve robust policies and procedures for recognizing superb academic programs and students. The OAA website, *http://www.omegalpha.org*, provides information about OAA goals and objectives, as well as the OAA vision for recognizing and advancing excellence in systems engineering, particularly in academia.

QUESTIONS AND PROBLEMS

1. Pick a system with which you are familiar and verify that it is indeed a system as per the system definition given at the beginning of Section 1.
2. Name and identify the components, attributes, and relationships in the system you picked in Question 1.
3. Pick a system that alters material and identify its structural components, operating components, and flow components.
4. Select a complex system and discuss it in terms of the hierarchy of systems.
5. Select a complex system and identify some different ways of establishing its boundaries.
6. Identify and contrast a physical and conceptual system.
7. Identify and contrast a static and a dynamic system.
8. Identify and contrast a closed and an open system.
9. Pick a natural system and describe it in terms of components, attributes, and relationships; repeat for a human-made system and for a human-modified system.
10. Identify the purpose(s) of the above human-made system and name some possible measures of worth.
11. For the above human-made system, describe its state at some point in time, describe one of its behaviors, and summarize its process.
12. For the above human-made system, name two components that have a relationship, identify what need each component fills for the other component, and describe how the attributes of these two components must be engineered so that the pair functions together effectively in contributing to the system's purpose(s).
13. Give an example of a first-order relationship, a second-order relationship, and redundance.
14. For a human-modified system, identify some of the ways in which the modified natural system could be degraded and some of the ways in which it could be improved.
15. Give an example of a random dynamic system property and of a steady-state dynamic system property.
16. Give an example of a system that reaches equilibrium and of a system that disintegrates over time.
17. Is a government with executive, legislative, and judicial branches three systems or a single system? Why?
18. Identify a system-of-systems whose analysis could yield insights not available by separately analyzing the individual systems of which it is composed.
19. Explain cybernetics by using an example of your choice.
20. Give a system example at any five of the levels in Boulding's hierarchy.
21. Select a system at one of the higher levels in Boulding's hierarchy and describe if it does or does not incorporate the lower levels.
22. Identify a societal need, define the requirements of a system that would fill that need, and define the objective(s) of that system.
23. What are the similarities between systemology and synthesis?
24. What difficulty is encountered in attempting to classify technical systems?
25. Name some of the factors driving technological advancement and change.
26. What benefits could result from improving systems thinking in society?
27. Identify the attributes of the Machine or Industrial Age and the Systems Age.

28. Explain the difference between analytic and synthetic thinking.

29. What are the special engineering requirements and challenges in the Systems Age?

30. What are the differences (and similarities) between systems engineering and the traditional engineering disciplines?

31. Given the recommendations in *Educating the Engineer of 2020*, what should be added to the curriculum with which you are familiar?

32. Give an example of a problem requiring an interdisciplinary approach and identify the needed disciplines.

33. Name an interdiscipline and identify the disciplines from which it was drawn.

34. Write your own (preferred) definition of systems engineering.

35. Go to the website of ISSS given in Section 7 and summarize the goal of the society.

36. Go to the website of INCOSE given in Section 7 and summarize the goals of the council.

37. Contrast the goals of ISSS and INCOSE as given in Section 7 or on the Web.

38. Go to the website of OAA and compare this honor society with one that you are familiar with.

Bringing Systems Into Being

The world in which we live may be divided into the natural world and the human-made world. Included in the former are all elements of the world that came into being by natural processes. The human-made world is made up of all human-originated systems, their product subsystems (including structures and services), and their other subsystems (such as those for production and support).

Systems engineering and analysis reveals unexpected ways of using technology to bring new and improved systems and products into being that will be more competitive in the global economy. New and emerging technologies are expanding physically realizable design options and enhancing capabilities for developing more cost-effective systems. And, unprecedented improvement possibilities arise from the proper application of the concepts and principles of systems engineering and analysis to legacy systems.

This chapter introduces a technologically based interdisciplinary process encompassing an extension of engineering through all phases of the system life cycle; that is, design and development, production or construction, utilization and support, and phase-out and disposal. Upon completion, this chapter should provide the reader with an in-depth understanding of the following:

- A detailed definition and description for the category of systems that are human-made, in contrast with a definition of general systems;
- The product as part of the engineered system, yet distinguishable from it, with emphasis on the system as the overarching entity to be brought into being;
- Product and system categories with life-cycle engineering and design as a generic paradigm for the realization of competitive products and systems;
- Engineering the relationships among systems to achieve sustainability of the product and the environment, synergy among human-made systems, and continuous improvement of human existence;
- System design evaluation and the multiple-criteria domain within which it is best pursued;
- Integration and iteration in system design, invoking the major activities of synthesis, analysis, and evaluation;

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- A morphology for synthesis, analysis, and evaluation and its effective utilization within the systems engineering process;
- The importance of investing in systems thinking and engineering early in the life cycle and the importance thereto of systems engineering management; and
- Potential benefits to be obtained from the proper and timely implementation of systems engineering and analysis.

The final section of this chapter provides a summary and extension of the key concepts and ideas pertaining to the process of bringing systems into being. It is augmented with some annotated references and website addresses identifying opportunities for further inquiry.

1 THE ENGINEERED SYSTEM[1]

The tangible outcome of systems engineering and analysis is an engineered or technical system, whether human-made or human-modified. This section and the material that follows pertain to the organized technological activities for bringing engineered systems into being. To begin on solid ground, it is necessary to define the engineered system in terms of its characteristics.

1.1 Characteristics of the Engineered System

An engineered or technical system is a human-made or human-modified system designed to meet functional purposes or objectives. Systems can be engineered well or poorly. The phrase "engineered system" in this book implies a well-engineered system. A well-engineered system has the following characteristics:

1. Engineered systems have *functional purposes* in response to identified *needs* and have the ability to achieve stated *operational objectives*.
2. Engineered systems are *brought into being* and *operate* over a life cycle, beginning with identification of needs and ending with phase-out and disposal.
3. Engineered systems have design momentum that steadily increases throughout design, production, and deployment, and then decreases throughout phase-out, retirement, and disposal.
4. Engineered systems are composed of a harmonized *combination of resources*, such as facilities, equipment, materials, people, information, software, and money.
5. Engineered systems are composed of *subsystems* and related *components* that *interact* with each other to produce a desired system response or behavior.
6. Engineered systems are part of a *hierarchy* and are influenced by external factors from larger systems of which they are a part and from sibling systems from which they are composed.

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[1] The phrase "engineering system" is occasionally used. However, it will be used in this text only to refer to the organized activity of technical and supporting people, together with design and evaluation tools and facilities utilized in the process of bringing the engineered system into being.

7. Engineered systems are *embedded* into the natural world and *interact* with it in desirable as well as undesirable ways.

Systems engineering is defined in several ways. Basically, systems engineering is a functionally-oriented, technologically-based interdisciplinary process for bringing systems and products (human-made entities) into being as well as for improving existing systems. The outcome of systems engineering is the engineered system as previously described. Its overarching purpose is to make the world better, primarily for people. Accordingly, human-made entities should be designed to satisfy human needs and/or objectives effectively while minimizing system life-cycle cost, as well as the intangible costs of societal and ecological impacts.

Organization, humankind's most important innovation, is the time-tested means for bringing human-made entities into being. While the main focus is nominally on the entities themselves, systems engineering embraces a better strategy. Systems engineering concentrates on *what the entities are intended to do* before determining *what the entities are composed of*. As simply stated within the profession of architecture, *form follows function*. Thus, instead of offering systems or system elements and products per se, the organizational focus should shift to designing, delivering, and sustaining functionality, a capability, or a solution.

1.2 Product and System Categories

It is interesting and useful to note that systems are often known by their products. They are identified in terms of the products they propose, produce, deliver, or in other ways bring into being. Examples are manufacturing systems that produce products, construction systems that erect structures, transportation systems that move people or goods, traffic control systems that manage vehicle or aircraft flow, maintenance systems that repair or restore, and service systems that meet the need of a consumer or patient. What the system does is manifested through the product it provides. The product and its companion system are inexorably linked.

As frameworks for study, or baselines, two generic product/system categories are presented and characterized in this section. Consideration of these categories is intended to serve two purposes. First, it will help explain and clarify the topics and steps in the process of bringing engineered or technical systems into being. Then, in subsequent chapters, these categories and examples will provide opportunities for look-back reference to generic situations. Although there are other less generic examples in those chapters, greater understanding of them may be imparted by reference to the categories established in this section.

Single-Entity Product Systems. A single-entity product system, for example, may manifest itself as a bridge, a custom-designed home entertainment center, a custom software system, or a unique consulting session. The product may be a consumable (a nonstandard banquet or a counseling session) or a repairable (a highway or a supercomputer). Another useful classification is to distinguish consumer goods from producer goods, the latter being employed to produce the former. A product, as considered in this textbook, is not an engineered system no matter how complex it might be.

The product standing alone is not an engineered system. Consider a bridge constructed to meet the need for crossing an obstacle (a river, a water body, or another roadway). The engineered system is composed of the bridge structure plus a construction subsystem, a maintenance subsystem, an operating and support subsystem, and a phase-out and demolition process. Likewise, an item of equipment for producer or consumer use is not a system within the definition and description of an engineered system given in Section 1.1.

Manufacturing plants that produce repairable or consumable products, warehouses or shopping centers that distribute products, hospital facilities that provide health care services, and air traffic control systems that produce orderly traffic flow are also single-entity systems when the plant, shopping center, or hospital is the product being brought into being. These entities, in combination with appended and companion subsystems, may rightfully be considered engineered systems.

The preceding recognizes the engineered system as more than just the consumable or repairable product, be it a single entity, a population of homogenous entities, or a flow of entities. The product must be treated as part of a system to be engineered, deployed, and operated. Although the product subsystem (including structure or service) directly meets the customer's need, this need must be functionally decomposed and allocated to the subsystems and components comprising the overall system.

Multiple-Entity Population Systems. Multiple-entity populations, often homogenous in nature, are quite common. Thinking of these populations as being aggregated generic products permits them to be studied probabilistically. However, the engineered system is more than just a single entity in the population, or even the entities as a population. It is composed of the population together with the subsystems of production, maintenance and support, regeneration, and phase-out and disposal.

A set of needs provides justification for bringing the population into being. This set of needs drives the life-cycle phases of acquisition and utilization, made up of design, construction or production, maintenance and support, renovation, and eventually ending with phase-out and demolition/disposal. As with single-entity product systems, the product is the subsystem that directly meets the customer's need.

Examples of repairable-entity populations include the following: The airlines and the military acquire, operate, and maintain aircraft with population characteristics. In ground transit, vehicles (such as taxicabs, rental automobiles, and commercial trucks) constitute repairable equipment populations. Production equipment types (such as machine tools, weaving looms, and autoclaves) are populations of equipment classified as producer goods.

Also consider repairable (renovatable) populations of structures, often homogenous in nature. In multi-family housing, a population of structures is composed of individual dwelling units constructed to meet the need for shelter at a certain location. In multi-tenant office buildings, the population of individual offices constitutes a population of renovatable entities. And in urban or suburban areas, public clinics constitute a distributed population of structures to provide health care.

The simplest multi-entity populations are called inventories. These inventories may be made up of consumables or repairables. Examples of consumables are small appliances, batteries, foodstuffs, toiletries, publications, and many other entities that are a part of everyday life. Repairable-entity inventories are often subsystems or components for prime equipment. For example, aircraft hydraulic pumps, automobile starters and alternators, and automation controllers are repairable entities that are components of higher-level systems.

Homogenous populations lend themselves to designs that are targeted to the end product or prime equipment, as well as to the population as a whole. Economies of scale, production and maintenance learning, mortality considerations, operational analyses based on probability and statistics, and so on, all apply to the repairable-entity population to a greater or lesser degree. But the system to be brought into being must be larger in scope than the population itself, if the end result is to be satisfactory to the producer and customer.

1.3 Engineering the Product and the System

People often acquire diverse products to meet specific needs without companion contributing systems to ensure the best overall results, and without adequately considering the effects of the products on the natural world, on humans, and on other human-made systems. Proper application of systems engineering and analysis ensures timely and balanced evaluation of all issues to harmonize overall results from human investments, minimizing problems and maximizing satisfaction.

Engineering has always been concerned with the economical use of limited resources to achieve objectives. The purpose of the engineering activities of design and analysis is to determine how physical and conceptual factors may be altered to create the most utility for the least cost, in terms of product cost, product service cost, social cost, and environmental cost. Viewed in this context, engineering should be practiced in an expanded way, with engineering of the system placed ahead of concern for product components thereof.[2]

Classical engineering focuses on physical factors such as the selection and design of physical components and their behaviors and interfaces. Achieving the best overall results requires focusing initially on conceptual factors, such as needs, requirements, and functions. The ultimate system, however, is manifested physically where the main objective is usually considered to be product performance, rather than the design and development of the overall system of which the product is a part. A product cannot come into being and be sustained without a production or construction capability, without support and maintenance, and so on. Engineering the system and product usually requires an interdisciplinary approach embracing both the product and associated capabilities for production or construction, product and production system maintenance, support and regeneration, logistics, connected system relationships, and phase-out and disposal.

A product may also be a service such as health care, learning modules, entertainment packets, financial services and controls, and orderly traffic flow. In these service examples, the engineered system is a health care system, an educational system, an entertainment system, a financial system, and a traffic control system.

Systems and their associated products are designed, developed, deployed, renewed, and phased out in accordance with processes that are not as well understood as they might be. The cost-effectiveness of the resulting technical entities can be enhanced by placing emphasis on the following:

1. Improving methods for determining the scope of needs to be met by the system. All aspects of a systems engineering project are profoundly affected by the scope of needs, so this determination should be accomplished first. Initial consideration of a broad set of needs often yields a consolidated solution that addresses multiple needs in a more cost-effective manner than a separate solution for each need.
2. Improving methods for defining product and system requirements as they relate to verified customer needs and external mandates. This should be done early in the design phase, along with a determination of performance, effectiveness, and specification of essential system characteristics.

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[2] According to the definition of engineering adopted by the Accreditation Board for Engineering and Technology (ABET), "Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize economically the materials and forces of nature for the benefit of mankind." This definition is understood herein to encompass both systems and products, with the product often being a structure or service.

3. Addressing the total system with all of its elements from a life-cycle perspective, and from the product to its elements of support and renewal. This means defining the system in functional terms before identifying hardware, software, people, facilities, information, or combinations thereof.
4. Considering interactions in the overall system hierarchy. This includes relationships between pairs of system components, between higher and lower levels within the system hierarchy, and between sibling systems or subsystems.
5. Organizing and integrating the necessary engineering and related disciplines into a top-down systems-engineering effort in a concurrent and timely manner.
6. Establishing a disciplined approach with appropriate review, evaluation, and feedback provisions to ensure orderly and efficient progress from the initial identification of needs through phase-out and disposal.

Any useful system must respond to identified *functional needs*. Accordingly, the elements of a system must not only include those items that relate directly to the accomplishment of a given operational scenario or mission profile but must also include those elements of logistics and maintenance support for use should failure of a prime element(s) occur. To ensure the successful completion of a mission, all necessary supporting elements must be available, in place, and ready to respond. System sustainability can help insure that the system continues meeting the functional needs in a competitive manner as the needs and the competition evolves. And, system sustainability contributes to overall sustainability of the environment.

1.4 Engineering for Product Competitiveness

Product competitiveness is desired by both commercial and public-sector producers worldwide. Thus, the systems engineering challenge is to bring products and systems into being that meet customer expectations cost-effectively.

Because of intensifying international competition, producers are seeking ways to gain a sustainable competitive advantage in the marketplace. Acquisitions, mergers, and advertising campaigns seem unable to create the intrinsic wealth and goodwill necessary for the long-term health of the organization. Economic competitiveness is essential. Engineering with an emphasis on economic competitiveness must become coequal with concerns for advertising, production distribution, finance, and the like.

Available human and physical resources are dwindling. The industrial base is expanding worldwide, and international competition is increasing rapidly. Many organizations are downsizing, seeking to improve their operations, and considering international partners. Competition has reduced the number of suppliers and subcontractors able to respond. This is occurring at a time when the number of qualified team members required for complex system development is increasing. As a consequence, needed new systems are being deferred in favor of extending the life of existing systems.

All other factors being equal, people will meet their needs by purchasing products and services that offer the highest value–cost ratio, subjectively evaluated. This ratio can be increased by giving more attention to the resource-constrained world within which engineering is practiced. To ensure economic competitiveness of the product and enabling system, engineering must become more closely associated with economics and economic feasibility. This is best accomplished through a system life-cycle approach to engineering.

2 SYSTEM LIFE-CYCLE ENGINEERING

Experience over many decades indicates that a properly functioning system that is effective and economically competitive cannot be achieved through efforts applied largely after it comes into being. Accordingly, it is essential that anticipated outcomes during, as well as after, system utilization be considered during the early stages of design and development. Responsibility for *life-cycle engineering,* largely neglected in the past, must become the central engineering focus.

2.1 The Product and System Life Cycles

Fundamental to the application of systems engineering is an understanding of the life-cycle process, illustrated for the product in Figure 1. The product life cycle begins with the identification of a need and extends through conceptual and preliminary design, detail design and development, production or construction, distribution, utilization, support, phase-out, and disposal. The life-cycle phases are classified as *acquisition* and *utilization* to recognize producer and customer activities.[3]

System life-cycle engineering goes beyond the product life cycle viewed in isolation. It must simultaneously embrace the life cycle of the production or construction subsystem, the life cycle of the maintenance and support subsystem, and the life cycle for retirement, phase-out, reuse, and disposal as another subsystem. The overall system is made up of four concurrent life cycles progressing in parallel, as is illustrated in Figure 2. This conceptualization is the basis for *concurrent engineering*.[4]

The need for the product comes into focus first. This recognition initiates conceptual design to meet the need. Then, during conceptual design of the product, consideration should simultaneously be given to its production. This gives rise to a parallel life cycle for a production and/or construction capability. Many producer-related activities are needed to prepare for the production of a product, whether the production capability is a manufacturing plant, construction contractors, or a service activity.

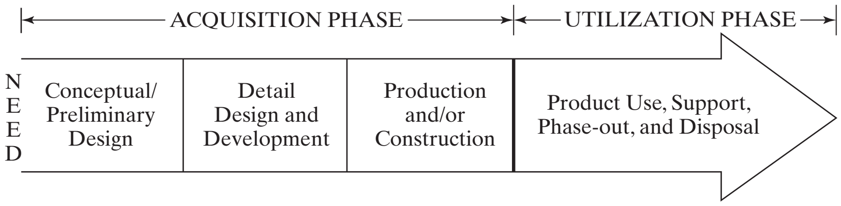

Figure 1 The product life cycle.

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[3] This classification represents a generic approach. Sometimes the *acquisition* process may involve both the customer (or procuring agency) and the producer (or contractor), whereas utilization may include a combination of contractor and customer (or ultimate user) activities. In some instances, the customer may not be the ultimate user (as is the case in the defense sector) but represents the user's interests during the acquisition process.

[4] *Concurrent engineering* is defined as a systematic approach to creating a system design that simultaneously considers all phases of the life cycle, from conception through disposal, to include consideration of production, distribution, maintenance, phase-out, and so on.

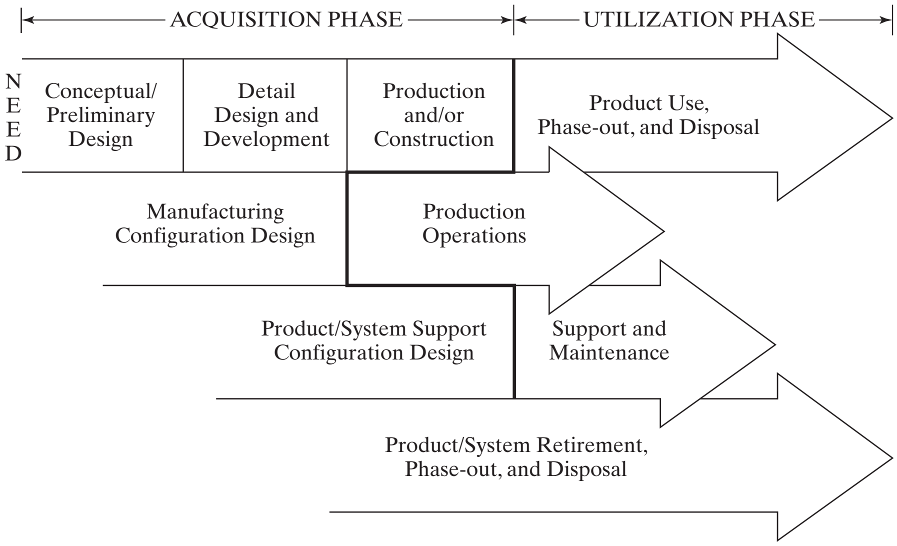

Figure 2 Life cycles of the system.

Also shown in Figure 2 is another life cycle of considerable importance that is often neglected until product and production design is completed. This is the life cycle for support activities, including the maintenance, logistic support, and technical skills needed to service the product during use, to support the production capability during its duty cycle, and to maintain the viability of the entire system. Logistic, maintenance, technical support, and regeneration requirements planning should begin during product conceptual design in a coordinated manner.

As each of the life cycles is considered, design features should be integrated to facilitate phase-out, regeneration, or retirement having minimal impact on interrelated systems. For example, attention to end-of-life recyclability, reusability, and disposability will contribute to environmental sustainability. Also, the system should be made ready for regeneration by anticipating and addressing changes in requirements, such as increases in complexity, incorporation of planned new technology, likely new regulations, market expansion, and others.

In addition, the interactions between the product and system and any related systems should begin receiving compatibility attention during conceptual design to minimize the need for product and system redesign. Whether the interrelated system is a companion product sold by the same company, an environmental system that may be degraded, or a computer system on which a software product runs, the relationship with the product and system under development must be engineered concurrently.

2.2 Designing for the Life Cycle

Design within the system life-cycle context differs from design in the ordinary sense. Life-cycle-guided design is simultaneously responsive to customer needs (i.e., to requirements expressed in functional terms) and to life-cycle outcomes. Design should not only transform a need into a system configuration but should also ensure the design's compatibility with related physical and functional requirements. Further, it should consider operational outcomes expressed as producibility, reliability, maintainability, usability, supportability, serviceability, disposability, sustainability, and others, in addition to performance, effectiveness, and affordability.

A detailed presentation of the elaborate technological activities and interactions that must be integrated over the system life-cycle process is given in Figure 3. The progression is iterative from left to right and not serial in nature, as might be inferred.

Although the level of activity and detail may vary, the life-cycle functions described and illustrated are generic. They are applicable whenever a new need or changed requirement is identified, with the process being common to large as well as small-scale systems. It is essential that this process be implemented completely—at an appropriate level of detail—not only in the engineering of new systems but also in the re-engineering of existing or legacy systems.

Major technical activities performed during the design, production or construction, utilization, support, and phase-out phases of the life cycle are highlighted in Figure 3. These are initiated when a new need is identified. A planning function is followed by conceptual, preliminary, and detail design activities. Producing and/or constructing the system are the function that completes the acquisition phase. System operation and support functions occur during the utilization phase of the life cycle. Phase-out and disposal are important final functions of utilization to be considered as part of design for the life cycle.

The numbered blocks in Figure 3 “map” and elaborate on the phases of the life cycles depicted in Figure 2 as follows:

1. The acquisition phase—Figure 3, Blocks 1–4.
2. The utilization phase—Figure 3, Blocks 5 and 6.
3. The design phase—Figure 3, Blocks 1–3.
4. The startup phase—Figure 3, Block 4.
5. The operation phase—Figure 3, Block 5.
6. The retirement phase—Figure 3, Block 6.

The communication and coordination needed to design and develop the product, the production capability, the system support capability, and the relationships with interrelated systems—so that they traverse the life cycle together seamlessly—is not easy to accomplish. Progress in this area is facilitated by technologies that make more timely acquisition and use of design information possible. Computer-Aided Design (CAD) technology with internet/intranet connectivity enables a geographically dispersed multidiscipline team to collaborate effectively on complex physical designs.

For certain products, the addition of Computer-Aided Manufacturing (CAM) software can automatically translate approved three-dimensional CAD drawings into manufacturing instructions for numerically controlled equipment. Generic or custom parametric CAD software can facilitate exploration of alternative design solutions. Once a design has been created in CAD/CAM, iterative improvements to the design are relatively easy to make. The CAD drawings also facilitate maintenance, technical support, regeneration (re-engineering), and disposal. A broad range of other electronic communication and collaboration tools can help integrate relevant geographically dispersed design and development activities over the life cycle of the system.

Concern for the entire life cycle is particularly strong within the U.S. Department of Defense (DOD) and its non-U.S. counterparts. This may be attributed to the fact that acquired defense systems are owned, operated, and maintained by the DOD. This is unlike the situation most often encountered in the private sector, where the consumer or user is usually not the producer. Those private firms serving as defense contractors are obliged to

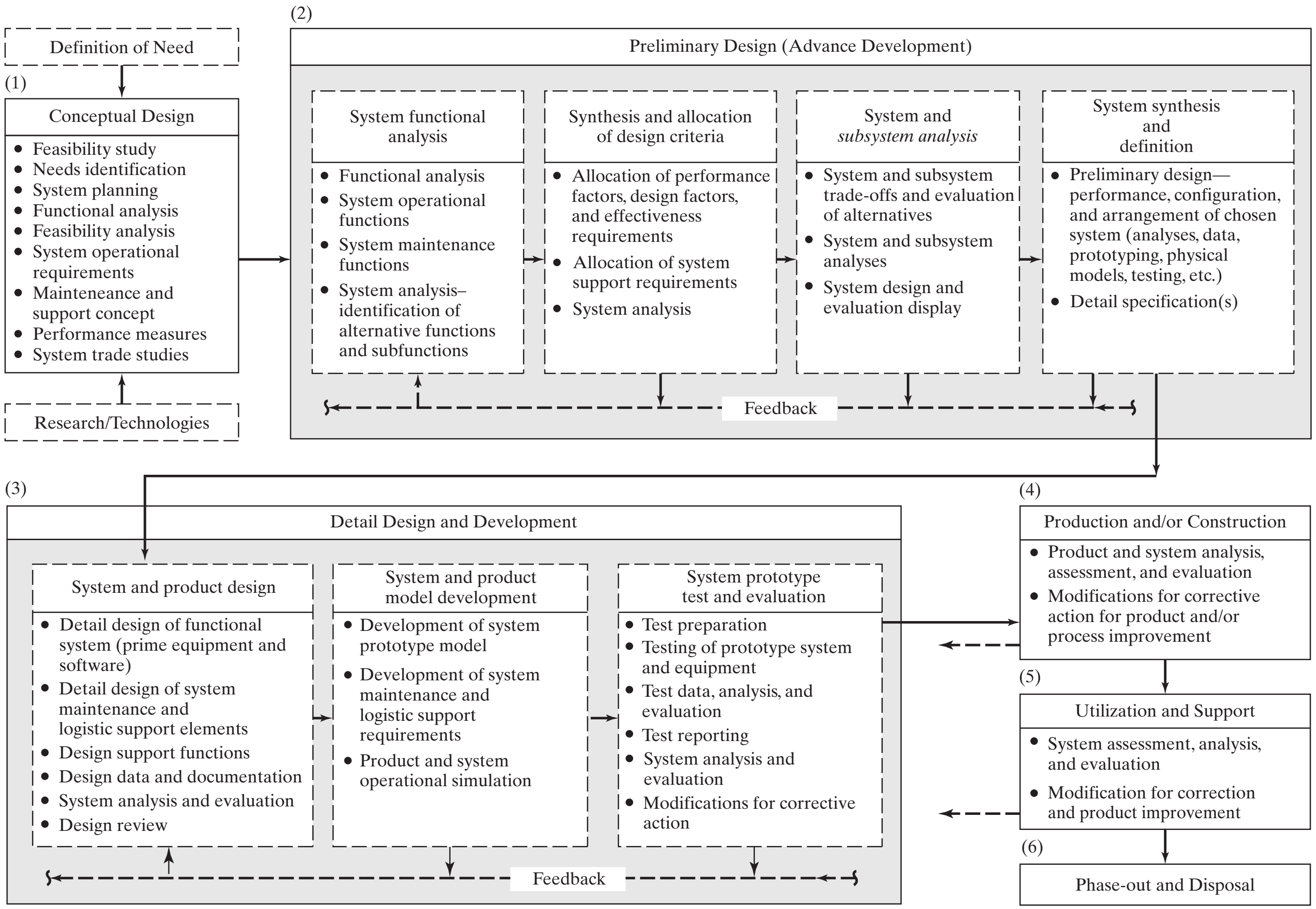

Figure 3 Technological activities and interactions within the system life-cycle process.

design and develop in accordance with DOD directives, specifications, and standards. Because the DOD is the customer and also the user of the resulting system, considerable DOD intervention occurs during the acquisition phase.[5]

Many firms that produce for private-sector markets have chosen to design with the life cycle in mind. For example, design for energy efficiency is now common in appliances such as water heaters and air conditioners. Fuel efficiency is a required design characteristic for automobiles. Some truck manufacturers promise that life-cycle maintenance costs will be within stated limits. These developments are commendable, but they do not go far enough. When the producer is not the consumer, it is less likely that potential operational problems will be addressed during development. Undesirable outcomes too often end up as problems for the user of the product instead of the producer.

3 THE SYSTEMS ENGINEERING PROCESS

Although there is general agreement regarding the principles and objectives of systems engineering, its actual implementation will vary from one system and engineering team to the next. The process approach and steps used will depend on the nature of the system application and the backgrounds and experiences of the individuals on the team. To establish a common frame of reference for improving communication and understanding, it is important that a "baseline" be defined that describes the systems engineering process, along with the essential life-cycle phases and steps within that process. Augmenting this common frame of reference are top-down and bottom-up approaches. And, there are other process models that have attracted various degrees of attention. Each of these topics is presented in this section.

3.1 Life-Cycle Process Phases and Steps

Figure 4 illustrates the major life-cycle process phases and selected milestones for a generic system. This is the "model" that will serve as a frame of reference for material presented in subsequent chapters. Included are the basic steps in the systems engineering process (i.e., requirements analysis, functional analysis and allocation, synthesis, trade-off studies, design evaluation, and so on).[6]

A newly identified need, or an evolving need, reveals a new system requirement. If a decision is made to seek a solution for the need, then a decision is needed whether to consider other needs in designing the solution. Based on an initial determination regarding the scope of needs, the basic phases of conceptual design and onward through system retirement and phase-out are then applicable, as described in the paragraphs that follow. The scope of needs may contract or expand, but the scope should be stabilized as early as possible during conceptual design, preferably based on an evaluation of value and cost by the customer.

Program phases described in Figure 4 are not intended to convey specific tasks, or time periods, or levels of funding, or numbers of iterations. Individual program requirements will vary from one application to the next. The figure exhibits an overall *process* that needs to be

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[5] This intervention is widely supported by a variety of both past and current Department of Defense Directives and Instructions. Among the most recent and notable is DOD Instruction 5000.02, "Operation of the Defense Acquisition System," December 8, 2008.

[6] Figure 4 exhibits more information and detail than can be adequately explained in this chapter. Its purpose is to provide context by consolidating terms and notation on a single page.

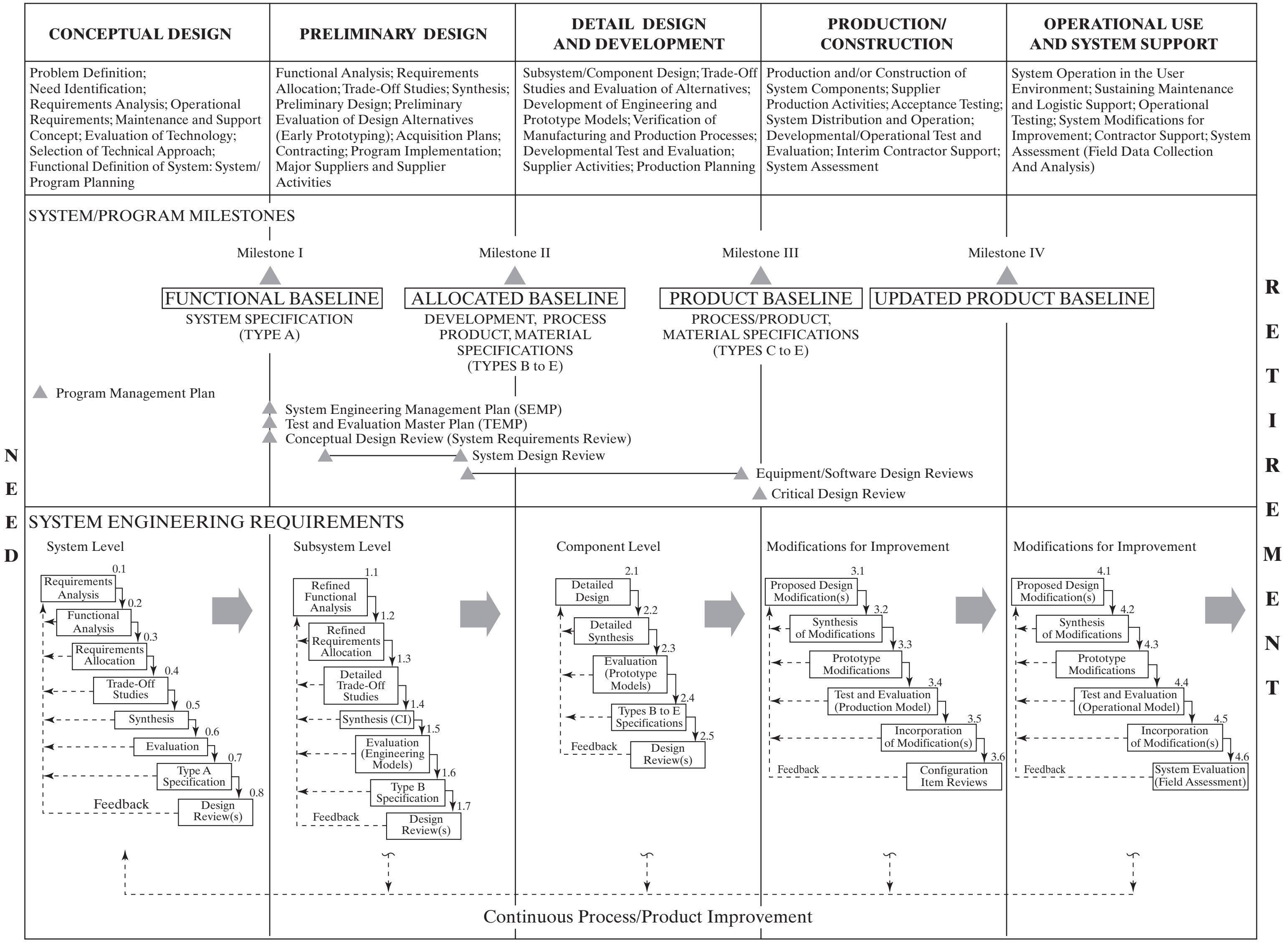


Figure 4 System process activities and interactions over the life cycle.

followed during system acquisition and deployment. Regardless of the type, size, and complexity of the system, there is a conceptual design requirement (i.e., to include requirements analysis), a preliminary design requirement, and so on. Also, to ensure maximum effectiveness, the concepts presented in Figure 4 must be properly "tailored" to the particular system application being addressed.

Figure 4 (Blocks 0.1–0.8, Blocks 1.1–1.7, and Blocks 2.1–2.5) shows the basic steps in the systems engineering process to be iterative in nature, providing a top-down definition of the system, and then proceeding down to the subsystem level (and below as necessary). Focused on the needs, and beginning with conceptual design, the completion of Block 0.2 defines the system in *functional* terms (having identified the "whats" from a requirements perspective). These "whats" are translated into an applicable set of "hows" through the iterative process of functional partitioning and requirements allocation, together with conceptual design synthesis, analysis, and evaluation. This conceptual design phase is where the initial configuration of the system (or system architecture) is defined.

During preliminary design, completion of Block 1.1 defines the system in *refined functional* terms providing a top-down definition of subsystems with preparation for moving down to the component level. Here the "whats" are extracted from (provided by) the conceptual design phase. These "whats" are translated into an applicable set of "hows" through the iterative process of functional partitioning and requirements allocation, together with preliminary design synthesis, analysis, and evaluation. This preliminary design phase is where the initial configuration of subsystems (or subsystem architecture) is defined.

Blocks 1.1–1.7 are an evolution from Blocks 0.1–0.8, Blocks 2.1–2.5 are an evolution from Blocks 1.1–1.7, and Blocks 3.1–3.6 are an evolution from Blocks 2.1–2.5. The overall process reflected in the figure constitutes an evolutionary design and development process. With appropriate feedback and design refinement provisions incorporated, the process should eventually converge to a successful design. The functional definition of the system, its subsystems, and its components serves as the baseline for the identification of resource requirements for production and then operational use (i.e., hardware, software, people, facilities, data, elements of support, or a combination thereof).

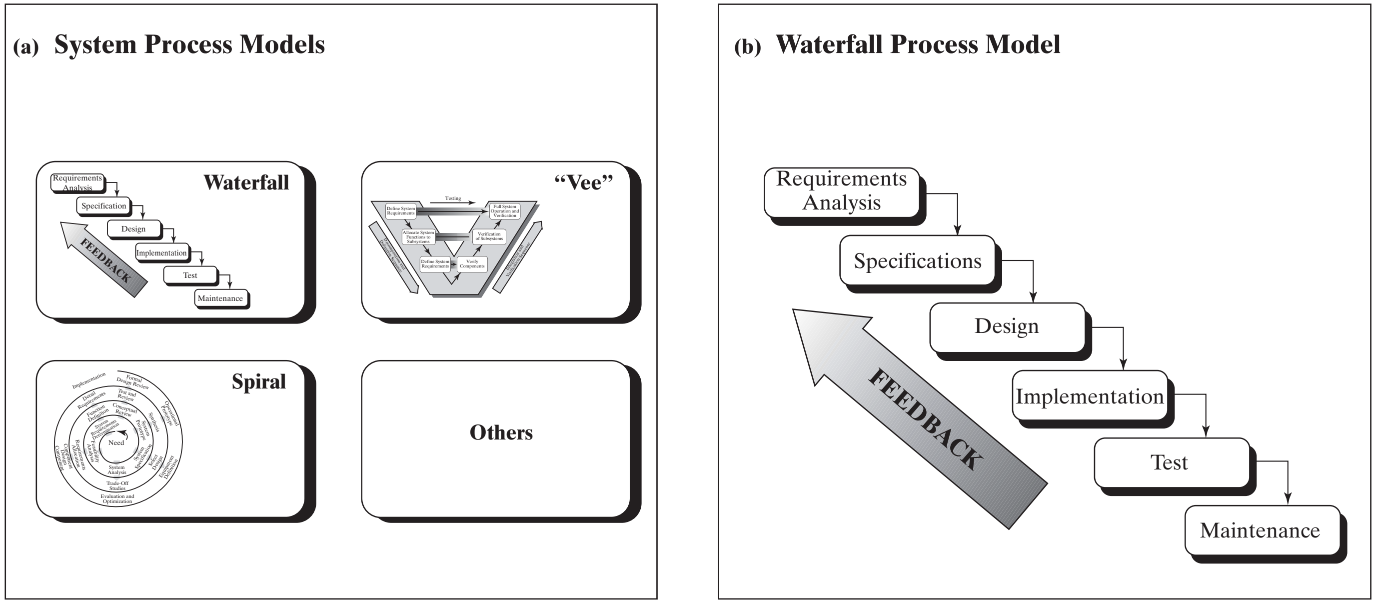
3.2 Other Systems Engineering Process Models

The overarching objective is to describe a *process* (as a frame of reference) that should be "tailored" to the specific program need.

The illustration in Figure 4 is not intended to emphasize any particular model, such as the "waterfall" model, the "spiral" model, the "vee" model, or equivalent. These well-known process models are illustrated and briefly described in Figure 5.

4 SYSTEM DESIGN CONSIDERATIONS

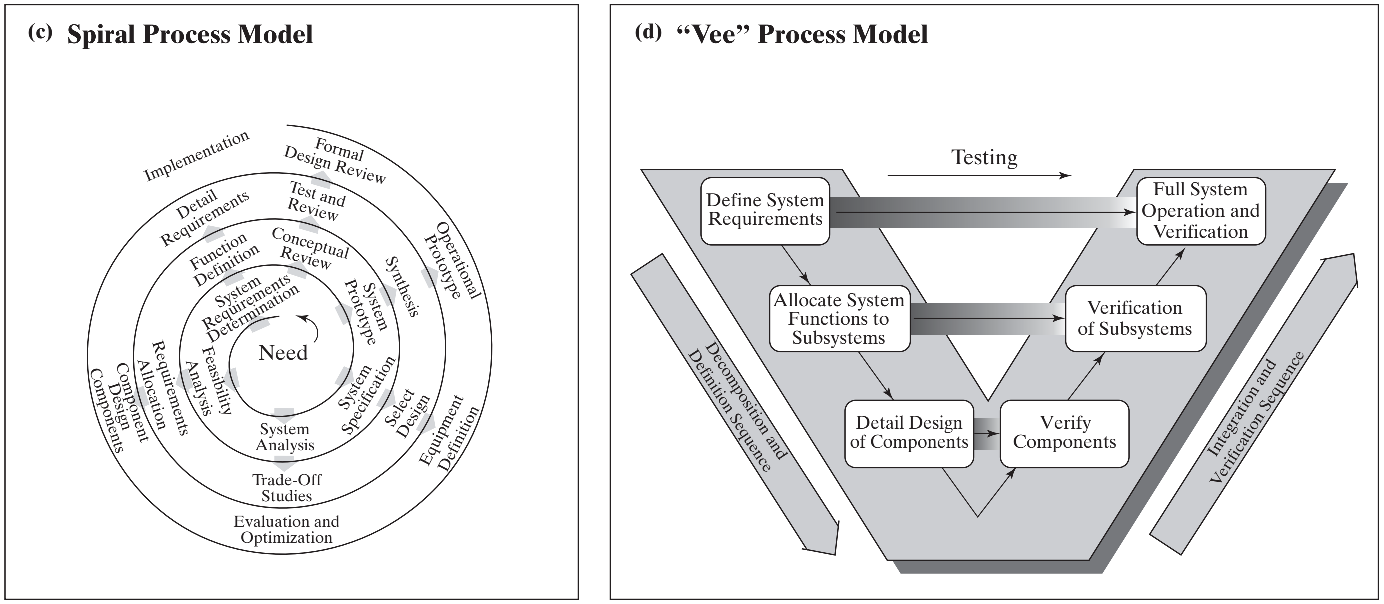
The systems engineering process is suggested as a preferred approach for bringing systems and their products into being that will be cost-effective and globally competitive. An essential technical activity within the process is that of system design evaluation. Evaluation must be inherent within the systems engineering process and be invoked regularly as the system design activity progresses. However, system evaluation should not proceed without either accepting guidance from customer requirements and applicable system design criteria, or direct involvement of the customer. When conducted with full



- It is observed that the preference expressed by individuals and groups for one of the system models is subjective.
- A study of the literature and current practice is needed to identify which model fits a specific situation best.

- The waterfall model, introduced by Royce in 1970, initially was used for software development. This model usually consists of five to seven series of steps or phases for systems engineering or software development. Boehm expanded this into an eight-step series of activities in 1981.
- A similar model splits the hardware and software into two distinct efforts. Ideally, each phase is carried out to completion in sequence until the product is delivered. However, this rarely is the case. When deficiencies are found, phases must be repeated until the product is correct.

Figure 5 Some systems engineering process models (sheet 1).



(c) Spiral Process Model

- The spiral process model of the development life cycle (developed by Boehm in 1986 using Hall's work in systems engineering from 1969) is intended to introduce a risk-driven approach for the development of products or systems.
- This model is an adaptation of the waterfall model, which does not mandate the use of prototypes. The spiral model incorporates features from other models, such as feedback, etc.
- Application of the spiral model is iterative and proceeds through the several phases each time a different type of prototype is developed. It allows for an evaluation of risk before proceeding to a subsequent phase.

(d) "Vee" Process Model

- Forsberg and Mooz describe what they call "the technical aspect of the project cycle" by the "Vee" process model. This model starts with user needs on the upper left and ends with a user-validated system on the upper right.
- On the left side, decomposition and definition activities resolve the system architecture, creating details of the design. Integration and verification flows upward to the right as successively higher levels of subsystems are verified, culminating at the system level.
- Verification and validation progress from the component level to the validation of the operational system. At each level of testing, the originating specifications and requirements documents are consulted to ensure that component/subsystems/system meet the specifications.

Figure 5 Some systems engineering process models (sheet 2).

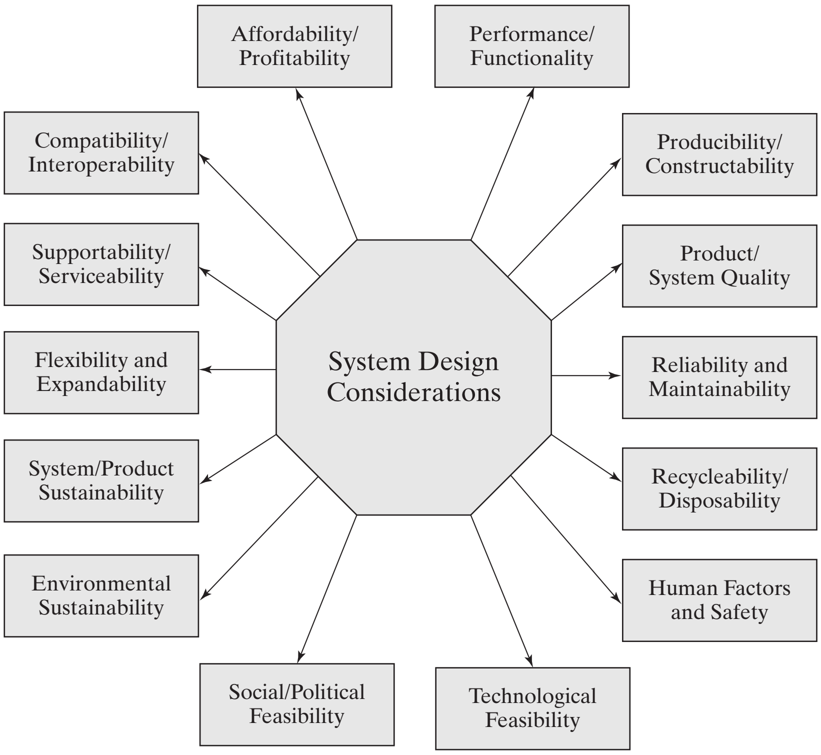


Figure 6 Some system design considerations.

recognition of customer requirements and design criteria, evaluation enhances assurance of continuous design improvement.

There are numerous system design considerations that should be identified and studied when developing design criteria. These are shown in Figure 6. Design considerations provide a broad range of possibilities from which the derivation of design criteria may evolve. A general discussion of this important topic is the focus of this section. Formal analytical and modeling approaches for performing systems analysis and design evaluation, incorporating multiple criteria, are not presented here.

4.1 Development of Design Criteria[7]

As depicted in Figure 7, the definition of needs at the system level is the starting point for determining customer requirements and developing design criteria. The requirements for the system as an entity are established by describing the functions that must be performed. The operational and support functions (i.e., those required to accomplish a specified mission scenario, or series of missions, and those required to ensure that the system is able to perform the needed functions when required) must be described at the top level. Also,

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[7] Design *criteria* constitute a set of "design-to" requirements, which can be expressed in both qualitative and quantitative terms. These requirements represent bounds on the "design-space" within which the designer must "negotiate" when engaged in the iterative process of synthesis, analysis, and evaluation.

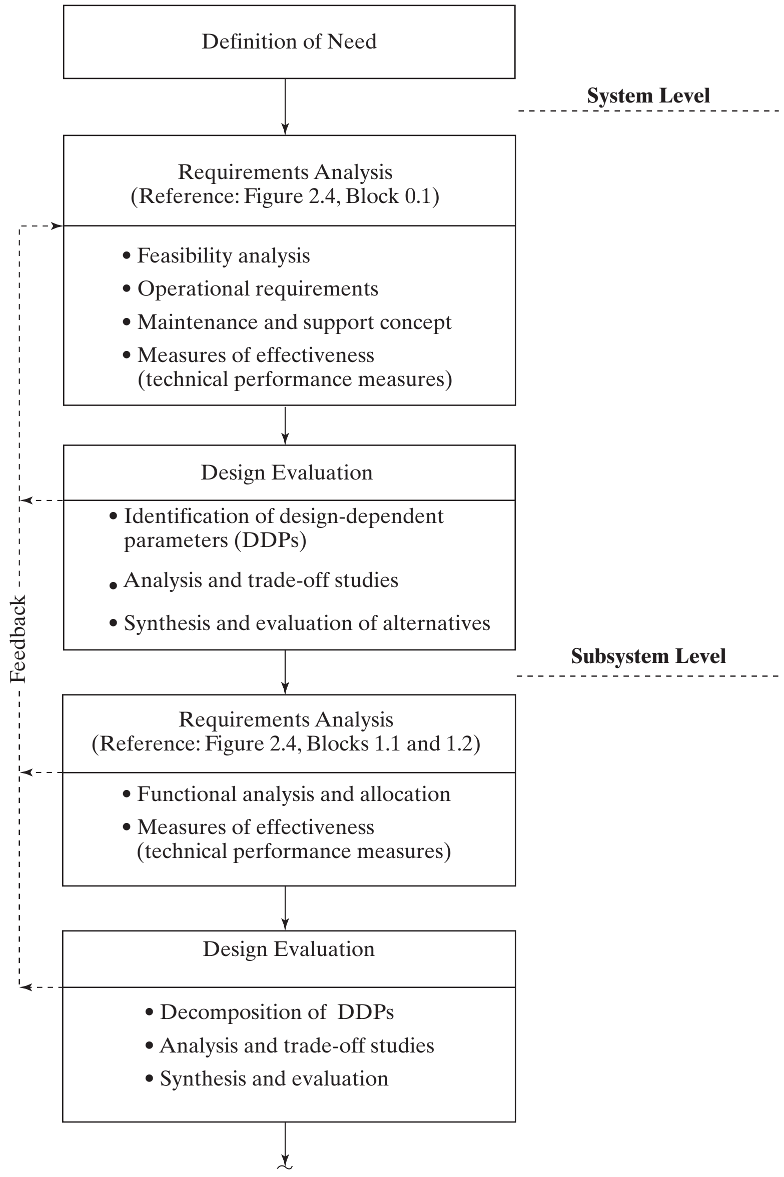

Figure 7 Decomposing system design requirements.

the general concepts and nonnegotiable requirements for production, systems integration, and retirement must be described.

In design evaluation, an early step that fully recognizes design criteria is to establish a *baseline* against which a given alternative or design configuration may be evaluated (refer to Figure 4, Block 0.1). This baseline is determined through the iterative process of requirements analysis (i.e., identification of needs, analysis of feasibility, definition of system operational and support requirements, and selection of concepts for production, systems integration, and retirement). A more specific baseline is developed for each *system level* in Figure 7. The functions that the system must perform to satisfy a specific scope of customer needs should be described, along with expectations for cycle time, frequency, speed, cost, effectiveness, and other relevant factors. Functional requirements must be met by incorporating design characteristics within the system at the appropriate level.

As part of this process, it is necessary to establish some system "metrics" related to performance, effectiveness, cost, and similar quantitative factors as required to meet customer expectations. For instance, what functions must the system perform, where are these to be accomplished, at what frequency, with what degree of reliability, and at what cost? Some of these factors may be considered to be more important than others by the customer which will, in turn, influence the design process by placing different levels of emphasis on meeting criteria. Candidate systems result from design synthesis and become the appropriate targets for design analysis and evaluation.

Evaluation is invoked to determine the degree to which each candidate system satisfies design criteria. Applicable criteria regarding the system should be expressed in terms of *technical performance measures* (TPMs) and exhibited at the system level. TPMs are measures for characteristics that are, or derive from, attributes inherent in the design itself. Attributes that depend directly on design characteristics are called *design-dependent parameters* (DDPs), with specific measures thereof being the TPMs. In contrast, relevant factors external to the design are called *design-independent parameters* (DIPs).

It is essential that the development of *design criteria* be based on an appropriate set of *design considerations*, considerations that lead to the identification of both *design-dependent* and *design-independent parameters* and that support the derivation of *technical performance measures*. More precise definitions for these terms are as follows:

1. Design considerations—the full range of attributes and characteristics that could be exhibited by an engineered system, product, or service. These are of interest to both the producer and the customer (see Figure 6).
2. Design-dependent parameters (DDPs)—attributes and/or characteristics inherent in the design for which predicted or estimated measures are required or desired (e.g., design life, weight, reliability, producibility, maintainability, pollutability, and others).
3. Design-independent parameters (DIPs)—factors external to the design that must be estimated and/or forecasted for use during design evaluation (e.g., fuel cost per pound, labor rates, material cost per pound, interest rates, and others). These depend upon the production and operating environment for the system.
4. Technical performance measures (TPMs)—predicted and/or estimated values for DDPs. They also include values for higher level (derived) performance considerations (e.g., availability, cost, flexibility, and supportability).
5. Design criteria—customer specified or negotiated target values for technical performance measures. Also, desired values for TPMs as specified by the customer as requirements.

The issue and impact of multiple criteria will be presented in the paragraphs that follow. Then, the next section will direct attention to design criteria as an important part of a morphology for synthesis, analysis, and evaluation. In so doing, the terms defined above will be better related to each other and to the system realization process.

4.2 Considering Multiple Criteria

In Figure 7, the prioritized TPMs at the top level reflect the overall performance characteristics of the system as it accomplishes its mission objectives in response to customer needs. There may be numerous factors, such as system size and weight, range and accuracy, speed of performance, capacity, operational availability, reliability and maintainability, supportability, cost, and so on. These *measures of effectiveness* (MOEs) must be specified in terms of a level of importance, as determined by the customer based on the criticality of the functions to be performed.

For example, there may be certain mission scenarios where system availability is critical, with reliability being less important as long as there are maintainability considerations built into the system that facilitate ease of repair. Conversely, for missions where the accomplishment of maintenance is not feasible, reliability becomes more important. Thus, the nature and criticality of the mission(s) to be accomplished will lead to the identification of specific requirements and the relative levels of importance of the applicable TPMs.

Given the requirements at the top level, it may be appropriate to develop a "design-objectives" tree similar to that presented in Figure 8. First-, second-, and third-order (and lower-level) considerations are noted. Based on the established MOEs for the system, a top-down breakout of requirements will lead to the identification of characteristics that should be included and made inherent within the design; for example, a first-order consideration may be *system value*, which, in turn, may be subdivided into *economic* factors and *technical* factors.

Technical factors may be expressed in terms of *system effectiveness*, which is a function of performance, operational availability, dependability, and so on. This leads to the consideration of such features as speed of performance, reliability and maintainability, size and weight, and flexibility. Assuming that maintainability represents a high priority in design, then such features as packaging, accessibility, diagnostics, mounting, and interchangeability should be stressed in the design. Thus, the *criteria* for design and the associated DDPs should be established early, during conceptual design, and then carried through the entire design cycle. The DDPs establish the extent and scope of the design space within which *trade-off* decisions may be made. During the process of making these trade-offs, requirements must be related to the appropriate hierarchical level in the system structure (i.e., system, subsystem, and configuration item) as in Figure 7.

5 SYSTEM SYNTHESIS, ANALYSIS, AND EVALUATION

System design is the prime mover of systems engineering, with system design evaluation being its compass. System design requires both integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation, as is shown conceptually in Figure 9. It is essential that the technological activities of synthesis, analysis, and evaluation be integrated and applied iteratively and continuously over the system life cycle. The benefits of continuous improvement in system design are thereby more likely to be obtained.

5.1 A Morphology for Synthesis, Analysis, and Evaluation

Figure 10 presents a high-level schematic of the systems engineering process from a product realization perspective. It is a morphology for linking applied research and technologies (Block 0) to customer needs (Block 1). It also provides a structure for visualizing the technological activities of synthesis, analysis, and evaluation. Each of these activities is summarized in the paragraphs that follow, with reference to relevant blocks within the morphology.

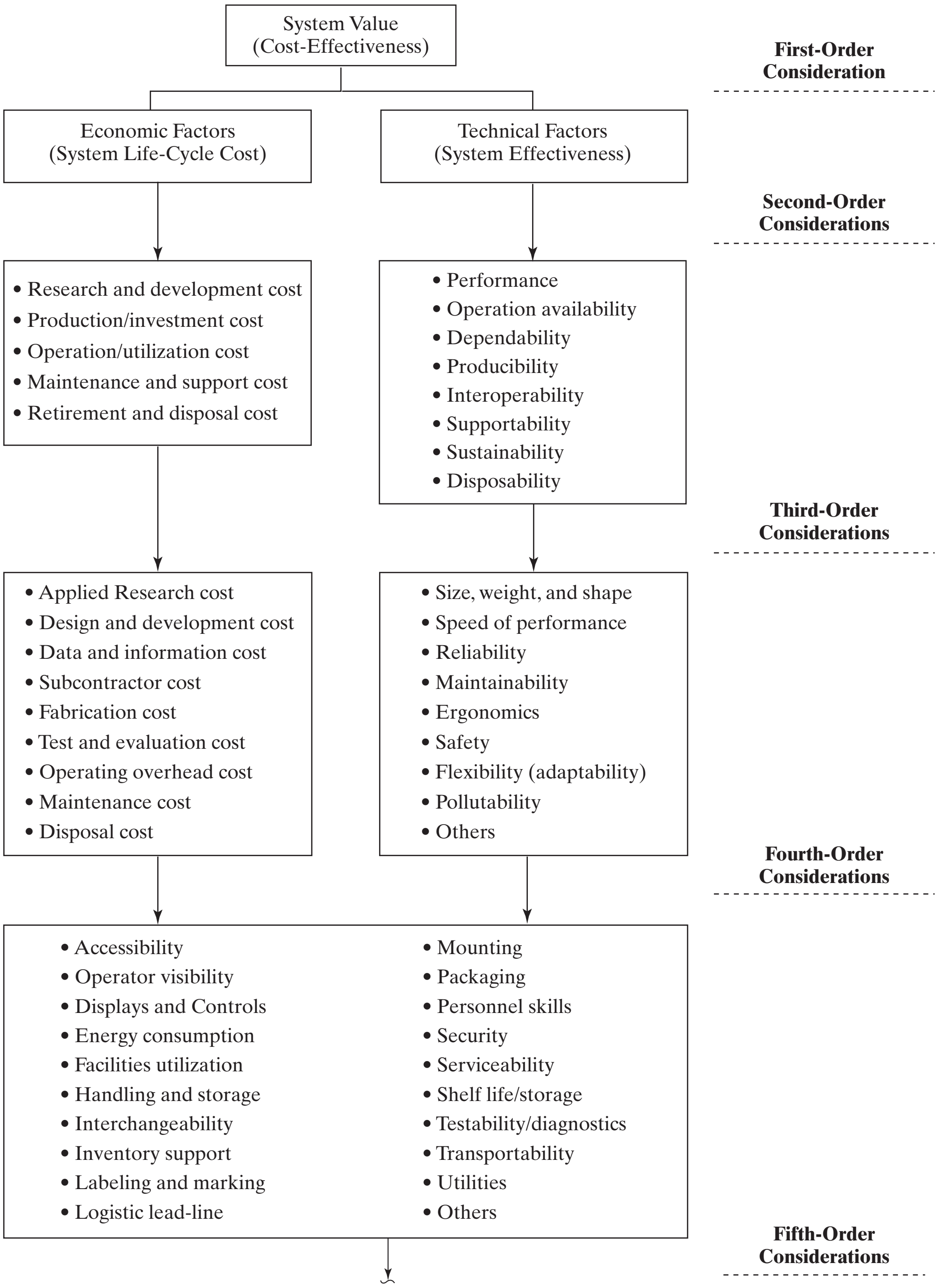

Figure 8 A hierarchy of system design considerations.

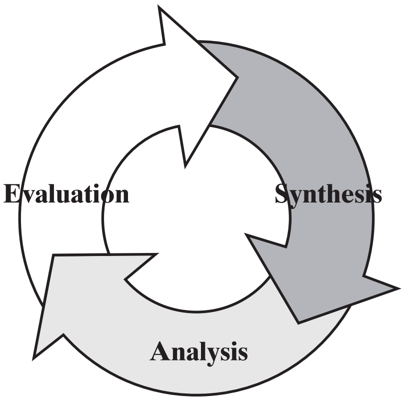

Figure 9 The relationship of synthesis, analysis, and evaluation.

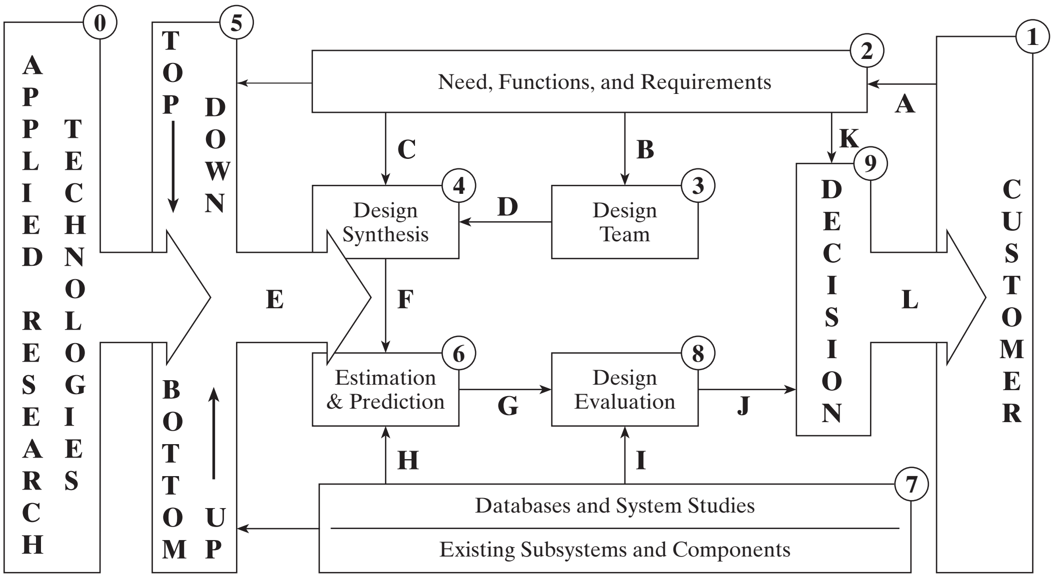

Figure 10 Systems engineering morphology for product realization.

Synthesis. To design is to synthesize, project, and propose what might be for a specific set of customer needs and requirements, normally expressed in functional terms (Block 2). Synthesis is the creative process of putting known things together into new and more useful combinations. Meeting a need in compliance with customer requirements is the objective of design synthesis.

The primary elements enabling design synthesis are the design team (Block 3), supported by traditional and computer-based tools for design synthesis (Block 4). Design synthesis is best accomplished by combining top-down and bottom-up activities (Block 5). Existing and newly developed components, parts, and subsystems are then integrated to generate candidate system designs in a form ready for analysis and evaluation.

Analysis. Analysis of candidate system and product designs is a necessary but not sufficient ingredient in system design evaluation. It involves the functions of estimation and prediction of DDP values (TPMs) (Block 6) and the determining or forecasting of DIP values from information found in physical and economic databases (Block 7).

Systems analysis and operations research provides a step on the way to system design evaluation, but adaptation of those models and methods to the domain of design is necessary. The adaptation explicitly recognizes DDPs.

Evaluation. Each candidate design (or design alternative) should be evaluated against other candidates and checked for compliance with customer requirements. Evaluation of each candidate (Block 8) is accomplished after receiving DDP values for the candidate from Block 6. It is the specific values for DDPs (the TPMs) that differentiate (or instance) candidate designs.

DIP values determined in Block 7 are externalities. They apply to and across all candidate designs being presented for evaluation. Each candidate is optimized in Block 8 before being presented for design decision (Block 9). It is in Block 9 that the best candidate is sought. Since the preferred choice is subjective, it should ultimately be made by the customer.

5.2 Discussion of the 10-Block Morphology

This section presents and discusses the functions accomplished by each block in the system design morphology that is exhibited in Figure 10. The discussion will be at a greater level of detail than the general description of synthesis, analysis, and evaluation given above.

The Technologies (Block 0). Technologies, exhibited in Block 0, are the product of applied research. They evolve from the activities of engineering research and development and are available to be considered for incorporation into candidate system designs. As a driving force for innovation, technologies are the most potent ingredient for advancing the capabilities of human-made entities.

It is the responsibility of the designer/producer to propose and help the customer understand what might be for each technological choice. Those producers able to articulate and deliver better technological solutions, on time and within budget, will attain and retain a competitive edge in the global marketplace.

The Customer (Block 1). The purpose of system design is to satisfy customer (and stakeholder) needs and expectations. This must be with the full realization that the perceived success of a particular design is ultimately determined by the customer, identified in Block 1; the customary being Number 1.

During the design process, all functions to be provided and all requirements to be satisfied should be determined from the perspective of the customer or the customer's representative. Stakeholder and any other special interests should also be included in the "voice of the customer" in a way that reflects all needs and concerns. Included among these must be ecological and human impacts. Arrow A represents the elicitation of customer needs, desired functionality, and requirements.

Need, Functions, and Requirements (Block 2). The purpose of this block is to identify and specify the desired behavior of the system or product in functional terms. A market study identifies a need, an opportunity, or a deficiency. From the need comes a definition of the basic requirements, often stated in functional terms. Requirements are the input for design and operational criteria, and criteria are the basis for the evaluation of candidate system configurations.

At this point, the system and its product should be defined by its function, not its form. Arrow A indicates customer inputs that define need, functionality, and operational requirements. Arrows B and C depict the translation and transfer of this information to the design process.

The Design Team (Block 3). The design team should be organized to incorporate in-depth technical expertise, as well as a broader systems view. Included must be expertise in each of the product life-cycle phases and elements contained within the set of system requirements.

Balanced consideration should be present for each phase of the design. Included should be the satisfaction of intended purpose, followed by producibility, reliability, maintainability, disposability, sustainability, and others. Arrow B depicts requirements and design criteria being made available to the design team and Arrow D indicates the team's contributed synthesis effort wherein need, functions, and requirements are the overarching consideration (Arrow C).

Design Synthesis (Block 4). To design is to project and propose what might be. Design synthesis is a creative activity that relies on the knowledge of experts about the state of the art as well as the state of technology. From this knowledge, a number of feasible design alternatives are fashioned and presented for analysis. Depending upon the phase of the product life cycle, the synthesis can be in conceptual, preliminary, or detailed form.

The candidate design is driven by both a top-down functional decomposition from Block 2 and a bottom-up combinatorial approach utilizing available system elements from Block 7. Arrow E represents a blending of these approaches. Adequate definition of each design alternative must be obtained to allow for life-cycle analysis in view of the requirements. Arrow F highlights this definition process as it pertains to the passing of candidate design alternatives to design analysis in Block 6.

Top-Down and Bottom-Up (Block 5). Traditional engineering design methodology is based largely on a bottom-up approach. Starting with a set of defined elements, designers synthesize the system/product by finding the most appropriate combination of elements. The bottom-up process is iterative with the number of iterations determined by the creativity and skill of the design team, as well as by the complexity of the system design.

A top-down approach to design is inherent within systems engineering. Starting with requirements for the external behavior of any component of the system (in terms of the function provided by that component), that behavior is then decomposed. These decomposed functional behaviors are then described in more detail and made specific through an analysis process. Then, the appropriateness of the choice of functional components is verified by synthesizing the original entity. Most systems and products are realized through an intelligent combination of the top-down and bottom-up approaches, with the best mix being largely a matter of judgment and experience.

Design Analysis (Block 6). Design analysis is focused largely on determining values for cost and effectiveness measures generated during estimation and prediction activities. Models, database information, and simulation are employed to obtain DDP values (or TPMs) for each synthesized design alternative from Block 4. Output Arrow G passes the analysis results to design evaluation (Block 8).

The TPM values provide the basis for comparing system designs against input criteria to determine the relative merit of each candidate. Arrow H represents input from the available databases and from relevant studies.

Physical and Economic Databases (Block 7). Block 7 provides a resource for the design process, rather than being an actual step in the process flow. There exists a body of knowledge and information that engineers, technologists, economists, and others rely on to perform the tasks of analysis and evaluation. This knowledge consists of physical laws, empirical data, price information, economic forecasts, and numerous other studies and models.

Block 7 also includes descriptions of existing system components, parts, and subsystems, often "commercial off-the-shelf." It is important to use existing databases in doing analysis and synthesis to avoid duplication of effort. This body of knowledge and experience can be utilized both formally and informally in performing needed studies, as well as in supporting the decisions to follow.

At this point, and as represented by Arrow I, DIP values are estimated or forecasted and provided to the activity of design evaluation in Block 8.

Design Evaluation (Block 8). Design evaluation is an essential activity within system and product design and the systems engineering process. It should be embedded appropriately within the process and then pursued continuously as design and development progresses.

Life-cycle cost is one basis for comparing alternative designs that otherwise meet minimum requirements under performance criteria. The life-cycle cost of each alternative is determined based on the activity of estimation and prediction just completed. Arrow J indicates the passing of the evaluated candidates to the decision process. The selection of preferred alternative(s) can only be made after the life-cycle cost analysis is completed and after effectiveness measures are defined and applied.

Design Decision (Block 9). Given the variety of customer needs and perceptions as collected in Block 2, choosing a preferred alternative is not just the simple task of picking the least expensive design. Input criteria, derived from customer and product requirements, are represented by Arrow K and by the DDP values (TPMs) and life-cycle costs indicated by Arrow J. The customer or decision maker must now trade off life-cycle cost against effectiveness criteria subjectively. The result is the identification of one or more preferred alternatives that can be used to take the design process to the next level of detail.

Alternatives must ultimately be judged by the customer. Accordingly, arrow L depicts the passing of evaluated candidate designs to the customer for review and decision. Alternatives that are found to be unacceptable in performance can be either discarded or reworked and new alternatives created. Alternatives that meet all, or the most important, performance criteria can then be evaluated based on estimations and predictions of TPM values, along with an assessment of risk.

6 IMPLEMENTING SYSTEMS ENGINEERING

Within the context of synthesis, analysis, and evaluation is the opportunity to implement systems engineering over the system life cycle in measured ways that can help ensure its effectiveness. These measured implementations are necessary because the complexity of technical systems continues to increase, and many systems in use today are not meeting the needs of the customer in terms of performance, effectiveness, and overall cost. New technologies are being introduced on a continuing basis, while the life cycles for many systems are being extended. The length of time that it takes to develop and acquire a new system needs to be reduced, the costs of modifying existing systems are increasing, and available resources are dwindling. At the same time, there is a greater degree of international cooperation, and competition is increasing worldwide.

6.1 Application Domains for Systems Engineering

There are many categories of human-made systems, and there are several application domains where the concepts and principles of systems engineering can be effectively implemented. Every time that there is a newly identified need to accomplish some function, a new *system* requirement is established. In each instance, there is a new design and development effort that must be accomplished at the *system* level. This, in turn, may lead to a variety of approaches at the subsystem level and below (i.e., the design and development of new equipment and software, the selection and integration of new commercial off-the-shelf items, the modification of existing items already in use, or combinations thereof).

Accordingly, for every new customer requirement, there is a needed design effort for the system overall, to which the steps described in Section 4 are applicable. Although the extent and depth of effort will vary, the concepts and principles for bringing a system into being are basically the same. Some specific application areas are highlighted in Figure 11, and application domains include the following:

1. Large-scale systems with many components, such as a space-based system, an urban transportation system, a hydroelectric power-generating system, or a health-care delivery system.
2. Small-scale systems with relatively few components, such as a local area communications network, a computer system, a hydraulic system, or a mechanical braking system, or a cash receipt system.

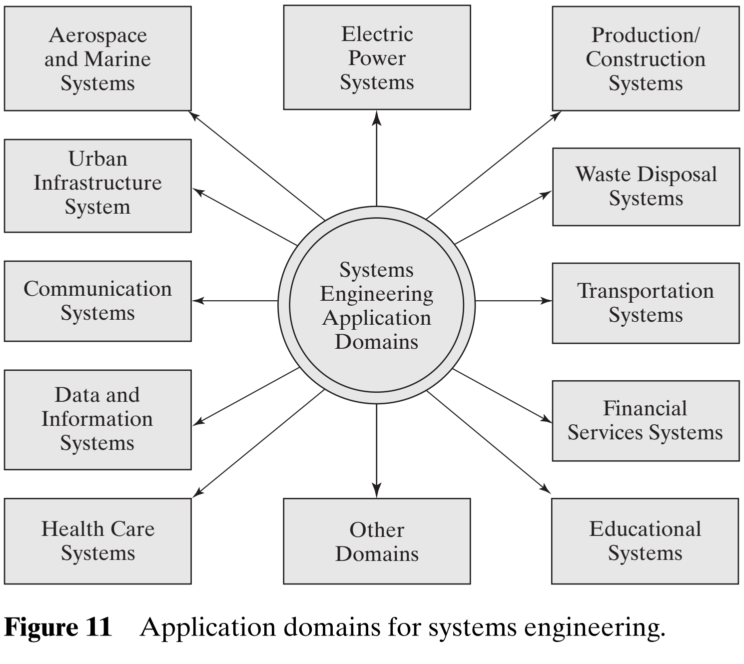

Figure 11 Application domains for systems engineering.

3. Manufacturing or production systems where there are input–output relationships, processes, processors, control software, facilities, and people.
4. Systems where a great deal of new design and development effort is required (e.g., in the introduction of advanced technologies).
5. Systems where the design is based largely on the use of existing equipment, commercial software, or existing facilities.
6. Systems that are highly equipment, software, facilities, or data intensive.
7. Systems where there are several suppliers involved in the design and development process at the local, and possibly international, level.
8. Systems being designed and developed for use in the defense, civilian, commercial, or private sectors separately or jointly.
9. Human-modified systems wherein a natural system is altered or augmented to make it serve human needs more completely, while being retained/sustained largely in its natural state.

6.2 Recognizing and Managing Life-Cycle Impacts

In evaluating past experiences regarding the development of technical systems, it is discovered that most of the problems experienced have been the direct result of not applying a *disciplined* top-down "systems approach." The overall requirements for the system were not defined well from the beginning; the perspective in terms of meeting a need has been relatively "short term" in nature; and, in many instances, the approach followed has been to "deliver it now and fix it later," using a bottom-up approach to design. In essence, the systems design and development process has suffered from the lack of good early planning and the subsequent definition and allocation of requirements in a complete and methodical manner. Yet, it is at this early stage in the life cycle when decisions are made that have a large impact on the overall effectiveness and cost of the system. This is illustrated conceptually in Figure 12.

Referring to Figure 12, experience indicates that there can be a large commitment in terms of technology applications, the establishment of a system configuration and its performance characteristics, the obligation of resources, and potential life-cycle cost at the early stages of a program. It is at this point when system-specific knowledge is limited, but when major decisions are made pertaining to the selection of technologies, the selection of materials and potential sources of supply, equipment packaging schemes and levels of diagnostics, the selection of a manufacturing process, the establishment of a maintenance approach, and so on. It is estimated that from 50% to 75% of the projected life-cycle cost for a given system can be committed (i.e., "locked in") based on engineering design and management decisions made during the early stages of conceptual and preliminary design. Thus, it is at this stage where the implementation of systems engineering concepts and principles is critical. It is essential that one start off with a good understanding of the customer need and a definition of system requirements.

The systems engineering process is applicable over all phases of the life cycle, with the greatest benefit being derived from its emphasis on the early stages, as illustrated in Figure 12. The objective is to influence design early, in an effective and efficient manner, through a comprehensive needs analysis, requirements definition, functional analysis and allocation, and then to address the follow-on activities in a logical and progressive manner with the provision of appropriate feedback. As conveyed in Figure 13, the overall objective is to influence design in the early phases of system acquisition, leading to the identification of individual discipline-based design needs. These should be applied in a timely manner as

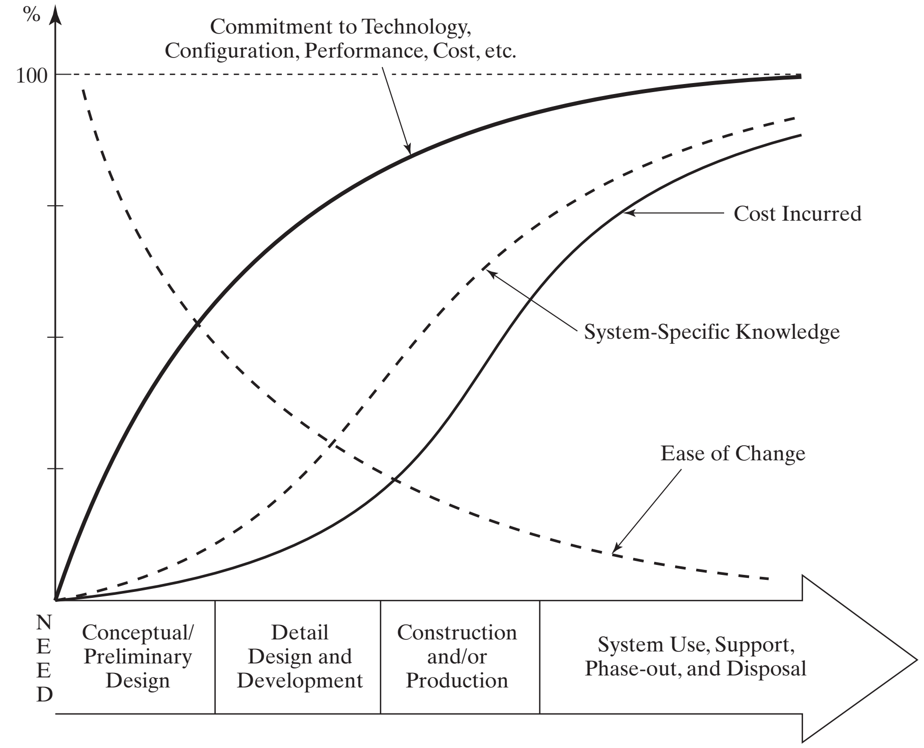

Figure 12 Life-cycle commitment, system-specific knowledge, and incurred cost.

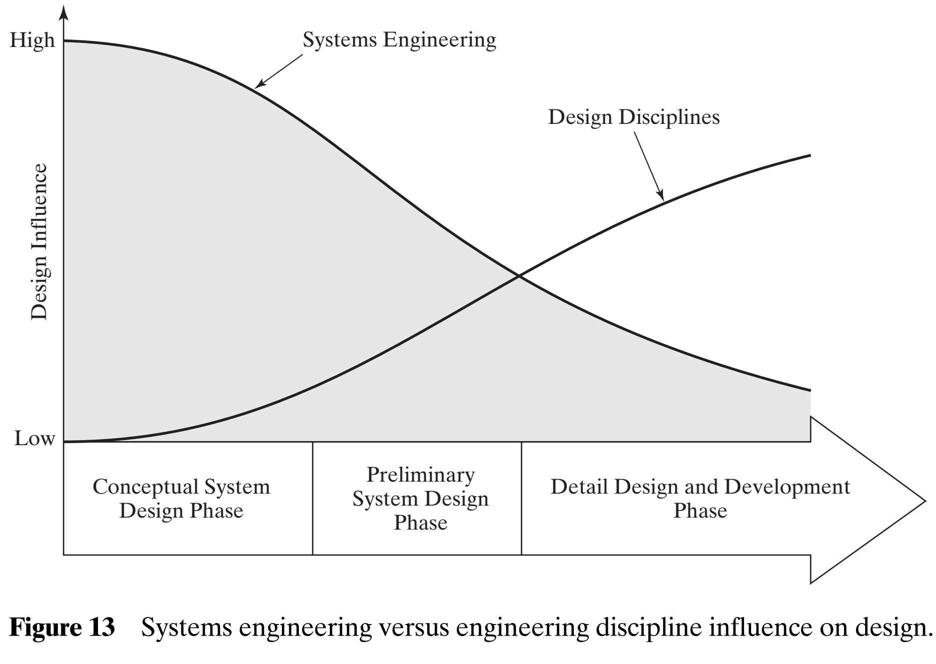

Figure 13 Systems engineering versus engineering discipline influence on design.

one evolves from system-level requirements to the design of various subsystems and components thereof.[8]

6.3 Potential Benefits from Systems Engineering

An understanding of the interrelationships among the factors identified in Figures 12 and 13 is essential if the full benefit of systems engineering is to be realized. There is a need to ensure that the applicable engineering disciplines responsible for the design of individual system elements are properly integrated. This need extends to the proper implementation of concurrent engineering to address the life cycles for the product and for the supporting capabilities of production, support, and phase-out, as is illustrated in Figure 2. A good communication network, with local-area and wide-area capability, must also be in place and available to all critical project personnel. This is a particular challenge when essential project personnel are located remotely, often worldwide.

Successful implementation of the systems engineering process depends not only on the availability and application of the appropriate technologies and tools but also on the planning and management of the activities required to accomplish the overall objective. Although the steps described in Section 3 may be specified for a given program, successful implementation (and the benefits to be derived) will not be realized unless the proper organizational environment is established that will encourage it to happen. There have been numerous instances where a project organization included a "systems engineering" function but where the impact on design has been almost nonexistent, resulting in objectives not being met.

Although some of the benefits associated with application of the concepts and principles of systems engineering have been provided throughout this chapter, it may be helpful to provide a compact summary for reference. Accordingly, application of the systems engineering process can lead to the following benefits:

1. Reduction in the cost of system design and development, production and/or construction, system operation and support, system retirement and material disposal; hence, a reduction in life-cycle cost should occur. Often it is perceived that the implementation of systems engineering will increase the cost of system acquisition. Although there may be a few more steps to perform during the early (conceptual and preliminary) system design phases, this investment could significantly reduce the requirements in the integration, test, and evaluation efforts accomplished late in the detail design and development phase. The bottom-up approach involved in making the system work can be simplified if a holistic engineering effort is initiated from the beginning. In addition experience indicates that the early emphasis on systems engineering can result in a cost savings later on in the production, operations and support, and retirement phases of the life cycle.
2. Reduction in system acquisition time (or the time from the initial identification of a customer need to the delivery of a system to the customer). Evaluation of all feasible alternative approaches to design early in the life cycle (with the support of available design aids such as the use of CAD technology) should help to promote greater design maturity earlier. Changes can be incorporated at an early stage before the

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[8] In Figure 13, the intent is to convey the degree of "design influence" imparted by application of the systems engineering process, and not to imply levels of human effort or cost. A single individual with the appropriate experience and technical expertise can exert a great deal of influence on design, whereas the establishment of a new organization and the assignment of many people to a project may have little beneficial effect.

design is "fixed" and more costly to modify. Further, the results should enable a reduction in the time that it takes for final system integration, tests, and evaluation.

3. More visibility and a reduction in the risks associated with the design decision-making process. Increased visibility is provided through viewing the system from a long-term and life-cycle perspective. The long-term impacts as a result of early design decisions and "cause-and-effect" relationships can be assessed at an early stage. This should cause a reduction in potential risks, resulting in greater customer satisfaction.

Without the proper organizational emphasis from top management, the establishment of an environment that will allow for creativity and innovation, a leadership style that will promote a "team" approach to design, and so on, implementation of the concepts and methodologies described herein may not occur. Thus, systems engineering must be implemented in terms of both *technology* and *management*. This joint implementation of systems engineering is the responsibility of systems engineering management.

7 SUMMARY AND EXTENSIONS

The overarching goal of systems engineering is embodied in the title of this chapter. This goal is to bring successful systems and their products into being. Accordingly, it is appropriate to devote this chapter to a high-level presentation of the essentials involved in the engineering of systems.

The engineered or technical system is to be brought into being; it is a system destined to become part of the human-made world. Therefore, the definition and description of the engineered system is given early in this chapter. In most cases, there is a product coexistent with or within the system, and in others the system is the product. But in either case, there must exist a human need to be met.

Since systems are often known by their products, product and system categories are identified as frameworks for study in this and subsequent chapters. Major categories are single-entity product systems and multiple-entity population systems. Availability of these example categories is intended to help underpin and clarify the topics and steps in the process of bringing engineered or technical systems into being.

The product and system life cycle is the *enduring paradigm* used throughout this book. It is argued that the defense origin of this life-cycle paradigm has profitable applications in the private sector. The life cycle is first introduced in Section 2 with two simple diagrams; the first provides the product and the second gives an expanded concurrent life-cycle view. Then, designing for the life cycle is addressed with the aid of more elaborate life-cycle diagrams, showing many more activities and interactions. Other systems engineering process models are then exhibited to conclude an overview of the popular process structures for bringing systems and products into being.

Since design is the fundamental technical activity for both the product and the system, it is important to proceed with full knowledge of all system design considerations. The identification of DDPs and their counterparts, DIPs, follows. Emanating from DDPs are technical performance measures to be predicted and/or estimated. The deviation or difference between predicted TPMs and customer-specified criteria provides the basis for design improvement through iteration, with the expectation of convergence to a preferred design. During this design activity, criteria or requirements must be given center stage. Accordingly, the largest section of this chapter is devoted to an explanation of design evaluation based on customer-specified criteria. The explanation is enhanced by the development and presentation of a 10-block morphology for synthesis, analysis, and evaluation.

This chapter closes with some challenges and opportunities that will surely arise during the implementation of systems engineering. The available application domains are numerous. A general notion is that systems engineering is an engineering interdiscipline in its own right, with important engineering domain manifestations. It is hereby conjectured that the systems engineering body of systematic knowledge will not advance significantly without engineering domain opportunities for application. However, it is clear that significant improvements in domain-specific projects do occur when resources are allocated to systems engineering activities early in the life cycle. Two views of this observed benefit are illustrated in this chapter.

It is recognized that some readers may need and desire to probe beyond the content of this textbook. If so, we would recommend two edited works: The *Handbook of Systems Engineering and Management*, A. P. Sage and W. B. Rouse (Eds), John Wiley & Sons, Inc., 2009, augments the technical and managerial topics encompassed by systems engineering. *Design and Systems*, A. Collen and W. W. Gasparski (Eds), Transaction Publishers, 1995, makes visible the pervasive nature of design in the many arenas of human endeavor from a philosophical and praxiological perspective.

Regarding the body of systems engineering knowledge, there is a timely project being pursued within the INCOSE—the SEBoK (Systems Engineering Body of Knowledge) activity involving hundreds of members. Interested individuals may review the current state of development and/or make contributions to it by visiting *http://www.incose.org*. An earlier effort along this line was to engage the intellectual leaders of INCOSE (including the authors) in the writing of 16 seminal articles. These were published in the inaugural issue of *Systems Engineering*, Vol. 1, No. 1, July–September 1994. Copies of this special issue and subsequent issues of the journal may be obtained through the INCOSE website.

QUESTIONS AND PROBLEMS

1. What are some of the characteristics of a human-made or engineered system that distinguish it from a natural system?
2. Describe some of the interfaces between the natural world and the human-made world as they pertain to the process of bringing systems/products into being.
3. Identify and describe a natural system of your choice that has been human-modified and identify what distinguishes it from a human-made system.
4. Describe the product or prime equipment as a component of the system; provide an explanation of the functions provided by each entity.
5. Put a face on the generic single-entity product system of Section 1.2 by picking a real structure or service with which you are familiar. Then, rewrite the textbook description based on the characteristics of the entity you picked.
6. Put a face on the generic multiple-entity population system of Section 1.2 by picking real equipment with which you are familiar. Then, rewrite the textbook description based on the characteristics of the equipment you picked.
7. Pick a consumer good and name the producer good(s) that need to be employed to bring this consumer good to market.

8. Pick a product, describe the enabling system that is required to bring it into being, and explain the importance of engineering the system and product together.

9. What are some of the essential factors in engineering for product competitiveness? Why is product competitiveness important?

10. What does system life-cycle thinking add to engineering as currently practiced? What are the expected benefits to be gained from this thinking?

11. Various phases of the product life cycle are shown in Figure 1 and expanded in Figure 2. Describe some of the interfaces and interactions between the life cycles of the system and the product life cycle.

12. What is the full meaning of the phrase "designing for the life cycle"?

13. Select a system of your choice and describe the applicable life-cycle phases and activities, tailoring your description to that system.

14. As best you can, identify life-cycle activities that occur in the waterfall model, the spiral model, and the "vee" model. Of these models, pick the one you prefer and explain why.

15. Design considerations are the first step on the way to deriving technical performance measures. Outline all of the steps, emphasizing the design-dependent parameter concept.

16. How are requirements related to technical performance measures? What is the remedy when requirements and TPMs are not in agreement?

17. Pick a design situation of your choice and itemize the multiple criteria that should be addressed.

18. Pick a top-level requirement and decompose it in accordance with the structure shown in Figure 7.

19. Candidate systems result from design synthesis and become the object of design analysis and evaluation. Explain.

20. Pick up a design consideration at the lowest level in Figure 8. Discuss its position and impact on each of the next higher levels.

21. Take synthesis, analysis, and evaluation as depicted in Figure 9 and then classify each activity exhibited by application of elements in the 10-block morphology of Figure 10.

22. Identify some of the engineering domain manifestations of systems engineering.

23. What are some of the impediments to the implementation of systems engineering?

24. What are some of the benefits that may result from the utilization of systems thinking and engineering?

25. Go to the INCOSE website and find the page about the journal *Systems Engineering*. Pick an article that touches upon a topic in this chapter and relate it thereto in no more than one paragraph.

26. Go to the INCOSE website and identify one individual from the Fellows group who most closely matches your own interest in systems engineering. Say why you would like to meet this person.

Conceptual System Design

From Chapter 3 of *Systems Engineering and Analysis,* Fifth Edition, Benjamin S. Blanchard, Wolter J. Fabrycky. Copyright © 2011 by Pearson Education, Inc. Published by Pearson Prentice Hall. All rights reserved.

Conceptual System Design

Conceptual design is the first and most important phase of the system design and development process. It is an early and high-level life-cycle activity with the potential to establish, commit, and otherwise predetermine the function, form, cost, and development schedule of the desired system and its product(s). The identification of a problem and an associated definition of need provide a valid and appropriate starting point for conceptual system design.

Selection of a path forward for the design and development of a preferred system architecture that will ultimately be responsive to the identified customer need is a major purpose of conceptual design. Establishing this foundation early, as well as initiating the early planning and evaluation of alternative technological approaches, is a critical initial step in the implementation of the systems engineering process. Systems engineering, from an organizational perspective, should take the lead in the solicitation of system *requirements* from the beginning and then address them in an integrated life-cycle manner.

This chapter addresses certain steps in the systems engineering process and, in doing so, provides basic insight and knowledge about the following:

- Identifying and translating a problem or deficiency into a definition of need for a system that will provide a preferred solution;
- Accomplishing advanced system planning and architecting in response to the identified need;
- Developing system operational requirements describing the functions that the system must perform to accomplish its intended purpose(s) or mission(s);
- Conducting exploratory studies leading to the definition of a technical approach for system design;
- Proposing a maintenance concept for the sustaining support of the system throughout its planned life cycle;
- Identifying and prioritizing technical performance measures (TPMs) and related criteria for design;
- Accomplishing a system-level functional analysis and allocating requirements to various subsystems and components;
- Performing systems analysis and producing trade-off studies;

- Developing a system specification; and
- Conducting a conceptual design review.

The completion of the steps above constitutes the *system definition* process at the conceptual level. Although the depth, effort, and cost of accomplishing these steps may vary, the process is applicable to any type or category of system, complex or simple, large or small. It is important that these steps, which encompass the front end of the systems engineering process, be thoroughly understood. Collectively, they serve as a learning objective with the goal being to provide a comprehensive step-by-step approach for addressing this critical early phase of the systems engineering process.

1 PROBLEM DEFINITION AND NEED IDENTIFICATION

The systems engineering process generally commences with the identification of a "want" or "desire" for something based on some "real" deficiency. For instance, suppose that a current system capability is not adequate in terms of meeting certain required performance goals, is not available when needed, cannot be properly supported, or is too costly to operate. Or, there is a lack of capability to communicate between point A and point B, at a desired rate X, with reliability of Y, and within a specified cost of Z. Or, a regional transportation authority is faced with the problem of providing for increased two-way traffic flow across a river that divides a growing municipality (to illustrate the overall process, this particular example is developed further in Sections 3, 4.

It is important to commence by first defining the "problem" and then defining the need for a specific system capability that (hopefully) is responsive. It is not uncommon to first identify some "perceived" need which, in the end, doesn't really solve the problem at hand. In other words, *why is this particular system capability needed?* Given the problem definition, a new system requirement is defined along with the priority for introduction, the date when the new system capability is required for customer use, and an estimate of the resources necessary for its acquisition. To ensure a good start, a comprehensive *statement of the problem* should be presented in specific qualitative and quantitative terms and in enough detail to justify progressing to the next step. It is essential that the process begin by defining a "real" problem and its importance.

The necessity for identifying the need may seem to be basic or self-evident; however, a design effort is often initiated as a result of a personal interest or a political whim, without the requirements first having been adequately defined. In the software and information technology area, in particular, there is a tendency to accomplish considerable coding and software development at the detailed level before adequately identifying the real need. In addition, there are instances when engineers sincerely believe that they know what the customer needs, without having involved the customer in the "discovery" process. The "design-it-now-fix-it-later" philosophy often prevails, which, in turn, leads to unnecessary cost and delivery delay.

Defining the problem is often the most difficult part of the process, particularly if there is a rush to get underway. The number of false starts and the resulting cost commitment can be significant unless a good foundation is laid from the beginning. A complete description of the need, expressed in quantitatively related criteria whenever possible, is essential. It is important that the problem definition reflects true customer requirements, particularly in an environment of limited resources.

Having defined the problem completely and thoroughly, a *needs analysis* should be performed with the objective of translating a broadly defined "want" into a more specific system-level requirement. The questions are as follows: *What is required of the system in "functional" terms? What functions must the system perform? What are the "primary" functions? What are the "secondary" functions? What must be accomplished to alleviate the stated deficiency? When must this be accomplished? Where is it to be accomplished? How many times or at what frequency must this be accomplished?*

There are many basic questions of this nature, making it important to describe the customer requirements in a *functional* manner to avoid a premature commitment to a specific design concept or configuration. Unless form follows function, there is likely to be an unnecessary expenditure of valuable resources. The ultimate objective is to define the *WHATs* first, deferring the *HOWs* until later.

Identifying the problem and accomplishing a needs analysis in a satisfactory manner can best be realized through a team approach involving the customer, the ultimate consumer or user (if different from the customer), the prime contractor or producer, and major suppliers, as appropriate. The objective is to ensure that proper and effective communications exist between all parties involved in the process. Above all, the "voice of the customer" must be heard, providing the system developer(s) an opportunity to respond in a timely and appropriate manner.

2 ADVANCED SYSTEM PLANNING AND ARCHITECTING

Given an identified "need" for a new or improved system, the advanced stages of system planning and architecting can be initiated. Planning and architecting are essential and coequal activities for bringing a new or improved capability into being. The overall "program requirements" for bringing the capability into being initiate an advanced system planning activity and the development of a *program management plan* (PMP), shown as the second block in Figure 1. While the specific nomenclature for this top-level plan may differ with each program, the objective is to prepare a "management-related" plan providing the necessary guidance for all subsequent managerial and technical activities.

Referring to Figure 1, the PMP guides the development of requirements for implementation of a systems engineering program and the preparation of a *systems engineering management plan* (SEMP), or *system engineering plan* (SEP). The "technical requirements" for the system are simultaneously determined. This involves development of a system-level architecture (functional first and physical later) to include development of system operational requirements, determination of a functional architecture, proposing alternative technical concepts, performing feasibility analysis of proposed concepts, selecting a maintenance and support approach, and so on, as is illustrated by Figure 2. The results lead to the preparation of the *system specification* (Type *A*). The preparation of the SEMP and the system specification should be accomplished concurrently in a coordinated manner. The two documents must "talk" to each other and be mutually supportive.

It can be observed from Figures 1 and 2 that the identified requirements are directly aligned and supportive of the activities and milestones shown in Figure A.1. The *system specification* (Type *A*) contains the highest-level architecture and forms the basis for the preparation of all lower-level specifications in a top-down manner. These lower-level specifications include *development* (Type *B*), *product* (Type *C*), *process* (Type *D*), and *material* (Type *E*) *specifications*, and are described further in Section 9. The *systems engineering management plan* is not detailed here. The systems engineering process and the steps illustrated in Figure 2 are described in the remaining sections of this chapter.

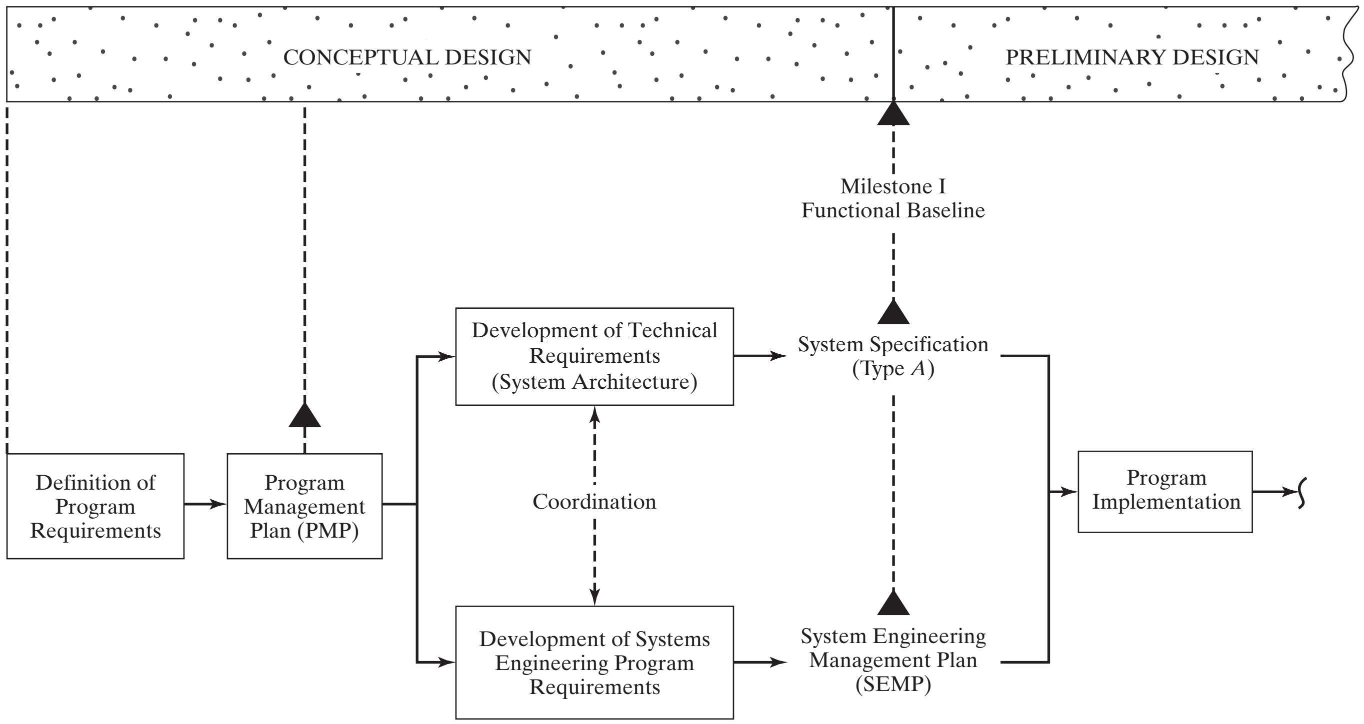


Figure 1 Early system advanced planning and architecting.

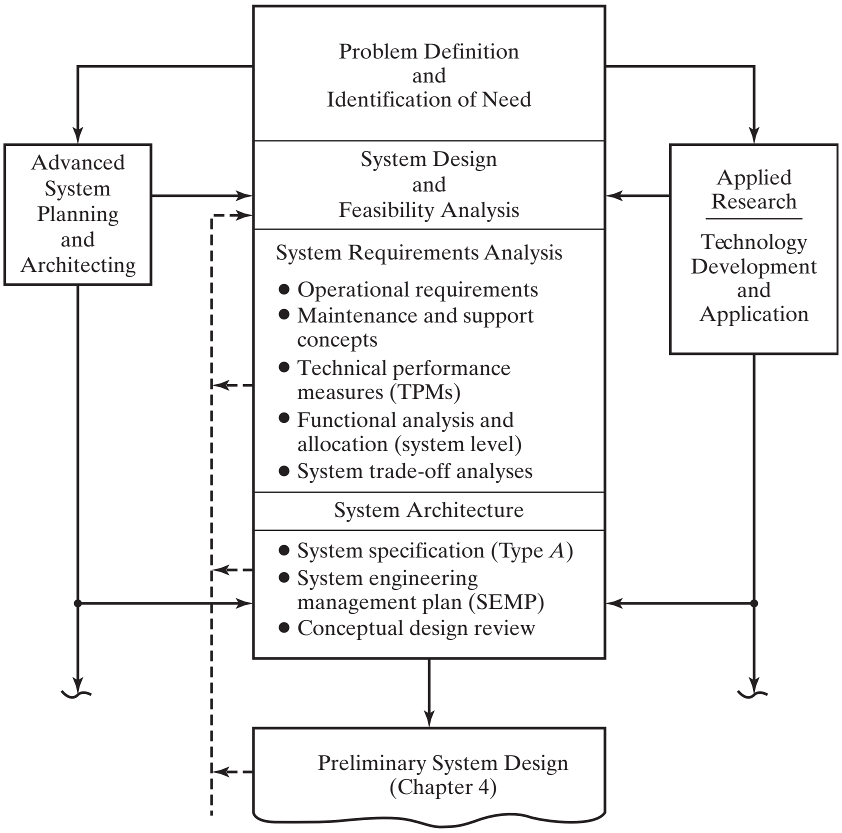


Figure 2 Major steps in the system requirements definition process.

3 SYSTEM DESIGN AND FEASIBILITY ANALYSIS

Having justified the need for a new system, it is necessary to (1) identify various system-level design approaches or alternatives that could be pursued in response to the need; (2) evaluate the feasible approaches to find the most desirable in terms of performance, effectiveness, maintenance and sustaining support, and life-cycle economic criteria; and (3) recommend a preferred course of action. There may be many possible alternatives; however, the number of these must be narrowed down to those that are physically feasible and realizable within schedule requirements and available resources.

In considering alternative system design approaches, different technology applications are investigated. For instance, in response to the river crossing problem (identified in Section 1), alternative design concepts may include a tunnel under the river, a bridge spanning the river, an airlift capability over the river, the use of barges and ferries on the river, or possibly re-routing the river itself. Then a feasibility study would be accomplished to determine a preferred approach. In performing such a study, one must address limiting factors such as geological and geotechnical, atmospheric and weather, hydrology and water flow, as well as the projected capability of each alternative to meet life-cycle cost objectives. In this case, the feasibility results might tentatively indicate that some type of bridge structure spanning the river appears to be best.

At a more detailed level, in the design of a communications system, is a fiber optics technology or the conventional twisted-wire approach preferred? In aircraft design, to what extent should the use of composite materials be considered? In automobile design, should high-speed electronic circuitry in a certain control application be incorporated or should an electromechanical approach be utilized? In the design of a data transmission capability, should a digital or an analogue format be used? In the design of a process, to what extent should embedded computer capabilities be incorporated? Included in the evaluation process are considerations pertaining to the type and maturity of the technology, its stability and growth potential, the anticipated lifetime of the technology, the number of supplier sources, and so on.

It is at this early stage of the system life cycle that major decisions are made relative to adopting a specific design approach and related technology application. Accordingly, it is at this stage that the results of such design decisions can have a great impact on the ultimate behavioral characteristics and life-cycle cost of a system. Technology applications are evaluated and, in some instances where there is not enough information available (or a good solution is not readily evident), research may be initiated with the objective of developing new knowledge to enable other approaches. Finally, it must be agreed that the "need" should dictate and drive the "technology," and not vice versa.

The identification of alternatives and feasibility considerations will significantly impact the operational characteristics of the system and its design for constructability, producibility, supportability, sustainability, disposability, and other design characteristics. The selection and application of a given technology has reliability and maintainability implications, may impact human performance, may affect construction or manufacturing and assembly operations in terms of the processes required, and may significantly impact the need for system maintenance and support. Each will certainly affect life-cycle cost differently. Thus, it is essential that life-cycle considerations be an inherent part of the process of determining the feasible set of system design alternatives.

4 SYSTEM OPERATIONAL REQUIREMENTS

Once the need and technical approach have been defined, it is necessary to translate this into some form of an "operational scenario," or a set of operational requirements. At this point, the following questions may be asked: *What are the anticipated types and quantities of equipment, software, personnel, facilities, information, and so on, required, and where are they to be located? How is the system to be utilized, and for how long? What is the anticipated environment at each operational site (user location)? What are the expected interoperability requirements (i.e., interfaces with other "operating" systems in the area)? How is the system to be supported, by whom, and for how long?* The answer to these and comparable questions leads to the definition of system operational requirements, the follow-on maintenance and support concept, and the identification of specific design-to criteria, and related guidelines.

4.1 Defining System Operational Requirements

System operational requirements should be identified and defined early, carefully, and as completely as possible, based on an established need and selected technical approach. The operational concept and scenario as defined herein is identified in Figure 2. It should include the following:

1. *Mission definition:* Identification of the prime and alternate or secondary missions of the system. What is the system to accomplish? How will the system accomplish

its objectives? The mission may be defined through one or a set of scenarios or operational profiles. It is important that the *dynamics* of system operating conditions be identified to the extent possible.

2. *Performance and physical parameters:* Definition of the operating characteristics or functions of the system (e.g., size, weight, speed, range, accuracy, flow rate, capacity, transmit, receive, throughput, etc.). What are the critical system performance parameters? How are they related to the mission scenario(s)?

3. *Operational deployment or distribution:* Identification of the quantity of equipment, software, personnel, facilities, and so on and the expected geographical location to include transportation and mobility requirements. How much equipment and associated software is to be distributed, and where is it to be located and for how long? When does the system become fully operational?

4. *Operational life cycle (horizon):* Anticipated time that the system will be in operational use (expected period of sustainment). What is the total inventory profile throughout the system life cycle? Who will be operating the system and for what period of time?

5. *Utilization requirements:* Anticipated usage of the system and its elements (e.g., hours of operation per day, percentage of total capacity, operational cycles per month, facility loading). How is the system to be used by the customer, operator, or operating authority in the field?

6. *Effectiveness factors:* System requirements specified as figures-of-merit (FOMs) such as cost/system effectiveness, operational availability (A_o), readiness rate, dependability, logistic support effectiveness, mean time between maintenance (MTBM), failure rate (λ), maintenance downtime (MDT), facility utilization (in percent), operator skill levels and task accomplishment requirements, and personnel efficiency. Given that the system will perform, how effective or efficient is it? How are these factors related to the mission scenario(s)?

7. *Environmental factors:* Definition of the environment in which the system is expected to operate (e.g., temperature, humidity, arctic or tropics, mountainous or flat terrain, airborne, ground, or shipboard). This should include a range of values as applicable and should cover all transportation, handling, and storage modes. How will the system be handled in transit? To what will the system be subjected during its operational use, and for how long? A complete environmental profile should be developed.

In addition to defining operational requirements that are system specific, the system being developed may be imbedded within an overall higher-level structure making it necessary to give consideration to *interoperability requirements*. For example, an aircraft system may be contained within a higher-level airline transportation system, which is part of a regional transportation capability, and so on. There may be both ground and marine transportation systems within the same overall structure, where major interface requirements must be addressed when system operational requirements are being defined.

In some instances, there may be both vertical and horizontal impacts when addressing the system in question, within the context of some larger overall configuration. There are two important questions to be addressed: *What is the potential impact of this new system on the other systems in the same SOS configuration? What are the external impacts from the other systems within the same SOS structure on this new system?*

4.2 Illustrating System Operational Requirements

Further consideration of system operational requirements (as presented in Section 4.1) is provided through five sample illustrations, each covering different degrees or levels of detail. The first illustration is an extension of the river crossing problem introduced in Section 1. The second illustration, covering operational requirements in more depth, is an aircraft system with worldwide deployment. The third illustration is a communication system with ground and airborne applications. The fourth illustration deals with commercial airline capability for a metropolitan area. The fifth illustration considers a hospital as part of a community healthcare system. Finally, it is noted that there may exist many other applications and situations to which the illustrated methodology applies.

The intent of these examples is to encourage consideration of operational requirements at a greater depth than before and to do so early in the system life cycle when the specification of such requirements will have the greatest impact on design. While it may be easier to delay such considerations until later in the system design process, the consequences of such are likely to be very costly in the long term. The objective in systems engineering is to "force" considerations of operational requirements as early as practicable in the design process.

Illustration 1: River Crossing Problem. Returning to the regional public transportation authority facing the problem of providing for capability that will allow for a significant increase in the two-way traffic flow across a river dividing a growing municipality (a *what*). Further study of the problem (i.e., the current deficiency) revealed requirements for the two-way flow of private vehicles, taxicabs, buses, rail and rapid transit cars, commercial vehicles, large trucks, people on motor cycles and bicycles, and pedestrians across the river. Through advanced system planning and consideration of possible architectures, various river crossing concepts were proposed and evaluated for physical and economic feasibility. These included going under the river, on the river, spanning the river, over the river, or possibly re-routing the river itself. Feasibility considerations determined that the river is not a good candidate for rerouting, both physically and due to its role in providing navigable traffic flow upstream and downstream.

Results from the study indicated that the most attractive approach is the construction of some type of a bridge structure spanning the river (a *how*). From this point on, it is necessary to delve further into the operational requirements leading to the selection and evaluation of a bridge type (suspension, pier and superstructure, causeway, etc.) by considering some detailed "design-to" factors as below:

1. *Mission definition and performance parameters:* The peak traffic flow rate(s) in units/people per hour during any 24-hour period shall be 4,000 for passenger cars, 120 for taxicabs, 20 for buses and trolley cars, 320 for commercial vehicles, 120 for large trucks, 100 people on bicycles, and 180 pedestrians.
2. *Operational deployment and distribution:* The proposed bridge shall be located at point *ABC*, along a straight part of the river, connecting the two community urban centers (e.g., Main Street in Community *X* and Center Street in Community *Y*). The location shall be based on the results from the study dealing with geological, geotechnical, hydrology and water flow, and related factors (refer to Section 3).

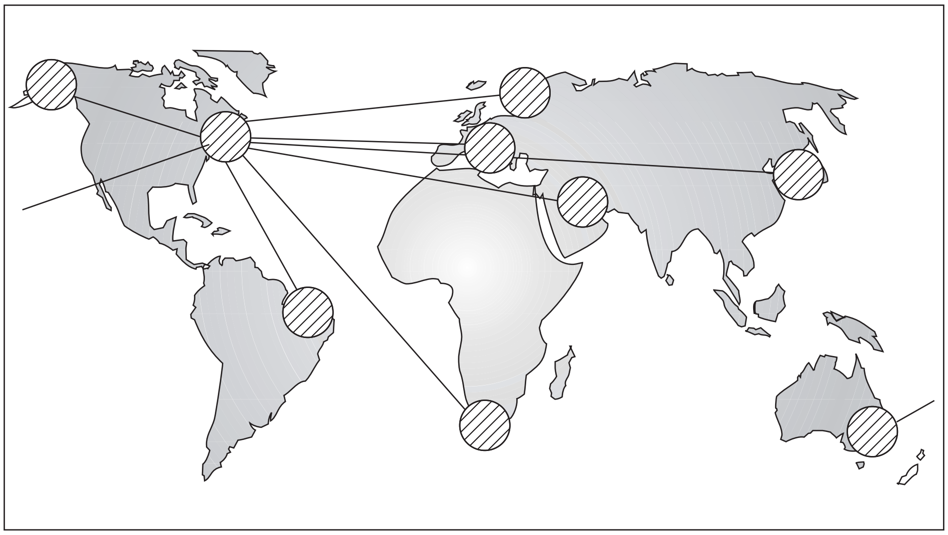
3. *Operational life cycle (horizon):* The proposed bridge shall be constructed and fully operational 5 years from the date of initial contract award, and the operational life cycle for the bridge shall be 50 years.
4. *Effectiveness factors:* The operational availability (A_o) for the overall system (i.e., the bridge itself along with all of its operational infrastructure) shall be at least 99.5%, the MTBM shall be 5 years or greater, and the maintenance downtime (MDT) shall be 1 day or less.
5. *Environmental factors:* The proposed bridge shall be fully operational in an environment with temperatures ranging from +125°F to –50°F ambient; in 100% humidity; in rain, sleet, and/or snow; able to withstand any shock and vibration due to a fully loaded traffic flow; and able to withstand any earth tremors of up to 6.0 on the Richter Scale. In the event of inclement weather (i.e., snow, sleet, or ice), the bridge road conditions shall be returned to complete operational status within 2 hours or less.
6. *Environmental sustainment factors:* There shall be no degradation to the river flow, adjoining river embankment, air quality, acoustical emission, and/or view-scope aesthetics. The material resources utilized in the construction of the bridge and its infrastructure shall be completely replenished in 5 years, or less, from the point in time when the bridge initially becomes fully operational.
7. *Economic factors:* The bridge and its infrastructure shall be designed such that the projected life-cycle cost (LCC) shall not exceed *$X*, and the annual operational and maintenance cost shall not exceed 1% of the system acquisition cost (design, construction, and test and evaluation). All future design decisions (i.e., modifications or otherwise) must be justified and based on total system life-cycle cost.

While some of the specific design-to qualitative and quantitative factors introduced in this example may vary from one project to the next, this example is presented with the intention of illustrating those considerations that must be addressed early in conceptual design as it pertains to the river crossing problem.

Illustration 2: Aircraft System. Based on the results from feasibility analysis of conceptual design alternatives, it was determined that there is a need for a new aircraft. These aircraft are to be procured and deployed in multiple quantities throughout the world. The anticipated geographical locations, estimated quantities per location, and average aircraft utilization times are projected in Figure 3.

In terms of missions, each aircraft will be required to fly three different mission profiles, as illustrated in Figure 4 and described in *Specification 12345.* Basically, an aircraft will be prepared for flight, take off and complete a specific mission scenario, return to its base, undergo maintenance as required, and be returned to a “ready” status. For planning purposes, all aircraft will be required to fly at least one each of the three different mission profiles per week.

The aircraft shall meet performance requirements in accordance with *Specification 12345*; the operational availability (A_o) shall be at least 90%; the MDT shall not exceed 3 hours; the maintenance time ($\overline{M}ct$) shall be 30 minutes or less; M_{max} at the 90th percentile shall be 2 hours; the maintenance labor hours per operating hour (MLH/OH) for the aircraft shall be 10 or less; and the cost per maintenance action at the organizational level shall not exceed $10,000. The aircraft will incorporate a built-in test capability that will allow for fault isolation to the unit level with an 85% self-test thoroughness. No special external support equipment will be allowed. Relative to the support infrastructure, there will be an intermediate-level maintenance capability located at each operational base. In addition, there will be two depot-level maintenance facilities. The overall support concept is illustrated in Figure 5.



Number of Units in Operational Use per Year

Geographical Operational Areas	Year Number										Total Units
	1	2	3	4	5	6	7	8	9	10	
1. North and South America	–	–	10	20	40	60	60	60	35	25	310
2. Europe	–	–	12	24	24	24	24	24	24	24	180
3. Middle East	–	–	12	12	12	24	24	24	24	24	156
4. South Africa	–	–	12	24	24	24	24	24	24	24	180
5. Pacific Rim 1	–	–	12	12	12	24	24	24	12	12	132
6. Pacific Rim 2	–	–	12	12	12	12	12	12	12	12	96
Total	–	–	70	104	124	168	168	168	131	121	1,054

Average Utilization: 4 Hours per Day, 365 Days per Year

Figure 3 System operational requirements (distribution and utilization).

Although the description given here is rather cursory in nature considering the total spectrum of system operational requirements, it is necessary as an *input* to design to define (1) the geographical location and the anticipated environment in which the system is to be utilized; (2) one or more typical mission scenarios in order to identify operational sequences, potential stresses on the system, and system effectiveness requirements; and (3) the system operational life cycle in order to determine performance factors, reliability and maintainability requirements, human engineering requirements, and the anticipated length and magnitude of the required maintenance and sustaining support capability. In essence, the overall concept conveyed in Figures 3–5, supplemented with the appropriate quantitative measures, must be defined to establish a future baseline for system design and development. While many of the specific quantitative factors specified in this problem are not introduced, the objective here is to further emphasize that such factors must be addressed early in determining operational requirements as an input to the design process.

Illustration 3: Communication System. A new communication system with an increased range capability and improved reliability is needed to replace several existing

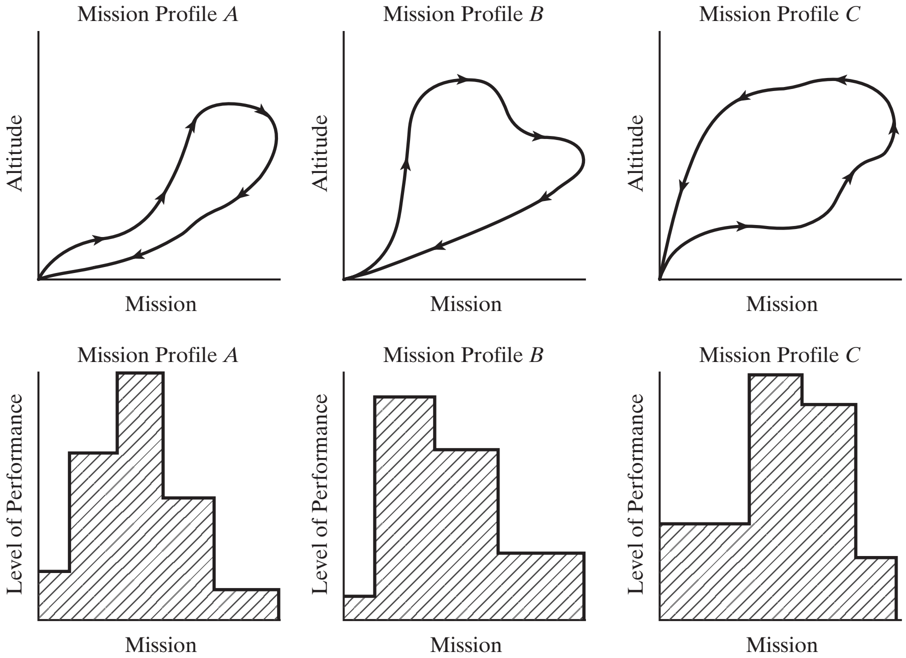


Figure 4 Typical aircraft operational profiles.

capabilities that are currently distributed in multiple quantities throughout the world. The system must accomplish three basic missions:

1. *Mission Scenario 1:* System elements are to be installed in low-flying light aircraft (10,000 feet altitude or less) in quantities of one per aircraft. The system shall enable communication with ground vehicles dispersed throughout mountainous and flat terrain and with a centralized area communication facility. It is anticipated that each aircraft will fly 15 missions per month with an average mission duration of 2 hours. A typical mission profile is illustrated in Figure 6. The communication system utilization requirement is 110% (1.1 hours of system operation for every hour of aircraft operation, which includes air time plus some ground time). The system must be operationally available 99.5% of the time and have a reliability mean time between failures (MTBF) of not less than 2,000 hours.
2. *Mission Scenario 2:* System elements are to be installed in ground vehicular equipment (e.g., car, light truck, or equivalent) in quantities of one per vehicle. The system shall enable communication with other vehicles at a range of 200 miles in relatively flat terrain, with overhead aircraft at an altitude of 10,000 feet or less, and with a centralized area communication facility. Sixty-five percent of the vehicles will be in operational use at any given point in time and the system shall be utilized 100% of the time for those vehicles that are operational. The system must have a reliability MTBF of at least 1,800 hours and a mean corrective maintenance time ($\overline{\text{M}}$ct) of 1 hour or less.
3. *Mission Scenario 3:* System elements are to be installed in 20 area communication facilities located throughout the world with 5 operational systems assigned to each

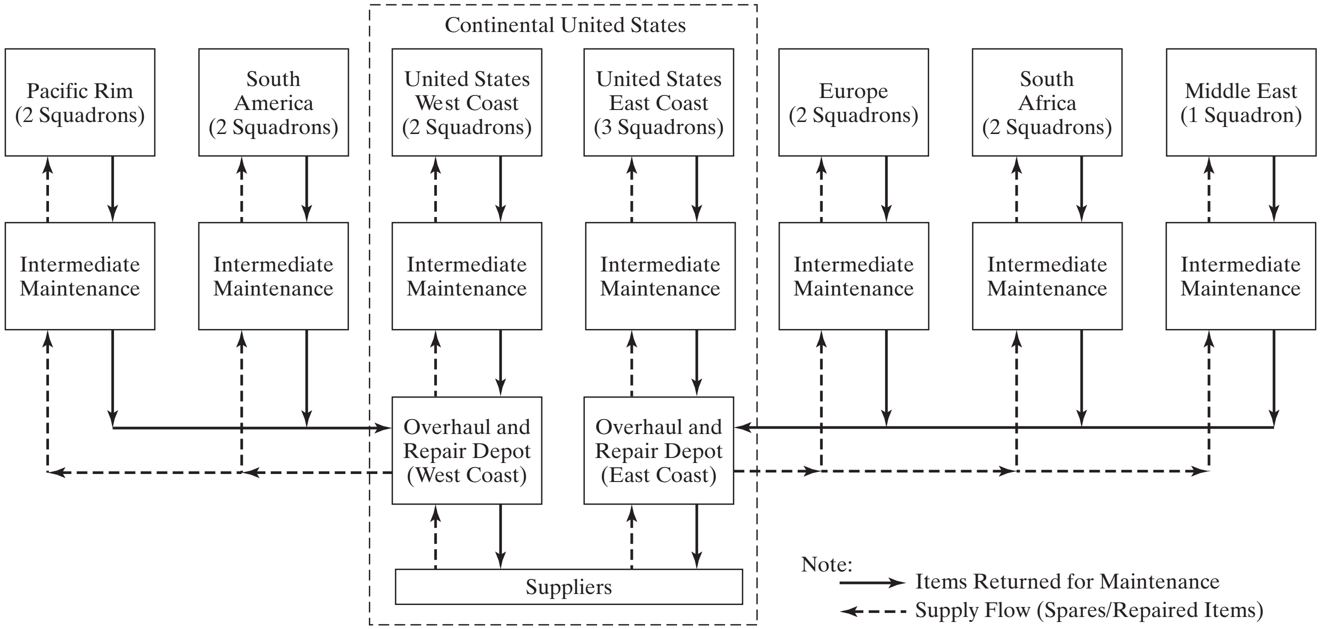


Figure 5 Top-level system maintenance and support infrastructure.

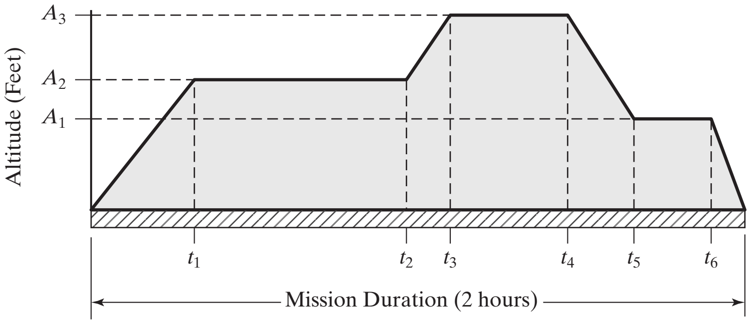


Figure 6 Mission profile.

facility. The system shall enable communication with aircraft flying at an altitude of 10,000 feet or less and within a radius of 500 miles from the facility and with ground vehicles at a range of 300 miles in relatively flat terrain. Four of the systems are utilized 24 hours a day, and the remaining system is a backup and used an average of 6 hours per day. Each operational system shall have a reliability MTBF of at least 2,500 hours and a $\overline{M}$ct of 30 minutes or less. Each communication facility shall be located at an airport.

In the interest of minimizing the total cost of support (e.g., test and support equipment, spares, and personnel), the transmitter–receiver, which is a major element of the system, shall be a common design for the vehicular, airborne, and ground applications. The antenna configuration may be unique in each instance.

Operational prime equipment/software shall be introduced into the inventory commencing 4 years from this date, and a maximum complement is acquired by 8 years. The maximum complement must be sustained for 10 years, after which a gradual phase-out will occur through attrition. The last equipment is expected to be phased out of the inventory in 25 years. The program schedule is illustrated in Figure 7.

Specifically, the requirements dictate the need for (1) 20 centralized communication facilities; (2) 11 aircraft assigned to each communication facility; and (3) 55 vehicles

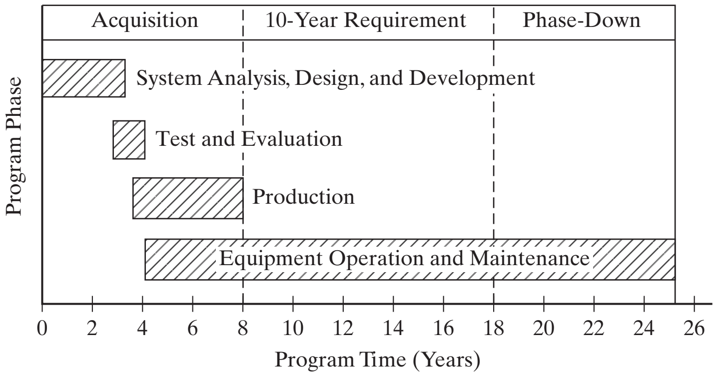


Figure 7 Program schedule.

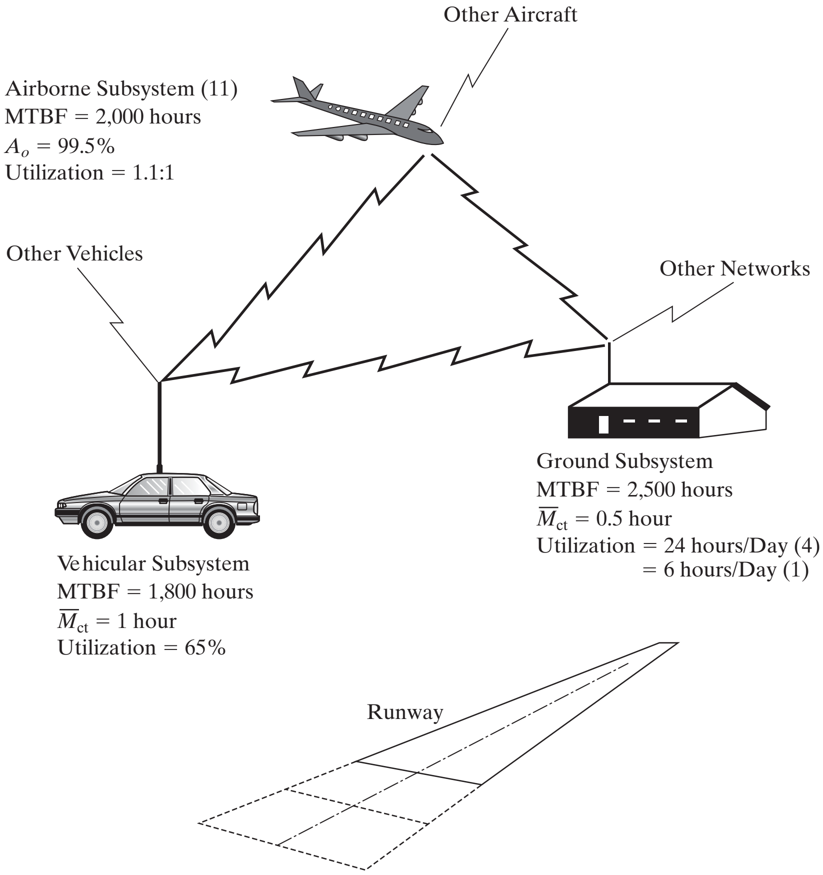


Figure 8 Communication network (typical).

assigned to each communication facility. Based on the three mission scenarios just defined, there is a total requirement for 1,420 prime equipments deployed in a series of communication networks (i.e., the total system), as illustrated in Figure 8.

In support of the program schedule and the basic need, it is necessary to develop an equipment inventory profile, as shown in Figure 9. This profile provides an indication of the total quantity of prime equipment in the user's inventory during any given year in the life cycle. The front end of the profile represents the production rate, which, of course, may vary considerably, depending on the type and complexity of equipment/software, the capacity of the production facility, and the cost of production. The total quantity of prime equipment produced is 1,491, which assumes (1) that 5% of the equipment will be condemned during the 10-year full-complement period due to loss or damage beyond economical repair, and (2) that production is accomplished on a one-time basis (to avoid production startup and shutdown costs). In other words, assuming that production is continuous, 1,491 pieces of equipment must be produced to cover attrition and yet maintain the operational requirements of 1,420 equipments through the 10-year period. After the 10-year period, the number of units is reduced by attrition and/or phase-out owing to obsolescence until the inventory is completely depleted.

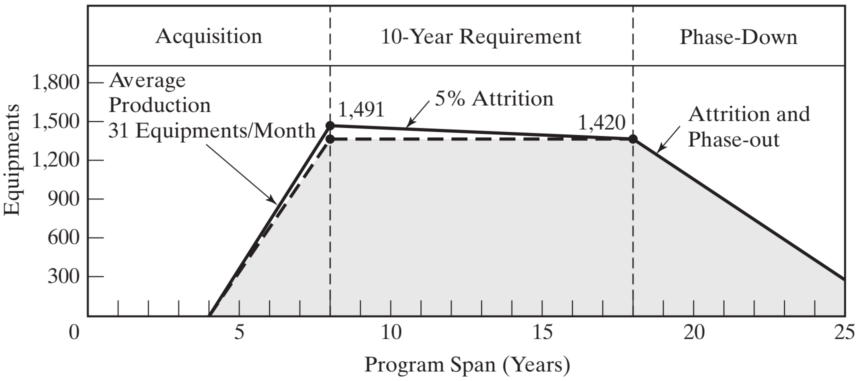


Figure 9 Basic inventory requirements over the system life cycle.

Definition of the operational requirements for the communication system (i.e., distribution, utilization, effectiveness factors, reliability and maintainability measures, etc.) provides the basis for determining the maintenance and support concept (refer to Section 5) and also the specific *design-to* requirements. As the system design and development process progresses, the operational requirements for the communication system are further refined on an iterative basis.

Illustration 4: Commercial Airline Upgrade. Three commercial airline carriers are proposing to serve a large metropolitan region 8 years hence. As future growth is expected, additional airline companies may become involved at a later time. For planning purposes, the combined anticipated passenger handling requirement follows the projection in Figure 10. The combined airline requirements are as shown.

1. Anticipated flight arrivals/departures are evenly spaced in the time periods indicated. It is assumed that 100 passengers constitute an average flight load.
2. The aircraft A_o is 95%. That is, 95% of all flights must be fully operational when scheduled (discounting aborts due to weather). Allowable factors for scheduled maintenance and passenger loading are as follows:

Function	Frequency	Downtime
Through service	Each through flight	30 minutes
Turnaround service	Each turnaround	1 hour
Termination check	Each terminal flight	6 hours
Service check	15 days	9 hours

Periodic and main base checkouts will be accomplished elsewhere.

3. Allowable unscheduled maintenance in the area shall be limited to the organizational level and will include the removal and replacement of line replaceable items, tire changes, and engine replacements as required. The specific MDT limits are as follows:
   - Engine change—6 hours
   - Tire change—1 hour
   - Any other item—1 hour

Time Period	Anticipated Flights per Day			
	Point *A*	Point *B*	Point *C*	Point *D*
6:00 A.M. – 11:00 A.M.	33	65	95	105
11:00 A.M. – 4:00 P.M.	17	43	50	55
4:00 P.M. – 9:00 P.M.	33	60	90	100
9:00 P.M. – 6:00 A.M.	3	10	15	18
Total	86	178	250	278

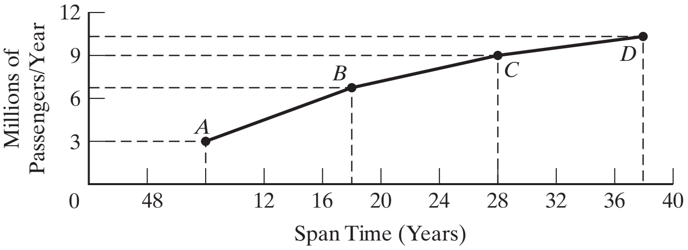


Figure 10 Projected passenger-handling requirement.

4. The metropolitan area must provide the necessary ground facilities to support the following types of aircraft (fully loaded): A-320, A-321, A-330, B-727, B-737, B-747, B-757, B-767, B-777, L-1011, and MD-80. In addition, provisions must be made for cargo handling and storage.

The airline carriers have identified a need to provide air transportation service but, from the airlines' standpoint, the metropolitan area must provide the necessary logistic resources (facilities, test and support equipment, ground handling equipment, people movers, operating and maintenance personnel, etc.) to support this service. This involves selecting a site for an air transportation facility; designing and constructing the facility; providing local transportation to and from the airline terminal; acquiring the test and support equipment, spare/repair parts, personnel, and data to support airline operations; and maintaining the total capability on a sustaining basis throughout the planned operational period.

Because of the size of the program and the growth characteristics projected in Figure 10, a three-phased construction program is planned. The schedule is presented in Figure 11.

The initial step is to select a location for the air transportation facility. The selection process considers available land, terrain, geology, wind effects, distance from the metropolitan area, access via highway and/or public transportation, noise and ecology requirements, and cost. Once a site has been established, the facility must include runways, holding area, flight control equipment, airline terminal, control tower, operations building, hangars, maintenance docks, fuel docks, cargo handling and storage capability, utilities, and all the required support directly associated with passenger needs and comfort.

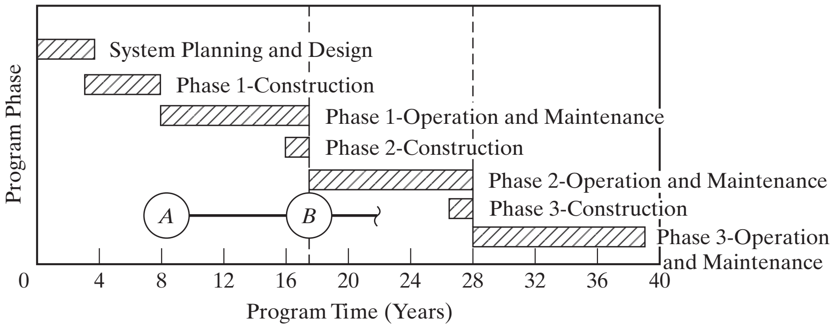


Figure 11 Program schedule.

The ultimate design configuration of the air transportation facility is based directly on the operational requirements—anticipated airline flight arrivals/departures, passenger loading, aircraft turnaround times, and maintenance and servicing requirements. For example, at a point 18 years hence (Figure 10, point *B*), the anticipated average number of flights is 65 per day between the hours of 6:00 A.M. and 11:00 A.M. The number of through flights is 30, the gate time for each is 45 minutes (to accomplish servicing and passenger loading), and the number of turnarounds is 35 with a gate time of 1 hour each. The total gate time required (considering no delays and assuming one gate for each aircraft arrival/departure) is 50 hours during the 6:00 A.M.–11:00 A.M. time period; thus, at least 10 gates are required in the passenger terminal to satisfy the load. This requirement, in turn, influences the size of the passenger waiting lobby and the number of airline personnel agents required. Further, the servicing and ground handling of the aircraft require certain consumables (fuel, oil, lubricants, etc.), spare/repair parts, test and support equipment (towing vehicles, fuel trucks, etc.), and technical data (operating and maintenance instructions). The possibility of unscheduled maintenance dictates the need for trained maintenance personnel, spare/repair parts, data, and a backup maintenance dock or hangar.

One can go on identifying requirements to support the basic need of the metropolitan area and the commercial airline companies. It readily becomes obvious that an understanding of operational requirements and logistic support plays a major role. There are requirements associated with the aircraft, the air transportation facility, and the transportation mode between the air transportation facility and the metropolitan area. The commercial airline illustration presented here only touches on a small segment of the problem. The problem should be addressed from a total systems approach considering the functions associated with all facets of the operation.

Illustration 5: Community Hospital. A different type of system was selected to illustrate that the same approach can be applied in the design of a wide variety of system configurations. More specifically, and based on the results of a feasibility study, the objective here is to design and construct a new hospital to meet the needs of a community with a population of approximately 150,000, including a 10% per year growth. This new hospital, to be considered as a system by itself, is to be part of a larger "Community Healthcare" capability, as illustrated in Figure 12. Note that we are addressing a *system-of- systems* (SOS) configuration.

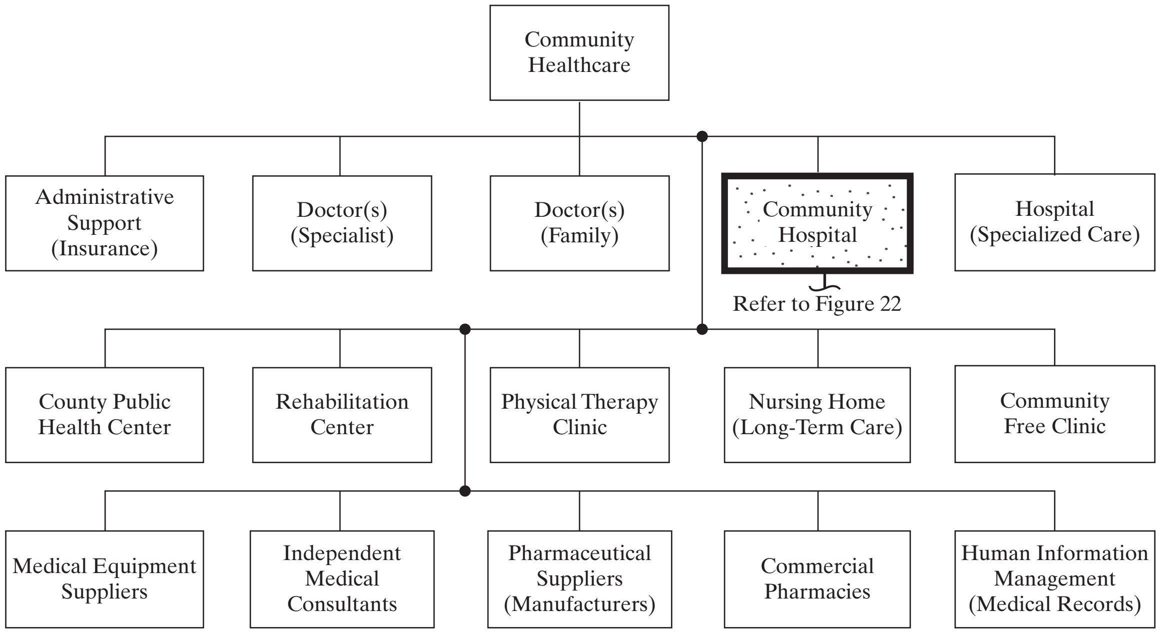


Figure 12 Community healthcare infrastructure.

The anticipated mission of the new hospital is to provide a variety of services for those in need, commencing 2 years from this date and with a planning horizon of 50 years. More specifically, the hospital shall be capable of the following:

1. Provide support for 120 patients who are admitted for surgical and related reasons. It is assumed that the average patient internship (stay) in the hopital shall be 3 days.
2. Process 40 patients per day through the "outpatient surgery" department (for minor surgical and same-day care procedures). The preregistration process shall be no longer than 30 minutes.
3. Process 100 patients per day for diagnostic imaging and/or laboratory testing. The preregistration process shall take 30 minutes or less.
4. Process 50 patients per day through its Emergency Room (ER), or Emergency Care, capability.
5. Transmit/receive the appropriate medical records within 15 minutes from the time of request.
6. Respond to the above requirements with an overall A_o of 95%, or greater.
7. The cost per patient per day shall not exceed *X* dollars ($).

Given these basic requirements, one can then proceed with the design of the hospital facility, its proposed location and layout, and so on. Further, it is essential that the design and construction of the community hospital be accomplished within the context of the overall "Community Healthcare" configuration shown in Figure 12, considering all of the interfaces that exist with the various other associated human-care capabilities shown. While this example is not presented to the same level of detail as the first four illustrations, it is hoped that one can understand the importantance for defining operational requirements early in conceptual design, regardless of the type of system being addressed.

Additional Illustrations. The five illustrations presented, derived from the results of feasibility analyses conducted earlier, are representative of typical "needs" for which system operational requirements must be defined at the inception of a program, and must serve as the basis for all subsequent program activities. These requirements must not only be implemented within the bounds of the specific system configuration in question but must also consider all possible external interfaces that may exist.

For example, as illustrated in Figure 13, one may be dealing with a number of different systems, all of which are closely related and may have a direct impact on each other. Also, there may be some "sharing" of capabilities across the board; for example, the air and ground transportation systems utilizing some of the same components which operate as part of the communication systems. Thus, the design of any new system must consider all possible impacts that it will have on other systems within the same SOS configuration (as shown in the figure), as well as those possible impacts that the other systems may have on the new system.

The methodology employed is basically the same for any system, whether the subject is a relatively small item as part of the river crossing bridge, installed in an aircraft or on a ship, a factory, or a large one-of-a-kind project such as the community hospital involving design and construction. In any case, the system must be defined in terms of its projected mission, performance, operational deployment, life cycle, utilization, effectiveness factors, and the anticipated environment.

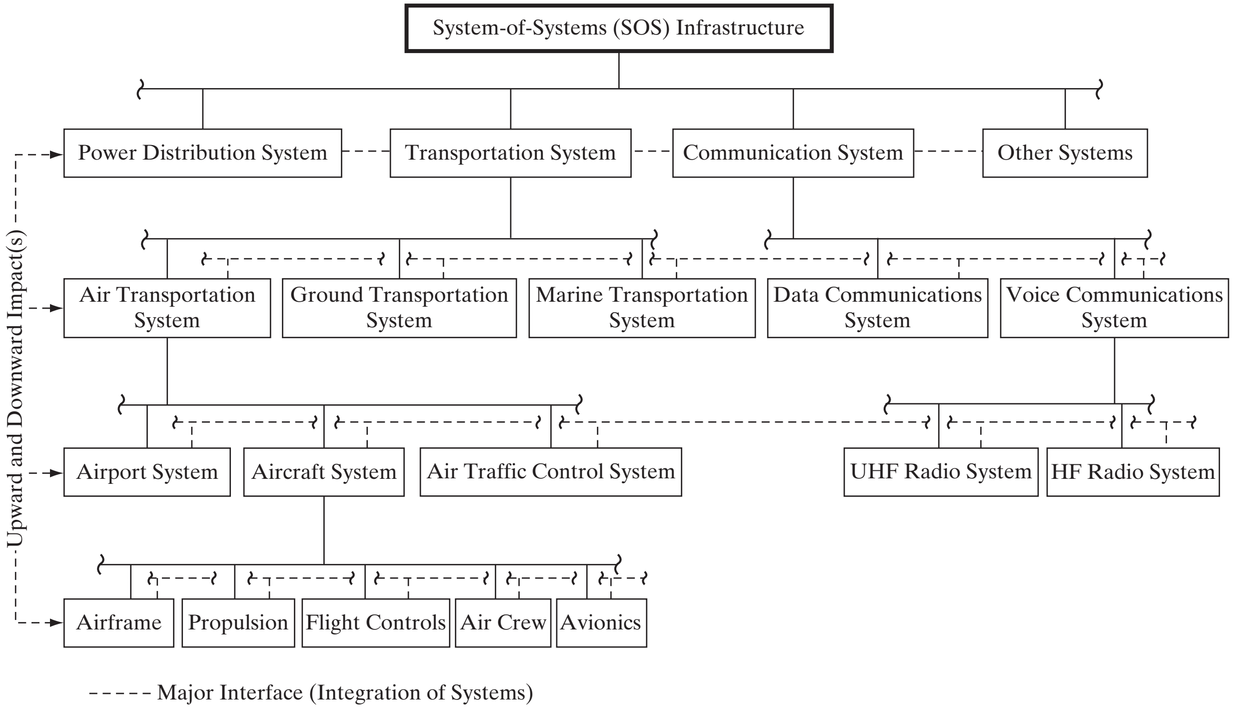


Figure 13 Multiple systems (system-of-systems).

5 SYSTEM MAINTENANCE AND SUPPORT

In addressing system requirements, the normal tendency is to deal primarily with those elements of the system that relate directly to the "performance of the mission," that is, prime equipment, operator personnel, operational software, operating facilities, and associated operational data and information. At the same time, too little attention is given to system maintenance and support and the sustainment of the system throughout its planned life cycle. In general, the emphasis has been directed toward only *part* of the system and not the entire system as an entity, which has led to costly results in the past.

To realize the overall benefits of systems engineering, it is essential that *all* elements of the system be considered on an integrated basis from the beginning. This includes not only the prime mission-related elements of the system but the maintenance and support infrastructure as well. The prime system elements must be designed in such a way that they can be effectively and efficiently supported through the entire system life cycle, and the maintenance and support infrastructure must be responsive to this requirement. This, in turn, means that one should also address the design characteristics as they pertain to transportation and handling equipment, test and support equipment, maintenance facilities, the supply chain process, and other applicable elements of logistic support.

The maintenance and support *concept* developed during the conceptual design phase evolves from the definition of system operational requirements described in Section 4. It constitutes a before-the-fact series of illustrations and statements leading to the definition of reliability, maintainability, human factors and safety, constructability and producibility, supportability, sustainability, disposability, and related requirements for design. It constitutes an "input" to the design process, whereas the maintenance *plan* (developed later) defines the follow-on requirements for system support based on a known design configuration and the results of supportability analysis.

The maintenance and support concept is reflected by the network and the activities and their interrelationships, illustrated in Figure 14. The network exists whenever there are requirements for corrective and/or preventive maintenance at any time and throughout the system life cycle. By reviewing these requirements, one should address such issues as the levels of maintenance, functions to be performed at each level, responsibilities for the accomplishment of these functions, design criteria pertaining to the various elements of support (e.g., type of spares and levels of inventory, reliability of the test equipment, personnel quantities and skill levels), and the effectiveness factors and "design-to" requirements for the overall maintenance and support infrastructure. Although the design of the prime elements of the system may appear to be adequate, the overall ability of the system to perform its intended mission objective highly depends on the effectiveness of the support infrastructure as well.

While there may be some variations that arise, depending on the type and nature of the system, the maintenance and support concept generally includes the following items:

1. *Levels of maintenance:* Corrective and preventive maintenance may be performed on the system itself (or an element thereof) at the site where the system is operating and used by the customer, in an intermediate shop near the customer's operational site, and/or at a depot or manufacturer's facility. Maintenance level pertains to the division of functions and tasks for each area where maintenance is performed. Anticipated frequency of maintenance, task complexity, personnel skill-level requirements, special facility needs, supply chain requirements, and so on, dictate to a great extent the specific functions to be accomplished at each level. Depending on the nature and mission of the system, there may be two, three, or four levels of maintenance; however, for the purposes of further discussion, maintenance may be classified as *organizational, intermediate*, and *manufacturer/depot/supplier*. Figure 15 describes the basic criteria and differences between these levels.

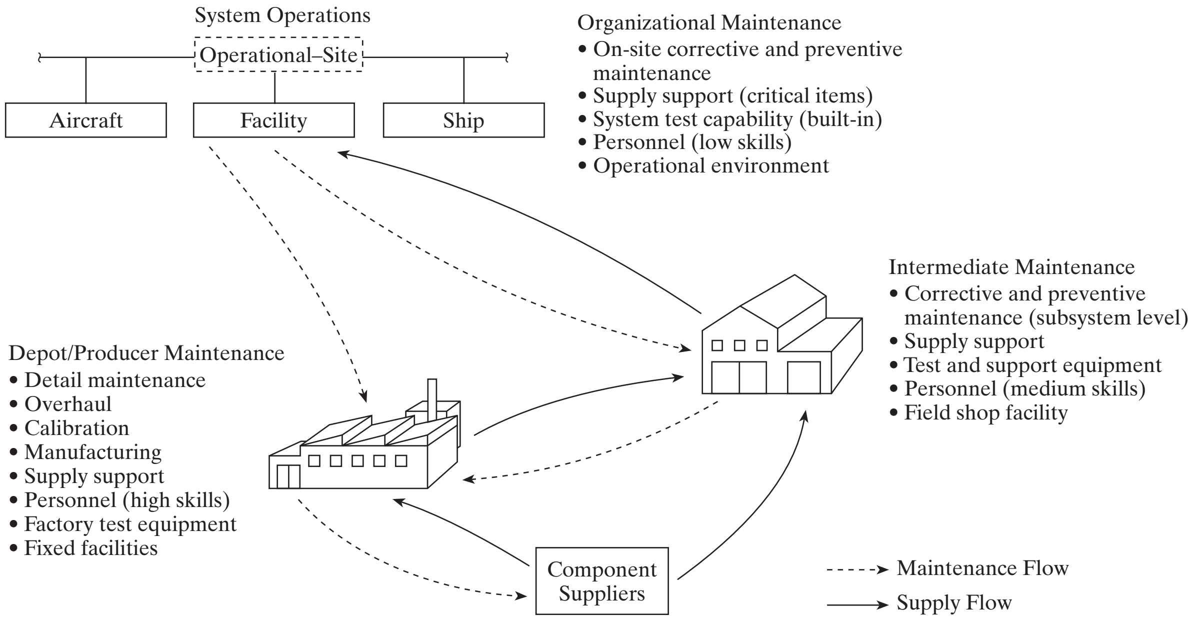


Figure 14 System operational and maintenance flow.

Criteria	Organizational Maintenance	Intermediate Maintenance		Supplier/Manufacturer/Depot Maintenance
Done where?	At the operational site or wherever the prime elements of the system are located	Mobile or semimobile units	Fixed units	Supplier/manufacturer/depot facility
		Truck, van, portable shelter, or equivalent	Fixed field shop	Specialized repair activity or manufacturer's plant
Done by whom?	System/equipment operating personnel (low-maintenance skills)	Personnel assigned to mobile, semimobile, or fixed units (intermediate-maintenance skills)		Depot facility personnel or manufacturer's production personnel (high-maintenance skills)
On whose equipment?	Using organization's equipment	Equipment owned by using organization		
Type of work accomplished?	Visual inspection Operational checkout Minor servicing External adjustments Removal and replacement of some components	Detailed inspection and system checkout Major servicing Major equipment repair and modifications Complicated adjustments Limited calibration Overload from organizational level of maintenance		Complicated factory adjustments Complex equipments repairs and modifications Overhaul and rebuild Detailed calibration Supply support Overload from intermediate level of maintenance

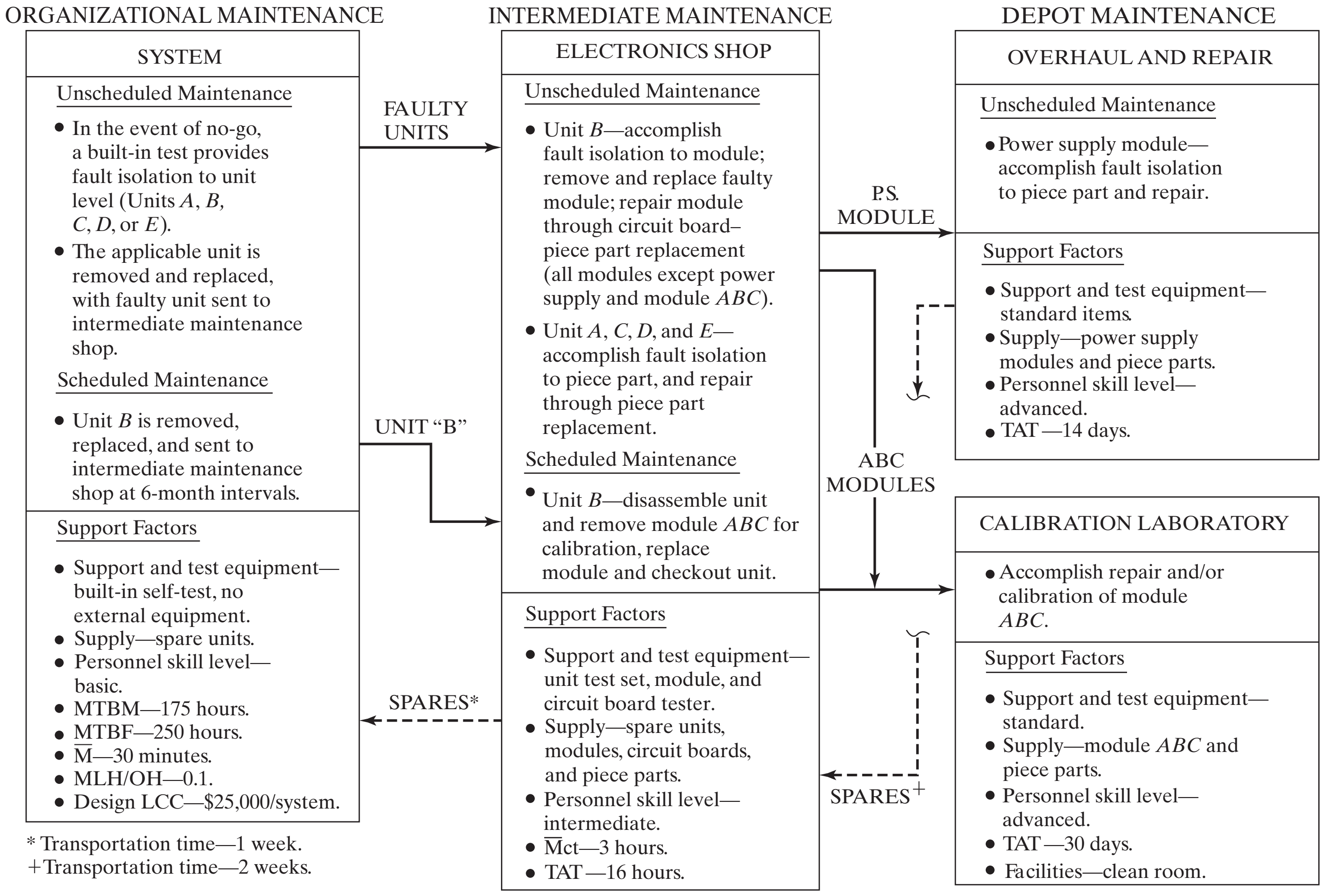
Figure 15 Major levels of maintenance.

2. *Repair policies:* Within the constraints illustrated in Figures 14 and 15, there are a number of possible policies specifying the extent to which the repair of an element or component of a system should be accomplished (if at all). A repair policy may dictate that an item should be designed such that, in the event of failure, it should be *nonrepairable, partially repairable*, or *fully repairable*. Stemming from the operational requirements described in Section 4 (refer to the five system illustrations), an initial "repair policy" for the system being developed should be established with the objective of providing some early guidelines for the design of the different components that make up the system. Referring to the example of the repair policy, illustrated in Figure 16, it can be seen that there are numerous quantitative factors, which were initially derived from the definition of system operational requirement, that provide "design-to" guidelines as an input to the overall design process; for example, the system shall be designed such that the MTBM shall be 175 hours or greater, the MDT shall be 2 hours or less, the MLH/OH shall not exceed 0.1, and so on. A repair policy should be initially developed and established during the conceptual design phase, and subsequently updated as the design progresses and the results of the level-of-repair and supportability analyses become available.

3. *Organizational responsibilities:* The accomplishment of maintenance may be the responsibility of the customer, the producer (or supplier), a third party, or a combination thereof. In addition, the responsibilities may vary, not only with different components of the system but also as one progresses in time through the system operational use and sustaining support phase. Decisions pertaining to organizational responsibilities may affect system design from a diagnostic and packaging standpoint, as well as dictate repair policies, product warranty provisions, and the like. Although conditions may change, some initial assumptions are required at this point in time.

4. *Maintenance support elements:* As part of the initial maintenance concept, criteria must be established relating to the various elements of maintenance support. These elements include supply support (spares and repair parts, associated inventories, and provisioning data), test and support equipment, personnel and training, transportation and handling equipment, facilities, data, and computer resources. Such criteria, as an input to design, may cover self-test provisions, built-in versus external test requirements, packaging and standardization factors, personnel quantities and skill levels, transportation and handling factors, constraints, and so on. The maintenance concept provides some initial system design criteria pertaining to the activities illustrated in Figure 14, and the final determination of specific logistic and maintenance support requirements will occur through the completion of a supportability analysis as design progresses.

5. *Effectiveness requirements:* These constitute the effectiveness factors associated with the support capability. In the supply support area, they may include a spare-part demand rate, the probability that a spare part will be available when required, the probability of mission success given a designated quantity of spares in the inventory, and the economic order quantity as related to inventory procurement. For test equipment, the length of the queue while waiting for test, the test station process time, and the test equipment reliability are key factors. In transportation, transportation rates,



* Transportation time—1 week.
+Transportation time—2 weeks.

Figure 16 System maintenance and repair policy.