SYSTEMS ENGINEERING AND ANALYSIS

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PART I

INTRODUCTION TO SYSTEMS

1 SYSTEM DEFINITIONS AND CONCEPTS

Systems are as pervasive as the universe in which we live. At one extreme, they are as grand as the universe itself. At the other, they are as infinitesimal as the atom. Systems appeared first in natural forms, but with the appearance of human beings, a variety of human-made systems have come into existence. Only recently have we come to understand the underlying structure and characteristics of natural and human-made systems in a scientific way.

In this first chapter, some system definitions and system science concepts are presented that provide a basis for the study of systems engineering and analysis. This includes definitions of system characteristics, a classification of systems into various types, a discussion of the current state of system science, and a discussion of the transition to the systems age now under way. Finally, this chapter presents technology and the nature of engineering in the systems age.

1.1 SYSTEM DEFINITIONS AND ELEMENTS

A *system* is an assemblage or combination of elements or parts forming a complex or unitary whole, such as a river system or a transportation system; any assemblage or set of correlated members, such as a system of currency; an ordered and comprehensive assemblage of facts, principles, or doctrines in a particular field of knowledge or thought, such as a system of philosophy; a coordinated body of methods or a complex scheme or plan of procedure, such as a system of organization and management; any regular or special method or plan of procedure, such as a system of marking, numbering, or measuring.[1] Not every set of items, facts, methods, or procedures is a system. A

[1] This definition was adapted from *The Random House Dictionary of the English Language*. 2nd ed. (New York: Random House, Inc., 1994).

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 unity, functional relationship, and useful purpose.

The Elements of a System

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

1. *Components* are the operating parts of a system consisting of input, process, and output. Each system component may assume a variety of values to describe a system state as set by some control action and one or more restrictions.
2. *Attributes* are the properties or discernible manifestations of the components of a system. These attributes characterize the system.
3. *Relationships* are the links between components and attributes.

A system is a set of interrelated components working together toward some common objective or purpose. The set of components has the following properties:

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

The properties listed earlier ensure that the set of components constituting a system always has some characteristic or behavior pattern that cannot be exhibited by any of its subsets. 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.

The objective or purpose of a system must be explicitly defined and understood so that system components may be selected to provide the desired output for each given set of inputs. Once defined, the objective or purpose makes it possible to establish a measure of effectiveness indicating how well the system performs. Establishing the purpose of a human-made system and defining its measure of effectiveness is often a challenging task.

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.

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.

Structural, operating, and flow components have various attributes that affect their influence on the system. The attributes of an electrical system may be described in terms of inductance, capacitance, impedance, and so on. The system may change its condition over time in only certain ways, as in the *on* or *off* state of an electrical switching system. A system, condition, situation, or state is set forth to describe a set of components, attributes, and relationships.

A systems view is only one way of understanding complexity. Another is that of a *relational view*. Three major differences exist between a relation and a system. First, a relation exists between two and only two components, whereas a system is described by the interaction between many components. Second, a relation is formed out of the imminent qualities of the components, whereas a system is created by the particular position and spatial distribution of its components. The components of a relation are separated spatially, whereas a system is made up of the interacting distribution of its components. Third, the connection between the components of a relation is direct, whereas the connection in a system depends on a common reference to the entire set of components making up the system.

Relationships that are functionally necessary to each other may be characterized as *first order*. An example is symbiosis, the necessary relationship of dissimilar organisms, such as an animal and a parasite. *Second-order* relationships, called *synergistic*, are those that are complementary and add to system performance. *Redundance* in a system exists when duplicate components are present for the purpose of assuring continuation of the system function.

Systems and Subsystems

The definition of a system is not complete without consideration for its position in the hierarchy of systems. Every system is made up of *components*, and any component can be broken down into smaller components. If two hierarchial levels are involved in a given system, the lower is conveniently called a *subsystem*. For example, in an air transportation system, the aircraft, terminals, ground support equipment, and controls are subsystems. Equipment items, people, and information are components. Clearly, the designations of system, subsystem, and component are relative because the system at one level in the hierarchy is the 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 *input* to the system. In reverse, material, energy, and/or information that passes from the system to the environment is called *output*.

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 an objective. Each system has an objective, providing a purpose 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 components of this "fire control system" are the building, the fire engines, the firefighters and small equipment, the communication equipment, and the maintenance facilities. These components are the major subsystems of the fire department. Each of these subsystems has several contributing subsystems or components. At each level in the hierarchy, the description must include all components, all attributes of these components, and all relationships.

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. 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 wholistic sense is receiving continued attention. By bounding the total system for study purposes, the systems engineer or systems analyst will be more likely to achieve a satisfactory result. Focusing on systems, subsystems, and components in a hierarchy forces consideration of all 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.

1.2 A CLASSIFICATION OF SYSTEMS[2]

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

Natural and Human-Made Systems

The origin of systems gives a 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, or relationships.

[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.

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.

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 an 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.

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 coming upon the scene 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 a potent and pervasive technology.

A good 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 water-borne snail parasite) has produced an epidemic of intestinal disease along the Nile. These side effects were not adequately considered by those responsible for the project. A systems view encompassing both natural and human-made elements might have led to a better solution to the problem of flooding.

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 in guiding the state 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 equally in both physical and conceptual systems.

Process occurs at many different levels within systems. The subordinate process essential to the operation of a total system is provided by the subsystem. The subsystem may, in turn, be dependent 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.

Static and Dynamic Systems

Another system dichotomy is the distinction of static and dynamic systems. A *static system* is one having structure without activity, as exemplified by a bridge. A *dynamic system* combines structural components with activity. An example is a school, combining a building, students, teachers, books, and curricula.

For centuries people have viewed the universe of phenomena as unchanging. A mental habit of dealing with certainties and constants developed. The substitution of a process-oriented description for the static description of the world is one of the major characteristics separating modern science from earlier thinking.

A dynamic conception of the world 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 motion in the usual sense. A highway system is static, yet it contains the system elements of components, attributes, and relationships.

It is recognized that a system is static only in a limited frame of reference. A bridge is constructed over a period, and this is a dynamic process. It is then maintained and perhaps altered to serve its intended purpose more fully. Even a crystal passes through several forms during its period of growth.

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 that will check in for a flight, or the exact time each will arrive at the airport. However, these factors can be described in terms of probability distributions, and system operation is said to be *probabilistic*.

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 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. The reaction 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.

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. People-made systems have characteristics of open and closed systems. 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 an aircraft 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—the creation of more orderly states from less orderly states.

1.3 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.

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 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

[3] N. Wiener, *Cybernetics* (New York: John Wiley & Sons, Inc., 1948).

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 the heating system off.

Biological organisms are endowed with the capacity for self-regulation, called *homeostasis*. The biological organism and the physical world are both very complex. Instructive 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 given mathematical treatment.

A practical application of cybernetics has been the tremendous development of automatic equipment and processes, most controlled by microcomputers. 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 a new science of purposeful and optimal control applicable to complex processes in nature, society, and business organizations.

General Systems Theory

An even broader unifying concept than cybernetics took shape during the late 1940s. It was the idea that basic principles common to all systems could be found that went 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 was being sought. Ludwig von Bertalanffy used the phrase *general systems theory* around 1950 to describe this endeavor.[4]

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 the 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. The difficulties are greatest among the various disciplines, the physical and life sciences, the social and behavioral sciences, and the humanities.

[4] L. von Bertalanffy, "General System Theory: A New Approach to Unity of Science," *Human Biology*, December 1951. A related contribution was by K. Boulding, "General Systems Theory: The Skeleton of Science," *Management Science*, April 1956.

One approach to an orderly framework is the structuring of a hierarchy of levels of complexity for basic units of behavior in the various fields of inquiry. A *hierarchy of levels* can lead to a systematic approach to systems that has broad application. Such a hierarchy was formulated by Boulding approximately as follows[5]:

1. The level of static structure or *frameworks*, encompassing the geography and anatomy of the universe.
2. The level of the simple dynamic system of *clockworks*, encompassing a significant segment of chemistry, physics, and engineering science.
3. The level of the *thermostat* or cybernetic system, encompassing the transmission and interpretation of information.
4. The level of the *cell*, the self-maintaining structure or open system where life begins to be evident.
5. The level of the *plant*, with genetic-societal structure making up the world of botany.
6. The level of the *animal*, encompassing mobility, teleological behavior, and self-awareness.
7. The level of the *human*, encompassing self-consciousness and the ability to produce, absorb, and interpret symbols.
8. The level of *social organization*, where the content and meaning of messages, value systems, transcription of images into historical record, art, music, and poetry, and complex human emotion are of concern.
9. The level of the *unknowables*, where structure and relationship may be postulated but where answers are not yet available.

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-loop 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, its greatest benefit being that of communication across disciplines.

Systemology

The science of systems or their formation is called *systemology*. As system science is pushed forward by the formation of interdisciplines, humankind should benefit from a more appropriate application of the discipline. The problems and problem complexes faced by human beings are not organized along disciplinary lines. It is only through a new organization of scientific and professional effort based on the common attributes and characteristics of problems that beneficial progress will be made.

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

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 the discipline, and this is still so. However, recent developments have added to the respectability of most areas. Much credit for this can be given to the new respectability of interdisciplinary inquiry.

During the 1940s, scientists of established reputation accepted the challenge of attempting to understand a host of common processes in military operations. Their team effort was called *operations research*, and the focus of their attention was the science of 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 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 in the past 60 years has brought about an evolu tionary synthesis of knowledge. This has occurred not only within science, but 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. 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.

1.4 TRANSITION TO THE SYSTEMS AGE[6]

There is considerable evidence to suggest 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 people's position relative to these systems.

The Machine Age

Two ideas have been dominant in the way people seek to understand the world around them. 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 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.

[6] This section was adapted from R. L. Ackoff, *Redesigning the Future* (New York: John Wiley & Sons, Inc., 1974).

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 the sum of the solutions to its independent parts. In the *Machine Age*, understanding the world was taking 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 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.

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 product 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, are 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 the *systems aproach*. This way of thinking 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 can display choice of either means or ends, or both. It is interested in purely mechanical systems only insofar as they can be used as instruments of purposeful systems. Furthermore, the Systems Age is largely concerned with purposeful systems, some of whose parts are purposeful; 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, whereas competition continues to increase worldwide.

1.5 TECHNOLOGY AND TECHNICAL SYSTEMS

Technology is defined broadly as the branch of knowledge that deals with industrial arts, applied science, and engineering, or the sum of the ways in which social groups provide themselves with the material objects of their civilization.[7] A social group possessing inherent abilities and the knowledge to maintain its stock of technology is said to have a civilization. Modern civilizations possess pervasive and potent technical systems that provide needed products, systems, structures, and services.

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.

[7] This definition was adapted from *The Random House Dictionary of the English Language*, 2nd ed. (New York: Random House, Inc., 1994).

The entire history of humankind is closely related to the progress of technology. But, technological progress is often stressful on people and organizations alike. This need not be. The challenge should be to find ways for people 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 bigger and better systems produces an ever-changing set of requirements. The identification of the "true" need and the elicitation of "real" requirements is, in itself, a technological challenge. There has been a tendency to "design now and fix later," with a negative impact on the worth of many systems to intended users and society.

To transition from the past, to present and future technological states, is not a one-step process. Continuing cascades of technical advances arc available to society as time unfolds. Societal response is often to make one transition and then to adopt a static pattern of behavior. A better response would be to seek new but well-thought-out possibilities for advancement continuously.

Improvement in technological literacy should increase the population of individuals capable of participating in this desirable activity. One key to imparting this literacy are the communication technologies now expanding as never before. Thus, technology in this sphere may act favorably to aid the understanding and subsequent evaluation by society of technologies in other spheres.

Technical Systems[8]

The phrase *technical system* may be used to represent all types of human-made artifacts, including technical products and processes. Therefore, the technical system is the subject of the collection of activities that are preformed by engineers within the processes of engineering design, including generating, retrieving, processing, and transmitting information about products. It is also the subject of various tasks in the production process, including work preparation and planning, and in many economic considerations, both internal and social.

In museums we see thousands of technical objects and recognize them 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 a term that conceptually describes classes of technical objects.

Technical objects can be referred to as simply objects, products, things, machines, implements, 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 ships that represent the technical means by which humans achieve their ends. But, to be complete, this definition must recognize the hierarchical nature of sys-

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

tems 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 or technical (human-made). 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: e.g., civil engineering, electrical engineering, and mechanical engineering. However, from a practical and organizational viewpoint, this does not permit a precise definition of a machine system or electrical system because no firm boundary can be drawn by describing these systems as products of mechanical or electrical engineering. Modern developments of technical systems have generally blurred the boundaries. Electrical 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.

1.6 ENGINEERING IN THE SYSTEMS AGE

Engineering activities of analysis and design for human-made or technical systems are not an end 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 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. 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 a knowledge of the context of the system being brought into being.

System Complexity and Scope

The world is increasing in complexity because of human intervention. Through the advent of advanced technologies, transportation times have been 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 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 is needed.

Although relatively small products, such as a wireless telephone, an electrical household appliance, or even an automobile may employ a limited amount 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 disciplines. An example is that of a ground mass-transit system.

Civil engineers are required for the layout and/or design of railroad tracks, tunnels, bridges, cables, and facilities. Electrical engineers are involved in the design of automatic train control provisions, 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 support in 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 aspects of passenger vehicles and vehicle 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 and to promote the technical aspects of the system (i.e., to keep the politicians and local citizens informed). General systems engineers are required to ensure that all aspects of the system are properly integrated and function as a single entity.

Although the preceding example is not all inclusive, it is evident that many different engineering disciplines are directly involved. In fact, there are some large projects, such as the development of a new airplane, where the number of engineers assigned 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 be conversant with such interface areas as purchasing, accounting, personnel, and legal.

Another major factor associated with large projects is that much system development, production, evaluation, and support is 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.

Technological Growth and Change

Technological growth and change is occurring continuously and is stimulated by an attempt to respond to some unmet current need and/or by attempting to perform ongoing activities in a more effective and efficient manner. In addition, changes are being stimulated by social factors, political objectives, and ecological constraints.

Generally, people are not satisfied with the impact of the human-made or technical systems on the natural world and on ourselves. 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 considerations.

Some examples of these considerations may be cited. For instance, 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. All have stimulated beneficial technological innovation.

The response in fulfilling technology requirements is dependent on the scientists and engineers available in the needed fields of expertise and whether they are up to date and creative in their respective specialty areas. In some fields, such as electronics and the medical profession (from the standpoint of engineering innovations), technological growth is rapid. Engineers in these fields have an extremely difficult time maintaining their skills.

The continuing trend in technological advances has created an increasing demand for engineers in many fields. There will always be a demand for engineers who can synthesize and adapt. Certain technical specialties will become obsolete with time. The astute engineer should be able to detect trends and plan accordingly for satisfactory transition by acquiring knowledge to broaden his or her horizons. To help in this process is one aim of this book.

QUESTIONS AND PROBLEMS

1. Identify and describe an example system for each system category named in the dictionary definition of Section 1.1.
2. Pick a system that alters material and identify its structural components, operating components, and flow components.
3. Pick a natural system and describe it in terms of components, attributes, and relationships; repeat for a human-made system.
4. Select a complex system and discuss it in terms of the hierarchy of systems.
5. Identify and contrast a physical and a conceptual system.
6. Identify and contrast a static and a dynamic system.
7. Identify and contrast a closed and an open system.
8. Describe cybernetics through an example of your choice.
9. Give a system example at each level in Boulding's hierarchy.
10. Give an example of a problem requiring an interdisciplinary appoach and identify the needed disciplines.
11. Identify the attributes of the Machine Age and the Systems Age.
12. What are the special engineering requirements in the Systems Age?
13. What benefits could result from increasing societies' technological literacy?
14. What is the difficulty encountered in attempting to classify technical systems?
15. Why is technological and economic feasibility no longer the sole determinant of success in engineering undertakings?

2 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 world that came into being by natural processes. The human-made world is made up of all products, systems, and structures made by people for the use of people. But we are not satisfied with the impact of the human-made world on the natural world and ourselves. Never before have there been greater improvement possibilities from the proper application of the concepts and principles of systems engineering.

Systems engineering and analysis, when coupled with new and emerging technologies, reveals unexpected opportunities for bringing new and improved systems and products into being that will be more competitive in the world economy. These technologies are acting to expand physically realizable design options and to enhance capabilities for developing more cost-effective entities for human use. This chapter introduces a technologically based process encompassing an extension of engineering through all phases of the system life cycle—design and development, production or construction, utilization and support, and phaseout and disposal.

2.1 ENGINEERING FOR PRODUCT COMPETITIVENESS

Product competitiveness is desired by both commercial and public-sector producers worldwide. It is the product, or consumer good, that must meet customer expectations. Accordingly, the systems engineering challenge is to bring products and systems into being that meet these expectations cost-effectively.

Because of intensifying international competition, producers are seeking ways to gain a sustainable competitive advantage in the marketplace. Acquisitions, mergers, and extensive advertising seem unable to create the intrinsic wealth and good will so essential 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, finance, production, and the like.

Available resources are dwindling. The industrial base is expanding, and international competition is increasing at a rapid pace. Many organizations are downsizing, looking to improve their operations, and seeking international partners. Competition has also 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. Also, needed new systems are being deferred in favor of extending the life of existing systems.

Engineering has always been concerned with the economical use of limited resources for the benefit of people.[1] The purpose of engineering activities of design and analysis is to determine how physical factors may be altered to create the most utility for the least cost, in terms of product cost, product service cost, and social cost. Viewed in this context, engineering must be practiced in an expanded way, with engineering of the system placed ahead of concern for components thereof. Specifically, emphasis must be placed on the following:

1. Improving methods for defining product and system requirements as they relate to true customer needs. This should be done early in the design phase, along with a determination of performance, effectiveness, and essential system characteristics.
2. Addressing the total system with all of its elements from a life-cycle perspective, and from the product or prime equipment to its elements of support. This means defining the system in functional terms before identifying hardware, software, people, facilities, information, or combinations thereof.
3. Considering the overall system hierarchy and interactions between various levels in the hierarchy. This includes intra-relationships among system elements and interrelationships between higher and lower levels within the system.
4. Organizing and integrating the necessary engineering and related disciplines into the main systems engineering effort in a timely concurrent manner.
5. Establishing a disciplined approach with appropriate review, evaluation, and feedback provisions to insure orderly and efficient progress from the initial identification of need through phaseout and disposal.

Products, systems, and structures are designed and developed 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 giving more attention to what they are to do, before addressing what they are composed of. Simply stated, form should follow function.

[1] According to the definition of engineering adapted 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."

All other factors being equal, people will meet their needs by purchasing goods 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 regarding the end item, engineering must become more closely associated with economics and economic feasibility. This is best accomplished through a life-cycle approach to engineering.

2.2 SYSTEM LIFE-CYCLE ENGINEERING

In general, classical engineering has focused mainly on product performance as the main objective rather than on development of the overall system of which the product is a part.[2] Experience in recent decades indicates that a properly functioning system that is competitive cannot be achieved through efforts applied largely after it comes into being. Accordingly, it is essential that engineers be sensitive to utilization outcomes during the early stages of system design and development, and that they assume the responsibility for *life-cycle engineering* that has been largely neglected in the past.

The System Life Cycle

Fundamental to the application of systems engineering is an understanding of the system life-cycle process illustrated for the product in Figure 2.1. The life cycle begins with the identification of a need and extends through conceptual and preliminary design, detail design and development, production and/or construction, product use, phaseout, and disposal. The program phases are classified as *acquisition* and *utilization* to recognize producer and customer activities.[3]

A detailed presentation of the elaborate technological activities and interactions that must be integrated over the system life-cycle process is given in Figure 2.2. The

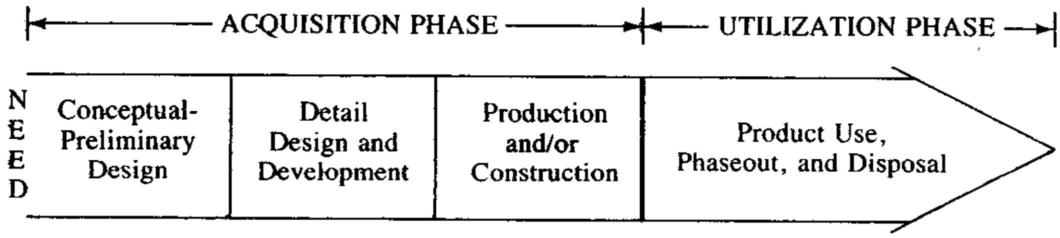


Figure 2.1 The product life cycle.

[2] A *product*, for example, may be a television set, an automobile, or an appliance. The product cannot come into being without a manufacturing capability, a support capability, and so on. Accordingly, in dealing with systems, one must not only consider the product, but its manufacturing process, utilization, maintenance and support, and retirement and disposal.

[3] This classification represents a generic approach. Sometimes the *acquisition* process may involve both the customer (or procurring agency) and the producer (or contractor), whereas utilization may include a combination of contractor and consumer (or ultimate user) activities. In some instances, the customer may not be the ultimate consumer (as is the case in the defense sector) but must represent the consumer's interests in the acquisition process. Additionally, the product phaseout and material disposal may involve contractor support. The situation will vary depending on the type and nature of the system.

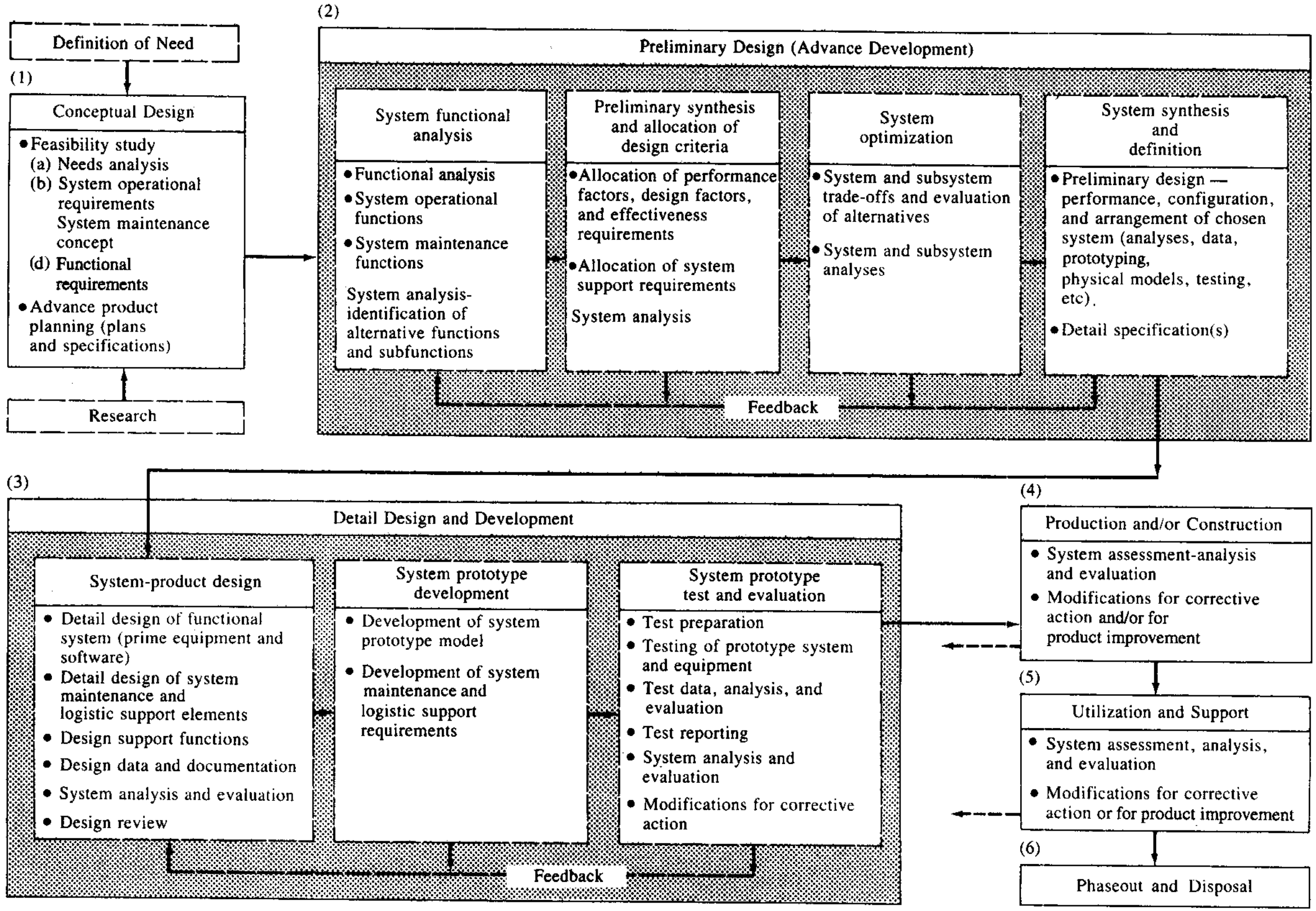


Figure 2.2 The system life-cycle process.

progression is iterative from left to right, and not serial in nature as might be implied. 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, not only in the acquisition of new systems but also in the re-engineering of existing or legacy systems.

Designing for the Life Cycle

Design within the system life-cycle context is different from design in the ordinary sense. Life-cycle focused 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 definitive product and system configuration, but should ensure the design's compatibility with related physical and functional requirements. Further, it should consider operational outcomes expressed as producibility, reliability, maintainability, supportability, serviceability, disposability, and others, as well as performance, effectiveness, and affordability.

Major technical functions performed during the acquisition and utilization phases of the life cycle are summarized in Figure 2.2. When a new customer need is identified, a planning function is initiated followed by conceptual, preliminary, and detail design activities. Producing and/or constructing the system is the function that completes the acquisition phase. System operation and support functions constitute the utilization phase of the life cycle. Phaseout and disposal are important final functions to be considered in design for the life cycle.

System life-cycle engineering goes beyond the product life cycle. It must simultaneously embrace the life cycle of the manufacturing process as well as the life cycle of the product support and service capability. Actually, there are three concurrent life cycles progressing in parallel as is illustrated in Figure 2.3. This 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 bringing a manufacturing capability into being. It requires many production-related activities to become ready for manufacturing.

Also shown in Figure 2.3 is another life cycle of great importance which is often neglected until product and production design is completed. This is the life cycle for the maintenance and logistic support activities needed to service the product during use and to support the manufacturing capability during its duty cycle. Logistic and maintenance requirements planning should begin during product conceptual design in a coordinated manner.

The communication and coordination needed to develop the product, the manufacturing process, and the support capability in a coordinated manner is not easy to

[4] *Concurrent Engineering* is defined as a systematic approach to creating a product design that simultaneously considers all elements of the product life cycle, from conception through disposal, to include consideration of manufacturing processes, transportation processes, maintenance processes, and so on.

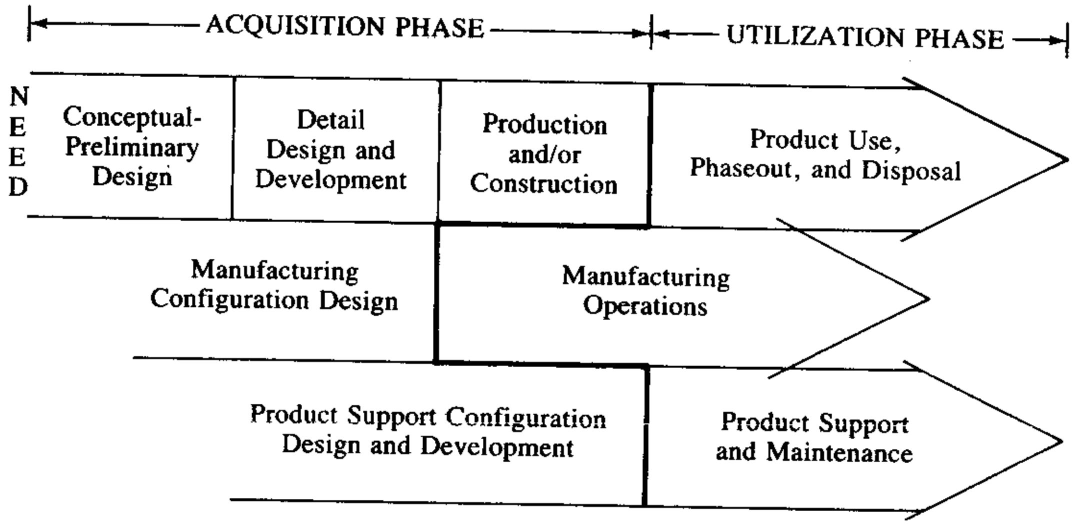


Figure 2.3 Product, manufacturing, and support life cycles.

achieve. Progress in this area is facilitated by new technologies that make more timely acquisition and the use of design information possible. Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technology are only two of these. Others are being developed which can integrate relevant design and development activities over the entire life cycle of the system.

Concern for the entire *life cycle* is strong within the Department of Defense (DOD). 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 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 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 like water heaters and air conditioners. Fuel efficiency is a required design characteristic for automobiles. Some truck manufacturers promise that life-cycle maintenance requirements 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 of the user of the product instead of the producer.

[5]This intervention is guided by DODR 5000.2, "Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS) Acquisition Programs" Washington, D.C.: (Department of Defense, 1996). This is supported by a host of directives, specifications, and standards.

2.3 SYSTEMS ENGINEERING DEFINITIONS

There is no commonly accepted definition of *systems engineering* in the literature. Both the definition and approach seem to be based on the background and experience of the individual or organization.[6] Variety is evident from three published definitions given subsequently.

1. "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 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."[7]
2. "An interdisciplinary approach encompassing the entire technical effort to evolve 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; (b) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making."[8]
3. "An interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability."[9]

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 fit together is frequently overlooked.

[6] An overwiew of systems engineering technology, approach, challenges, and related issues is presented in the Inaugural Issue of *Systems Engineering*. The Journal of the International Council on Systems Engineering (INCOSE), Volume 1, Number 1, July/September, 1994.

[7] DSMC, *Systems Engineering Management Guide*, Defense Systems Management College, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 1990, pp. 12.

[8] EIA/IS 632, "Systems Engineering," Electronic Industries Association, 2001 Pennsylvania Avenue N.W., Washington, D.C., 1994, pp. 43.

[9] IEEE P1220, "Standard for Application and Management of the Systems Engineering Process," Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, N.Y., 1994, pp. 11.

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, phaseout, 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. Many of these are not well integrated with other design activities, causing costly modifications later on.
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.

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 should lead to a change in "culture."

2.4 THE SYSTEMS ENGINEERING PROCESS

Although there is general agreement regarding the principles and objectives of systems engineering, its actual implementation will vary from one program to the next. The process approach and steps used will depend on the backgrounds and experiences of the individuals involved. 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. Also, there are other process models that have attracted various degrees of attention. Each of these topics are presented in this section.

Life-Cycle Process Phases and Steps

Figure 2.4 illustrates the major life-cycle process phases and selected milestones for a typical 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, evaluation, and so on). A newly identified need, as well as an evolving need, reveals a new system requirement. The basic phases of conceptual design and onward through system retirement and phaseout are then applicable, as described in the paragraphs that follow.

Program phases described in Figure 2.4 are not intended to convey specific periods or levels of funding. Individual program requirements will vary from one application to the next. The figure reflects an overall *process* that needs to be followed in system acquisition. 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 2.4 must be properly "tailored" to the particular system being addressed.[10]

Figure 2.4 (Blocks 0.1 to 0.8) shows the basic steps in the system 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). On completion of Block 0.2, the system is defined in *functional* terms (having identified the "whats" from a requirements perspective). These "whats" are translated into an applicable set of "hows" through the iterative activities of functional partitioning, requirements allocation, trade-off studies, synthesis, and evaluation. This is where the initial requirements for the system configuration (or system architecture) are defined.

The functional definition of the system serves as the baseline for the identification of resource requirements (i.e., hardware, software, people, facilities, data, elements of support, or a combination thereof). Depending on the degree of definition required, these steps may often be accomplished concurrently (i.e., functional requirements are described for certain complex elements of the system while, at the same time, the requirements for hardware, software, and the like, are being identified for other elements of the system).

As one proceeds from the top-down in the early phases of system design and development, there is a follow-on "bottom-up" procedure. During the latter phases of preliminary design (and in the detail design and development phase) components are combined, assembled, and integrated into the specified system configuration This, in turn, leads to the iterative process of system evaluation. Inherent within the systems engineering process must be a provision for continuous feedback and corrective action. The system engineering process is continuous, iterative, and must incorporate feedback actions to ensure convergence as is illustrated in Figure 2.5.

[10] B. S. Blanchard, "The System Engineering Process: An Application for the Identification of Resource Requirements," *Systems Engineering*, Journal of the International Council on Systems Engineering (INCOSE), Volume 1, Number 1, July/September 1994.

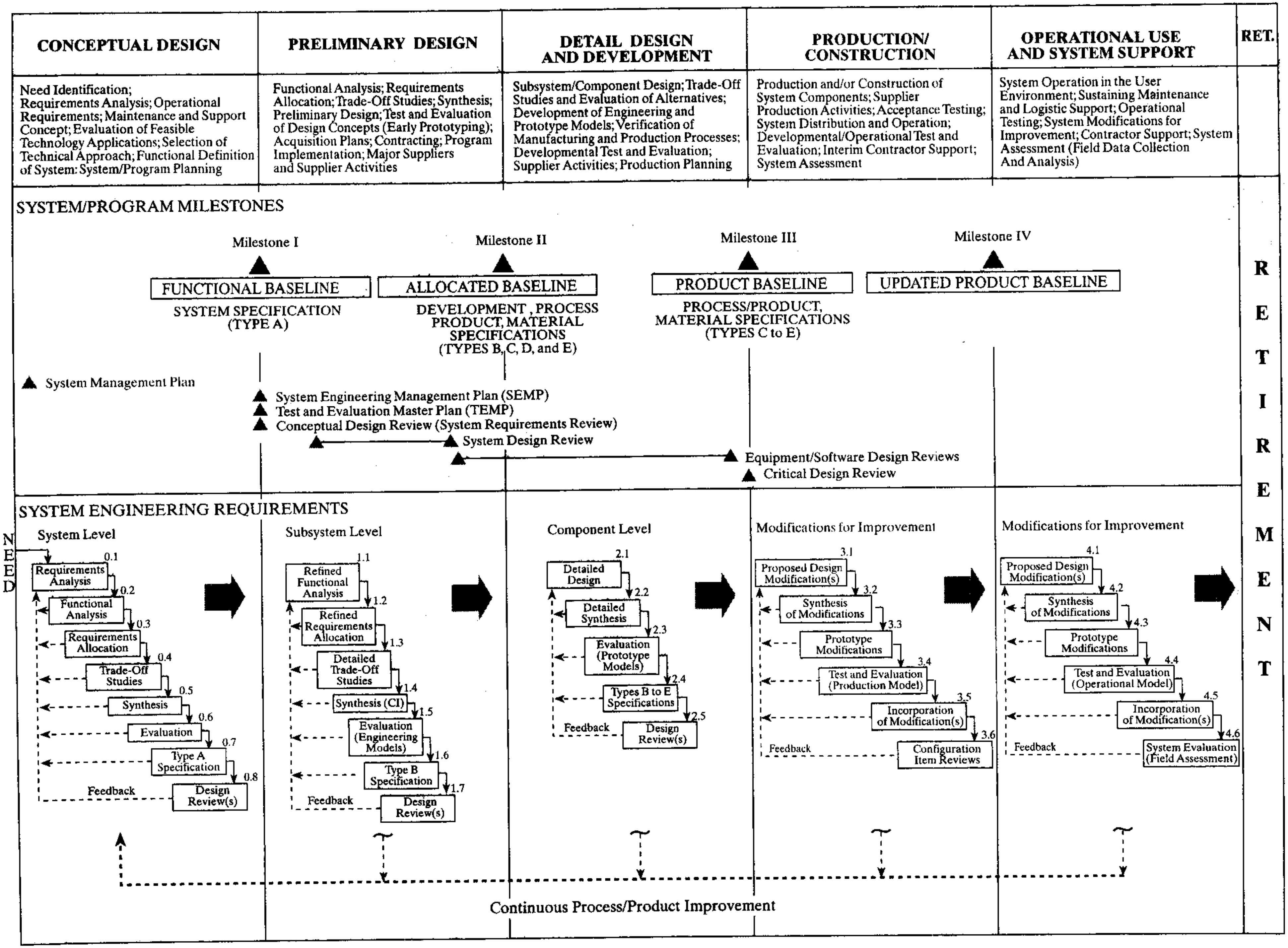


Figure 2.4 The system acquisition process ("baseline").

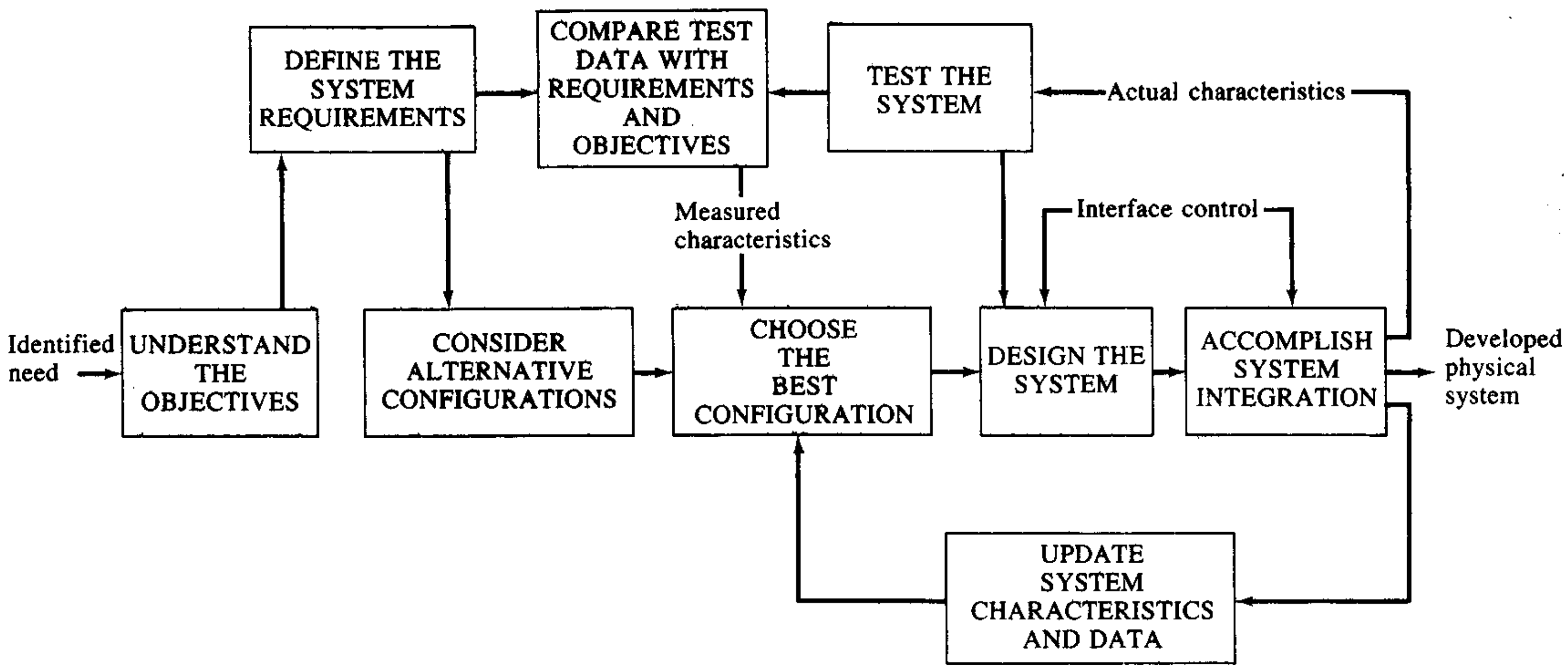


Figure 2.5 Feedback in the systems engineering process.

Top-Down and Bottom-Up Approaches

Traditional engineering design methods are based on a bottom-up approach. Starting with a set of known elements, design engineers create the product or system by synthesizing a combination of system elements. However, it is unlikely that the functional need will be met on the first attempt unless the system is simple. After determining the product's performance and deviation from what is required, the elements and their combination are altered and the performance determined again. This bottom-up process is iterative, with the number of iterations (and design efficiency) determined by the experience and creativity of the designer, as well as by the complexity of the product or system.

A more directed methodology is evoked by the systems engineering process, which is based on a top-down approach to design. Starting with requirements about the external behavior of any part of the system (expressed in terms of the function provided by that part), that behavior is analyzed to identify its functional characteristics. These functional behaviors are then described in more detail and made specific through refinement. Finally, the appropriateness of this choice of functional components is verified by synthesizing the original system part.

There are two main characteristics of the top-down process. First, the process is applicable to any part of the system. Starting with the system as a whole, repeated application of this process will result in partitioning of the system into smaller and smaller elements. Second, the process is self-consistent. External properties of the whole system, as described by the inputs and outputs and relations between parts, must be reproduced by the external properties of the set of interacting elements.

The beginning of the top-down approach recognizes that general functions are involved in transforming inputs into outputs. A designer must abstract from the particular case to the underlying generic case, and represent the generic case by several interacting functional elements. The use of functional elements is the essential difference in systems engineering methodology compared with systems integration. A particular functional element is applicable to a whole class of systems. Consequently, only a few such elements are needed to represent many real systems. Functional elements allow one to engage in system design before physical manifestations have been defined. This contrasts with designing a system by using the bottom-up methodology, where one starts out with a defined set of real elements (components) and synthesizes a system out of members from the set.

Two main differences occur in the bottom-up and top-down approaches. In the case of bottom-up design, physical realizability in terms of known elements is assured, whereas the top-down design process ends with the system elements as functional entities. Their physical realizability is not guaranteed. In the top-down approach, the requirements are always satisfied through every step of the design process because it is an inherent part of the methodology, whereas in the bottom-up approach the methodology provides no assurance that this will occur.

Systems engineering is not likely to replace bottom-up design completely. Every end product incorporates physical objects working together to meet the need. At some point in the design process there must be a transition from the functional (or abstract) to the physical. Accordingly, most projects will employ both methodologies: first systems engineering to reduce the complexity by partitioning the system into its elements and then bottom-up design to realize the elements for that system.

Other Systems Engineering Process Models

The systems engineering process, and the steps illustrated in Figure 2.4, is developed and described in detail in Part II of this text (Chapter 3 to 6). Again, the objective is to describe a *process* (as a frame of reference) that must be "tailored" to be specific program need. The illustration presented in Figure 2.4 is not intended to represent any particular model, such as the "waterfall" model, the "spiral" model, the "Vee" model, or equivalent. These are other well-known process models are illustrated and briefly described in Figure 2.6, with references to the literature found in Appendix F.

2.5 SYSTEM DESIGN EVALUATION

The systems engineering process is suggested as the best approach for bringing products, systems, and structures into being that will be cost-effective and competitive. An essential technical activity within the process is that of system design evaluation. But it should not be pursued in isolation. System design evaluation should be inherent within the systems engineering process and invoked regularly as the system design evolves. It is the assurance of continuous design improvement.[11]

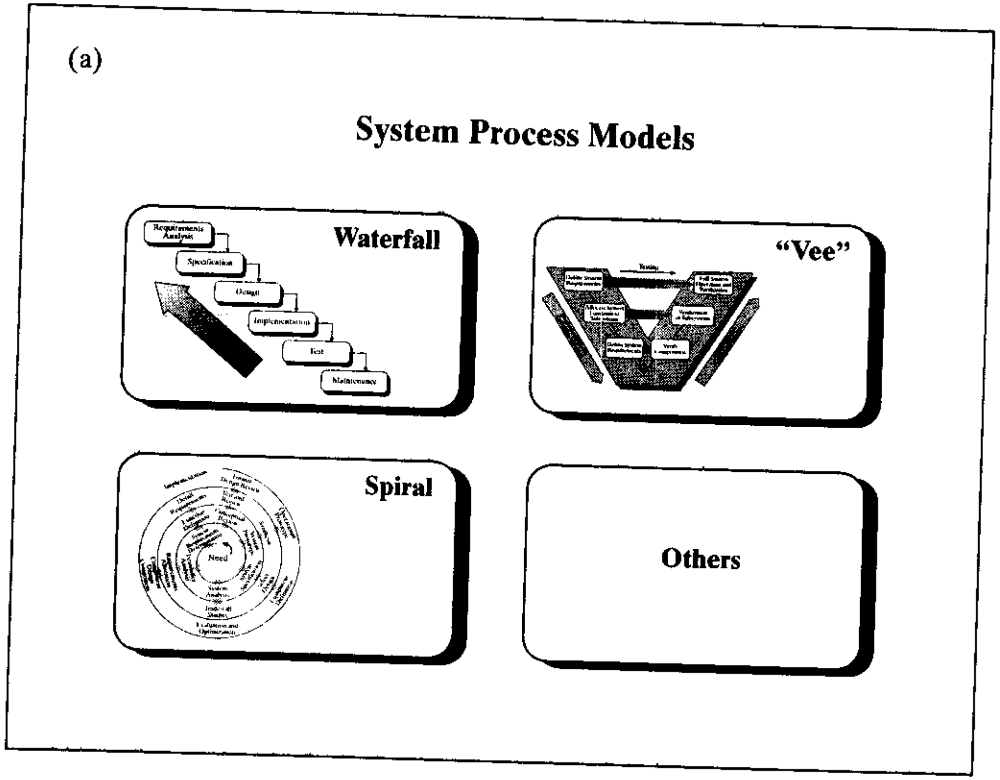
To design is to synthesize (i e., to put known elements together into a new combination). Thus, a design alternative is a projection of what could be. Evaluation is a prediction of how good the design alternative might be if it is chosen for implementation. System design evaluation is preceded by systems analysis, which, in turn, is preceded by synthesis. These relationships are shown conceptually in Figure 2.7.

Development of Design Criteria[12]

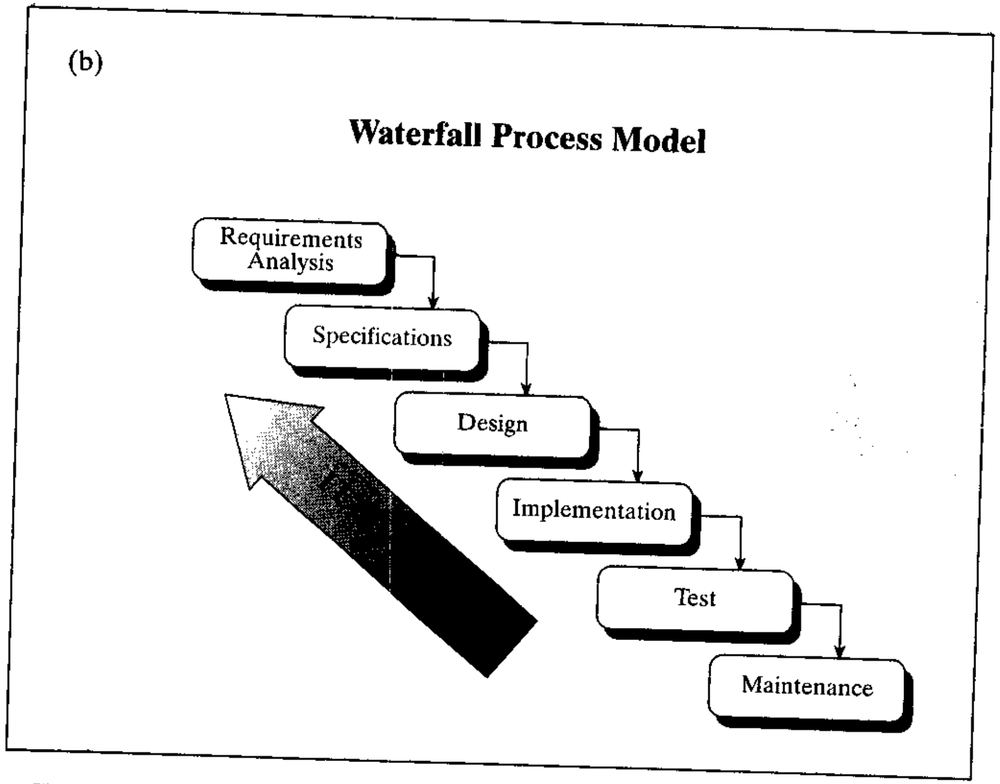
An initial step in a design evaluation effort is to establish the *baseline* against which a given design configuration is to be evaluated. This baseline is described through the iterative process of requirements analysis (i.e., the identification of need, the conduct of feasibility analysis, definition of system operational requirements and the maintenance concept). The functions that the system must perform to satisfy a specific consumer need should be described along with the expectations in terms of time, frequency, effectiveness, costs, and other such factors. These functional requirements,

[11] W. J. Fabrycky, "Modeling and Indirect Experimentation in System Design Evaluation," *Systems Engineering*, Journal of the International Council on Systems Engineering (INCOSE), Volume 1, Number 1, July/September 1994.

[12] Design *criteria* constitute a set of "design-to" requirements, which can be expressed in both qualitative and quantitative terms. These requirements represent the bounds within which the designer must "operate" when engaged in the iterative process of synthesis, analysis, and evaluation. Design criteria may be established for each level in the system hierarchical structure.



- 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. Refer to Appendix F.

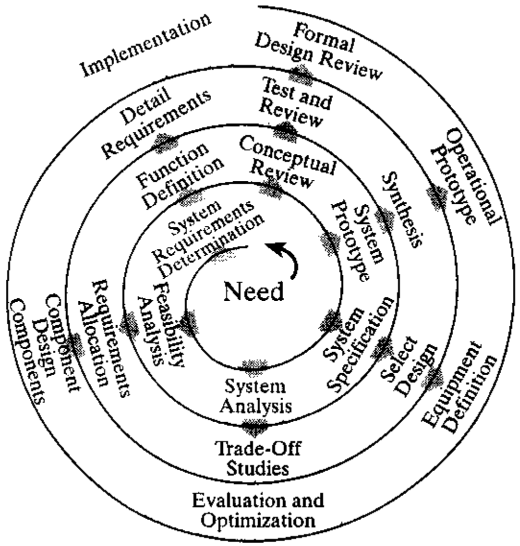


- The waterfall model, introduced by Royce in 1970, initially was used for software development. This model usually consists of five to seven series of steps or phases for systems engineering or software development. Boehm expanded this into an eight-step series of activities in 1981.
- A similar model 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 because when deficiencies are found, phases must be repeated until the product is correct.

Figure 2.6 System process models (examples—sheet 1).

(c)

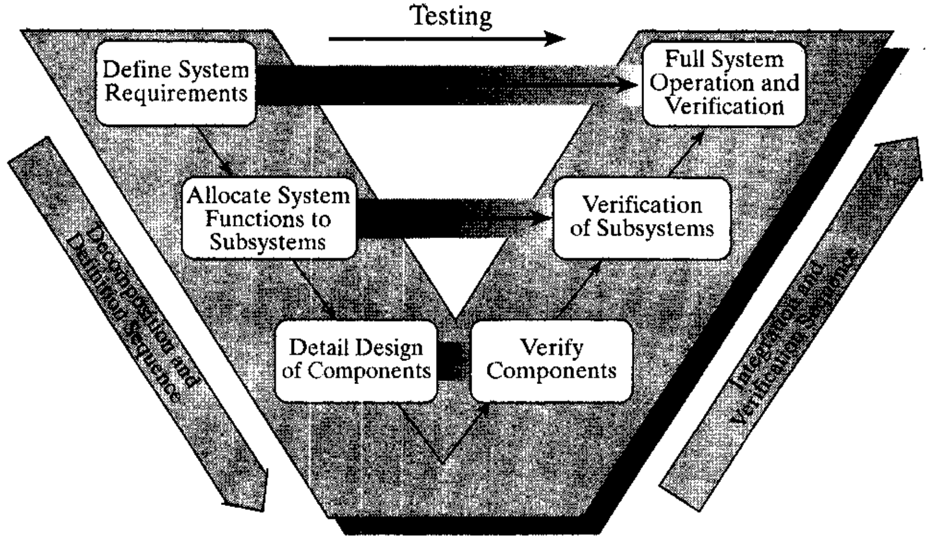
Spiral Process Model



- 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 adaption 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 that 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 systems 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 up and 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 all specifications.

Figure 2.6 System process models (examples—sheet 2).

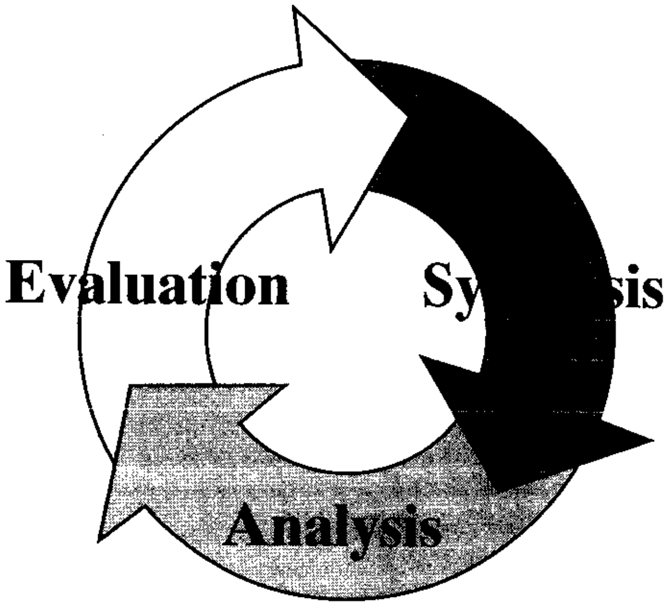


Figure 2.7 System design, analysis, and evaluation.

starting at the *system level*, will ultimately lead to determining the characteristics that should be incorporated within the design of the system and its elements.

Referring to Figure 2.8, the requirements for the system as an entity are established by describing the functions that must be performed. Both operational functions (i.e., those required to accomplish a specified mission scenario, or series of missions) and maintenance and support functions (i.e., those required to ensure that the system is operational when required) must be described at the top level. As part of this process, it is necessary to establish some system "metrics" related to performance, effectiveness, cost, and other such quantitative factors as required to meet customer expectations. For instance, what functions must the system perform, where are these to be accomplished, and 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 in placing different levels of emphasis on the selection of design criteria. The result is the identification and prioritization of *technical performance measures* (TPMs) for the system overall. The output from the requirements analysis process will establish an initial baseline for system evaluation (refer to Figure 2.4, Block 0.1).

With the applicable TPMs identified at the system level, the next step is to determine the specific characteristics that must be incorporated and be made inherent within the design itself. *Design-dependent parameters* (DDPs) are identified, analysis and trade-off studies are conducted by considering various possible design alternatives, design synthesis is performed, and the iterative process of design evaluation takes place. This process is accomplished at the system level, then the subsystem level, and on down to the level necessary to ensure that the ultimate system configuration will fully meet the expectations of the consumer. This process of design synthesis, analysis, and evaluation (as conveyed in Figure 2.7) is inherent within the overall systems engineering process (illustrated in Figure 2.4).

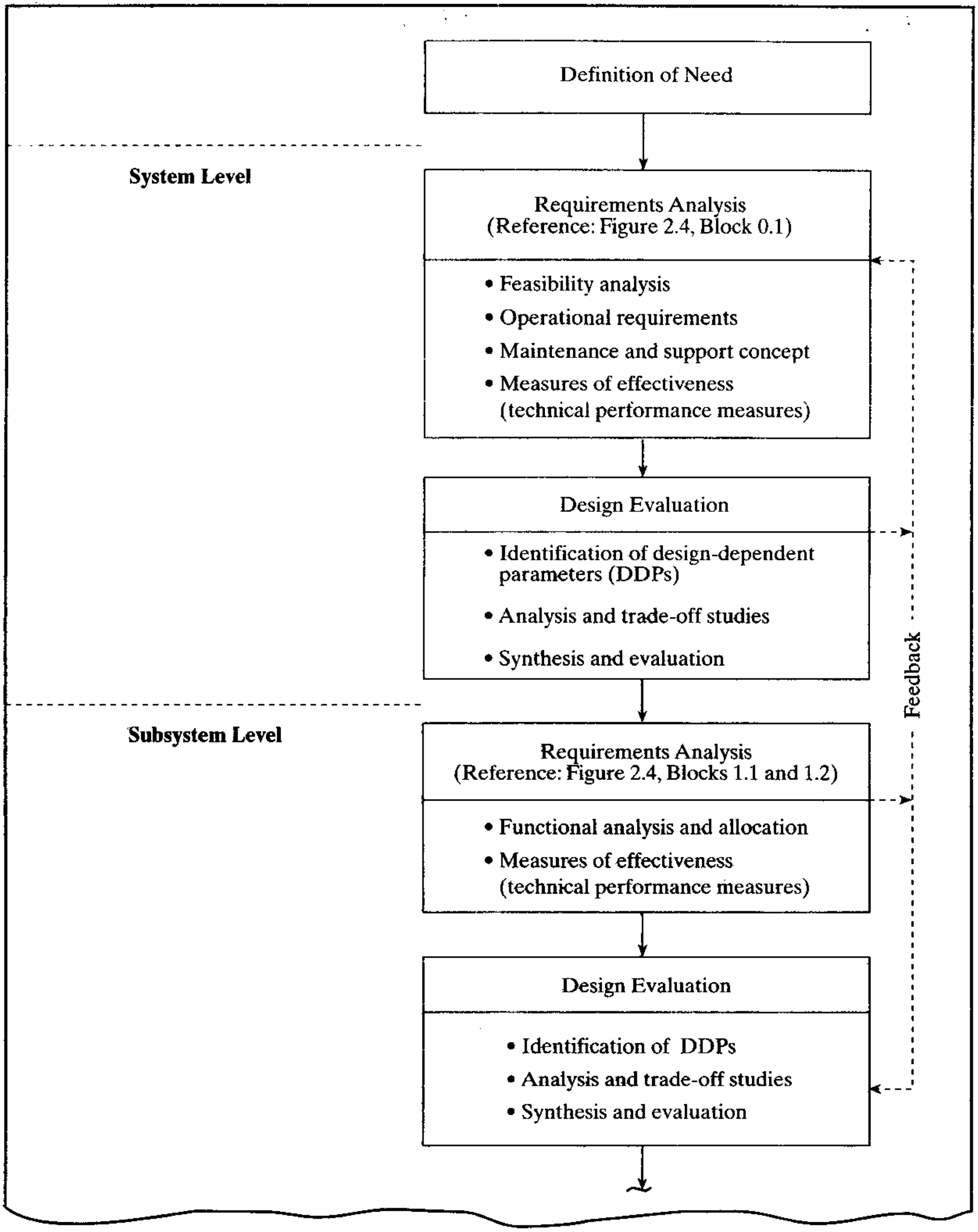


Figure 2.8 Decomposition of design criteria.

Design Evaluation and Multiple Criteria

In Figure 2.8, the prioritized TPMs at the top level reflect the overall performance characteristics of the system as it accomplishes its mission objectives in response to the needs of the customer. 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 some level of importance, as determined by the customer and the criticality of the functions to be performed. For instance, 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 will allow for 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.[13]

Given the requirements at the top level, it may be appropriate to develop a "design-objectives" tree similar to that presented in Figure 2.9. 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 inherent within the design (i.e., the identification of *design-dependent parameters* (DDPs). For instance, a first-order consideration may be *system value*, which, in turn, may be broken down 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 accessibility, diagnostic aids, packaging, mounting, and interchangeability should be stressed in the design. Thus, the *criteria* for design and the associated DDPs may be established early during conceptual design and then carried through the entire design cycle. The DDP's establish the extent and scope of the design space within which *trade-off* decisions may be made. During the process of making trade-off decisions, requirements must be related to the appropriate hierarchical level in the system structure (i.e., system, subsystem, and configuration item) as in Figure 2.8.

Generating and Evaluating Design Alternatives

As system development evolves, the design evaluation activity is iterative and continues through the steps illustrated in Figure 2.4 (i.e., from system-level design, to subsystem design, and down to the component level). For the purposes of illustration, the morphology (or "structure") shown in Figure 2.10 is presented as a frame of reference. Inherent within this structure are the elements of synthesis, analysis, and evaluation.

Referring to the figure, the top block (Block 0) reflects the set of requirements, or bounds, within which different design alternatives are synthesized. Referring to Figure 2.8, the results of the needs analysis, feasibility analysis, operational requirements, maintenance and support concept, and the applicable technical performance measures

[13] Establishing the appropriate levels of importance and the prioritization of TPMs is critical as it may be necessary to make compromises and "trade off" certain features during the design evaluation process (i.e., eliminate certain desired features in favor of others with a greater degree of importance).

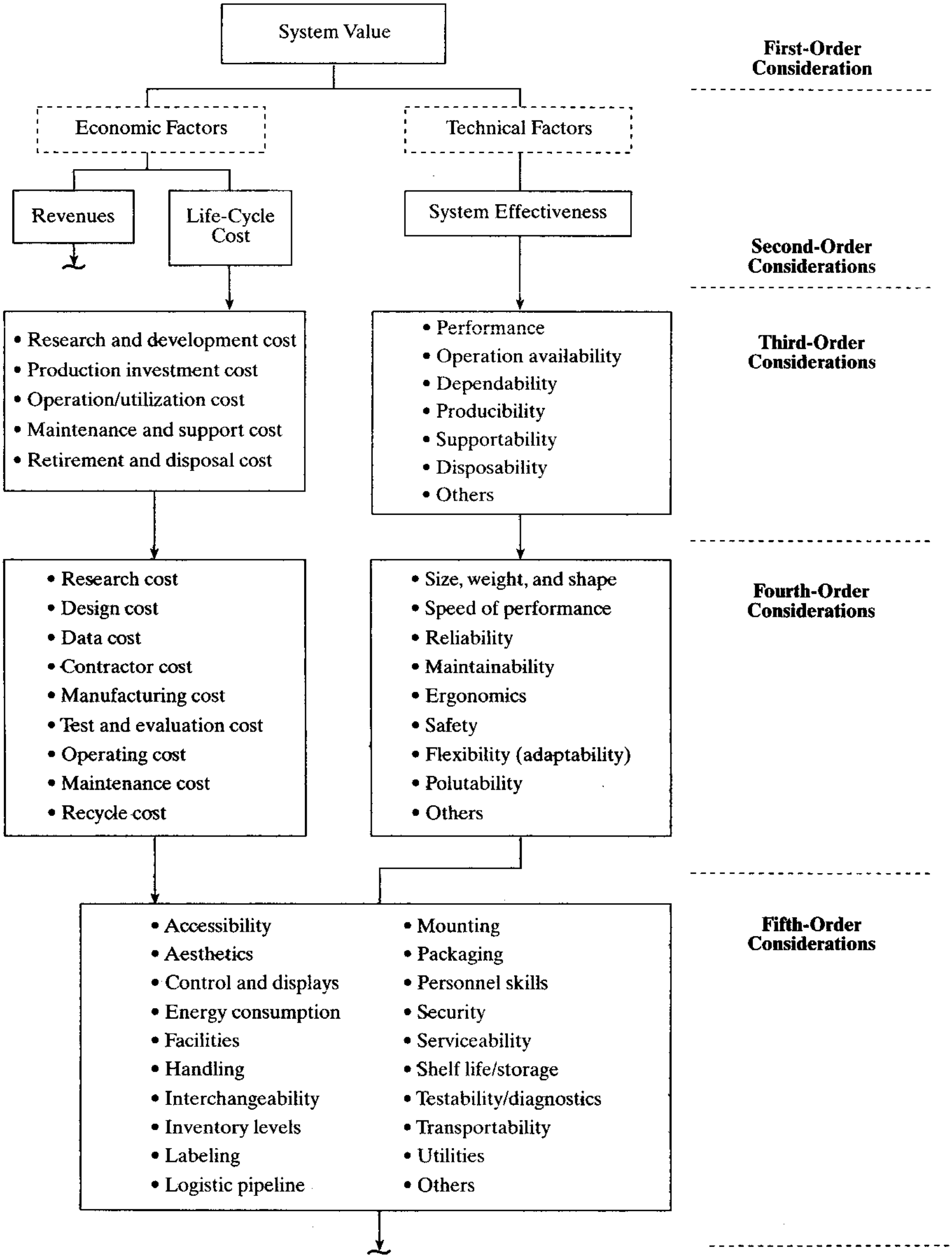


Figure 2.9 Design consideration hierarchy.

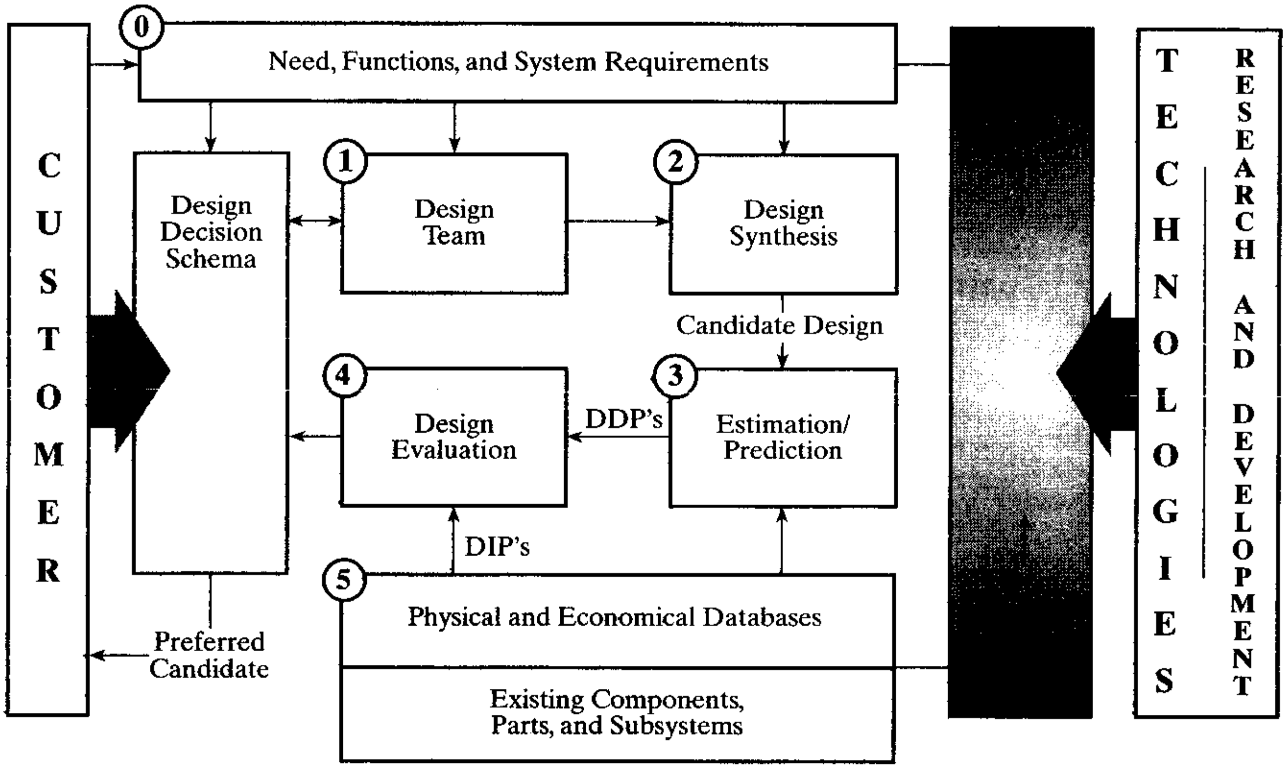


Figure 2.10 Morphology for design synthesis, analysis, and evaluation.

(TPMs) are specified, and the various design alternatives are evaluated in terms of these requirements. As design progresses, the individual designer or design team (Block 1), through creative activity, identifes the various feasible alternative candidates that may be evaluated in arriving at the best design solution. Through the use of various computer-aided design (CAD) or computer-aided engineering (CAE) tools, design synthesis can be accomplished (Block 2). This leads to the generation, through prediction and/or some form of estimation, of the appropriate metrics associated with each of the design alternatives being considered for evaluation (Block 3). The TPMs (Figure 2.8) and the appropriate DDPs (Figure 2.9) must be estimated or predicted and related to the applicable design alternative. The evaluation effort is then accomplished (Block 4), using DDP values and design independent parameters (DIPs) and other resource information as required (Block 5).

The subject of design evaluation and its applications, as an inherent part of the systems engineering process, are discussed throughout Chapters 3 to 6 (Part II) as one proceeds through the phases of conceptual design, preliminary system design, detail design and development, and test and evaluation. Analytical and modeling approaches for systems analysis and evaluation are treated in Chapter 7 to 11 (Part III).

2.6 IMPLEMENTING SYSTEMS ENGINEERING

Current trends indicate that, in general, the complexity of systems is increasing, and many of those 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 modifiying existing systems are getting higher, and available resources are dwindling. At the same time, there is a greater degree on international cooperation, and competition is increasing worldwide. These factors, when combined, create a need to address "systems" from a different perspective.

When evaluating past experiences regarding the development of systems, most of the problems noted have been the direct result of not applying a *disciplined* top-down "systems approach" in meeting the desired objectives. 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 strictly 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 can have a large impact on the overall effectiveness and cost of the system.

Referring to Figure 2.11 experience has indicated 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

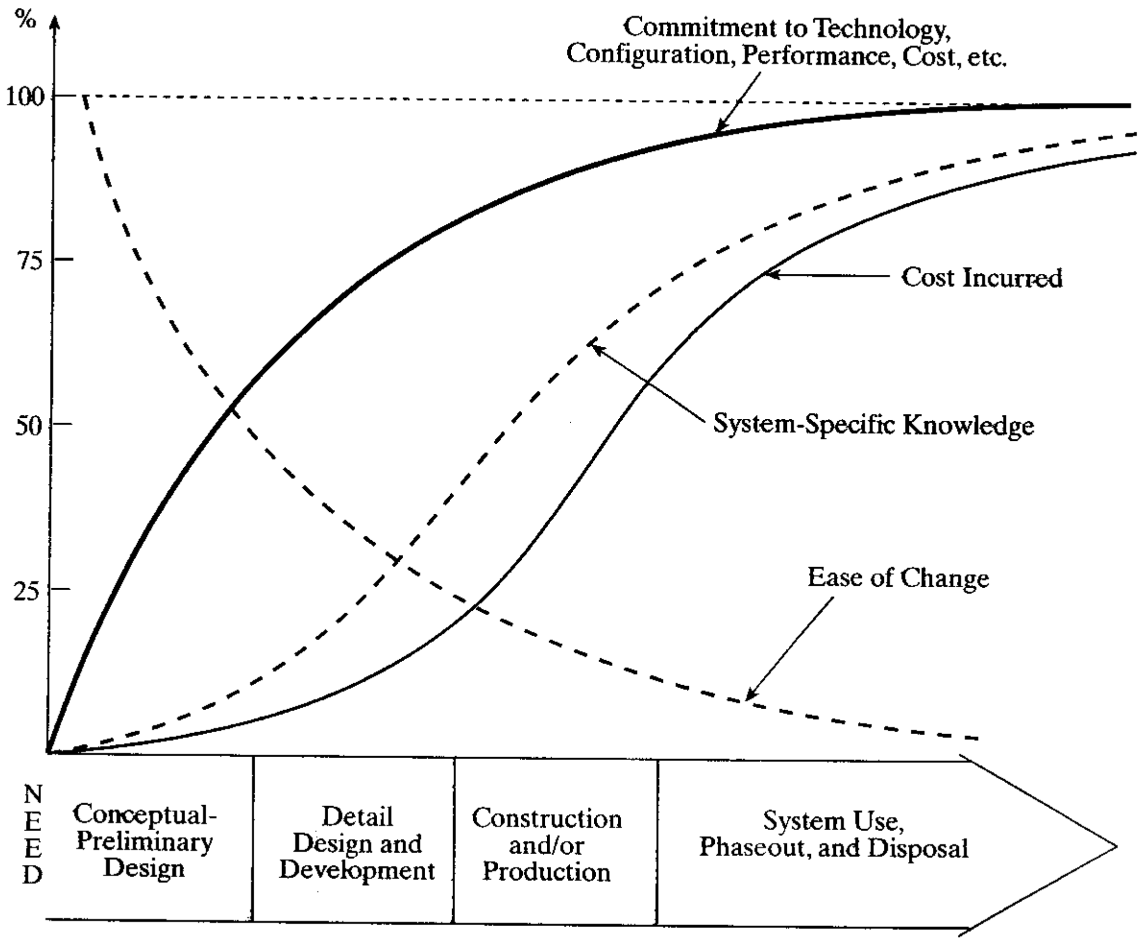


Figure 2.11 Commitment, system-specific knowledge, and cost.

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 commited (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, evolving through the process conveyed in Figure 2.2 and described further in Part II of this text.

Applications for Systems Engineering

There are many categories of human-made systems, and there are many applications 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 [COTS] items, the modification of existing items already in use, or combinations thereof). In any event, for every new consumer requirement, there is a required design effort for the system overall, and the steps described in Section 2.4 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 examples of application are highlighted in Figure 2.12, and some application categories include the following:

1. Large-scale systems with many components, such as a space-based system, an urban transportation system, or a hydroelectric power-generating system.
2. Small-scale systems with relatively few components, such as a local area communications system, a computer system, a hydraulic system, or a mechanical braking system.
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 COTS 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 national and possibly international level.

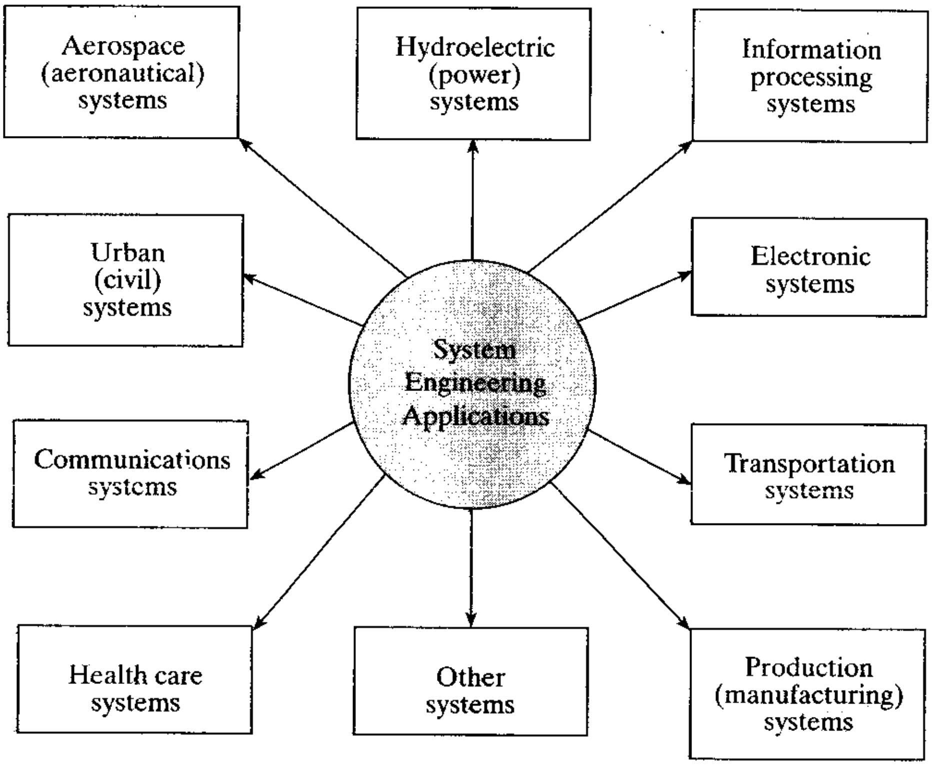


Figure 2.12 Application areas for systems engineering.

8. Systems being designed and developed for use in the defense, civilian, commercial, or private sectors separately or jointly.

The Management of Systems Engineering

The systems engineering process is applicable in all phases of the life cycle, with the greatest benefit being derived from emphasis in the early stages as illustrated in Figure 2.11. 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 appropriate feedback provisions. As conveyed in Figure 2.13, the overall objective is to influence design in the early phases of acquisition, leading to the identification of individual design disciplinary needs as one evolves from system-level requirements to design of the various subsystems and below.[14]

As the system design and development activity evolves, the objective is to ensure the proper integration of design requirements at the appropriate level in the system hierarchical structure. Having initially established specific design requirements as described in Section 2.5 (Figures 2.8 and 2.9), the goal from hereon is to ensure that these requirements are properly balanced and integrated as conveyed in Figure 2.14.

[14] It should be noted that in Figure 2.13 the intent is to convey the degree of "design influence" from the 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, conversely, the establishment of a new organization and the assignment of many people to a project may have little influence.

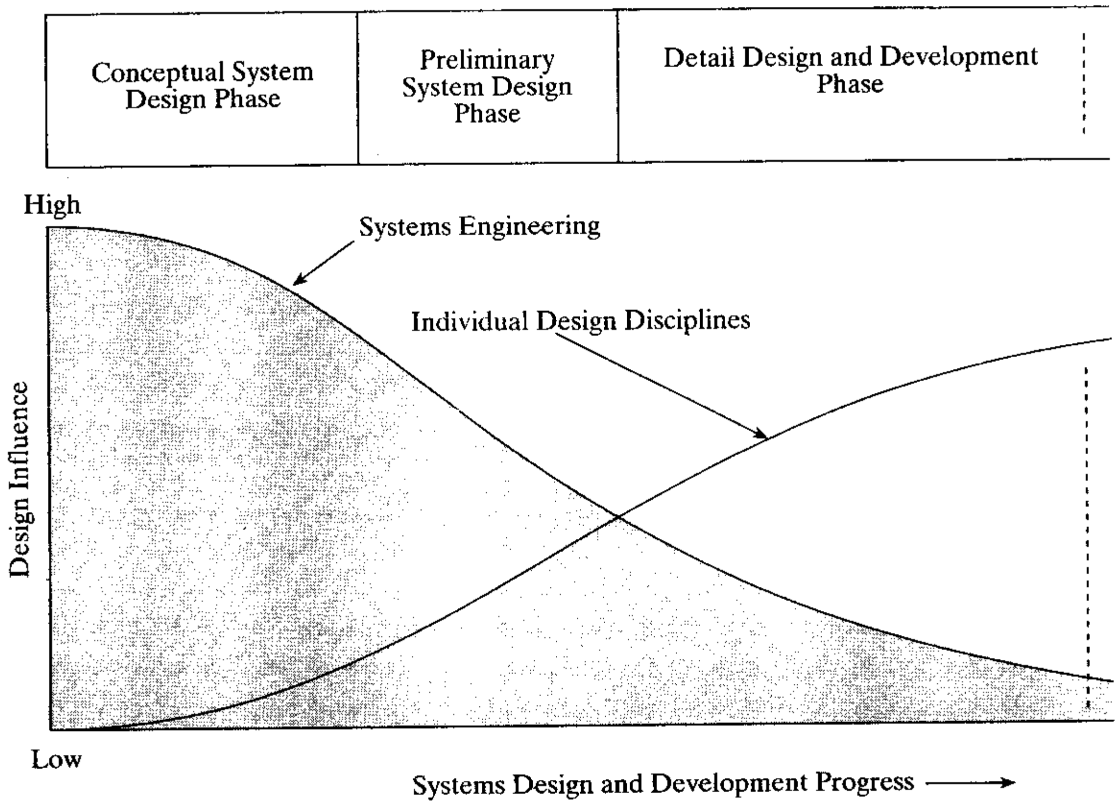


Figure 2.13 Systems engineering influence on design.

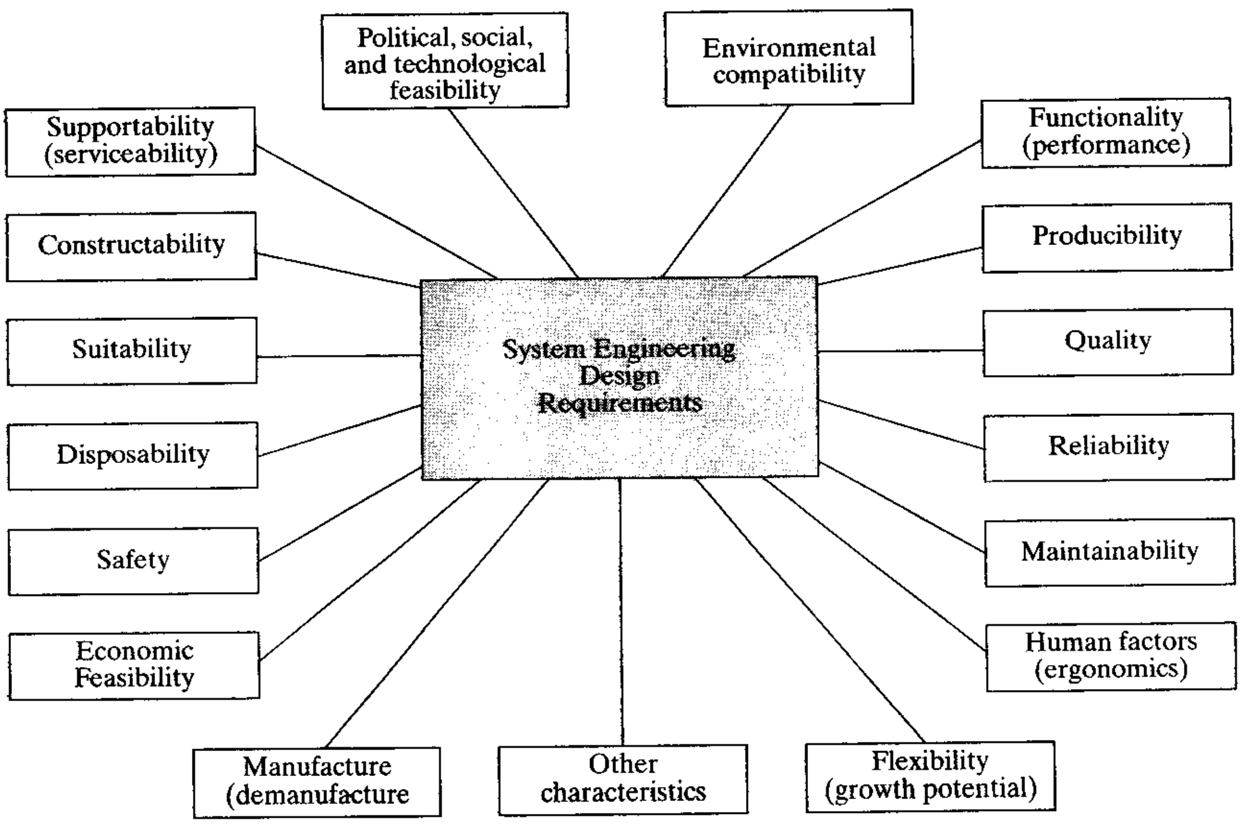


Figure 2.14 The integration of design considerations.

Referring to the figure, an understanding of the interrelationships among these various factors is critical. Given this, there is a requirement to ensure that the applicable engineering disciplines responsible for design of the individual system elements are properly integrated. Implementing the concepts and principles of concurrent engineering and the necessity to promote and establish a good communications network involving all critical project personnel is essential. Often, the various design disciplines (or "domains") are remotely located, and there is a major challenge in promoting the proper level of communications across the board. This goal has been facilitated to some extent through the use of CAD tools and the establishment of a network, such as the one conveyed in Figure 2.15. It is the role of systems engineering to first establish the requirements for design and then to ensure that the proper *design integration* occurs throughout the life cycle as required.

Successful implementation of the systems engineering process is dependent, not only on the availability and application of the appropriate technologies and tools, but on the planning and management of the activities required to accomplish the overall objective. Although the steps described in Section 2.4 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, with the objectives not being met.

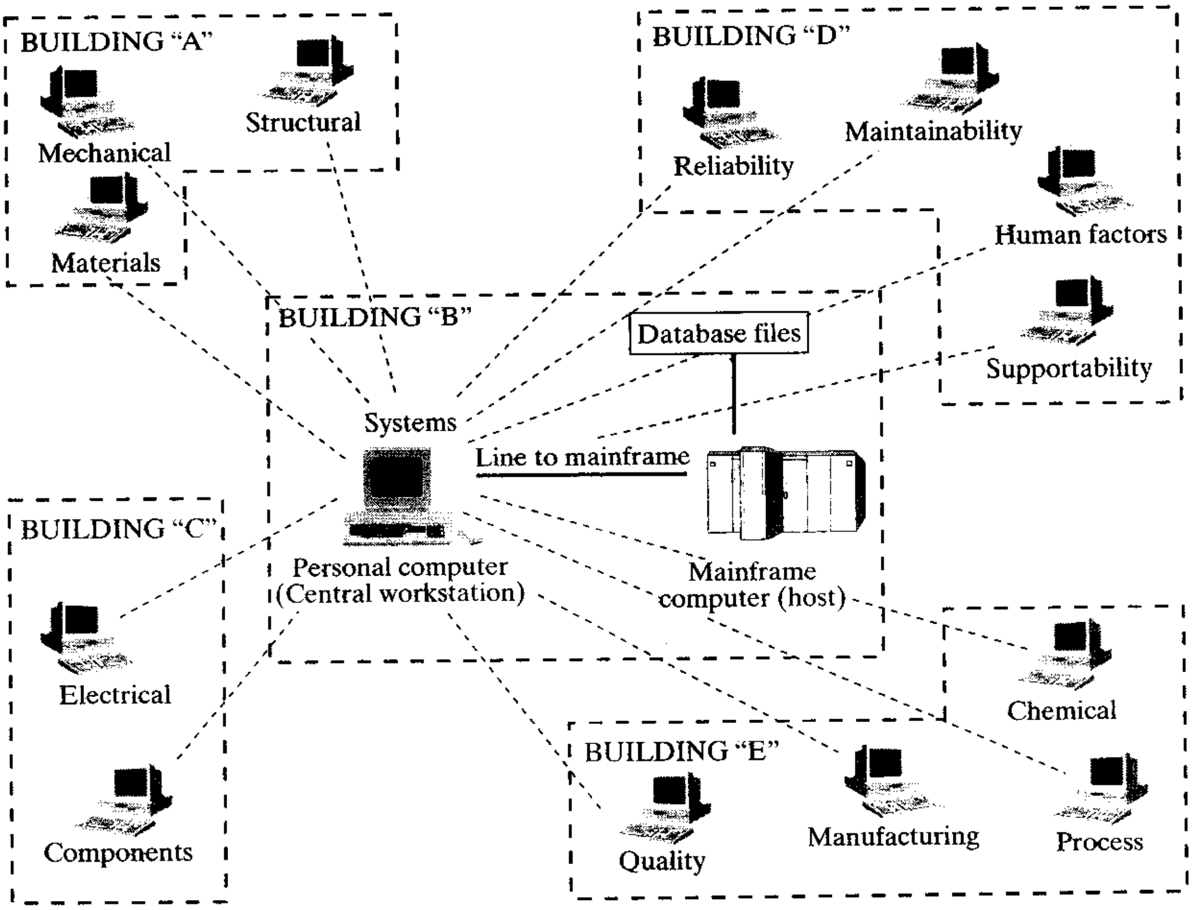


Figure 2.15 System design communications network (example).

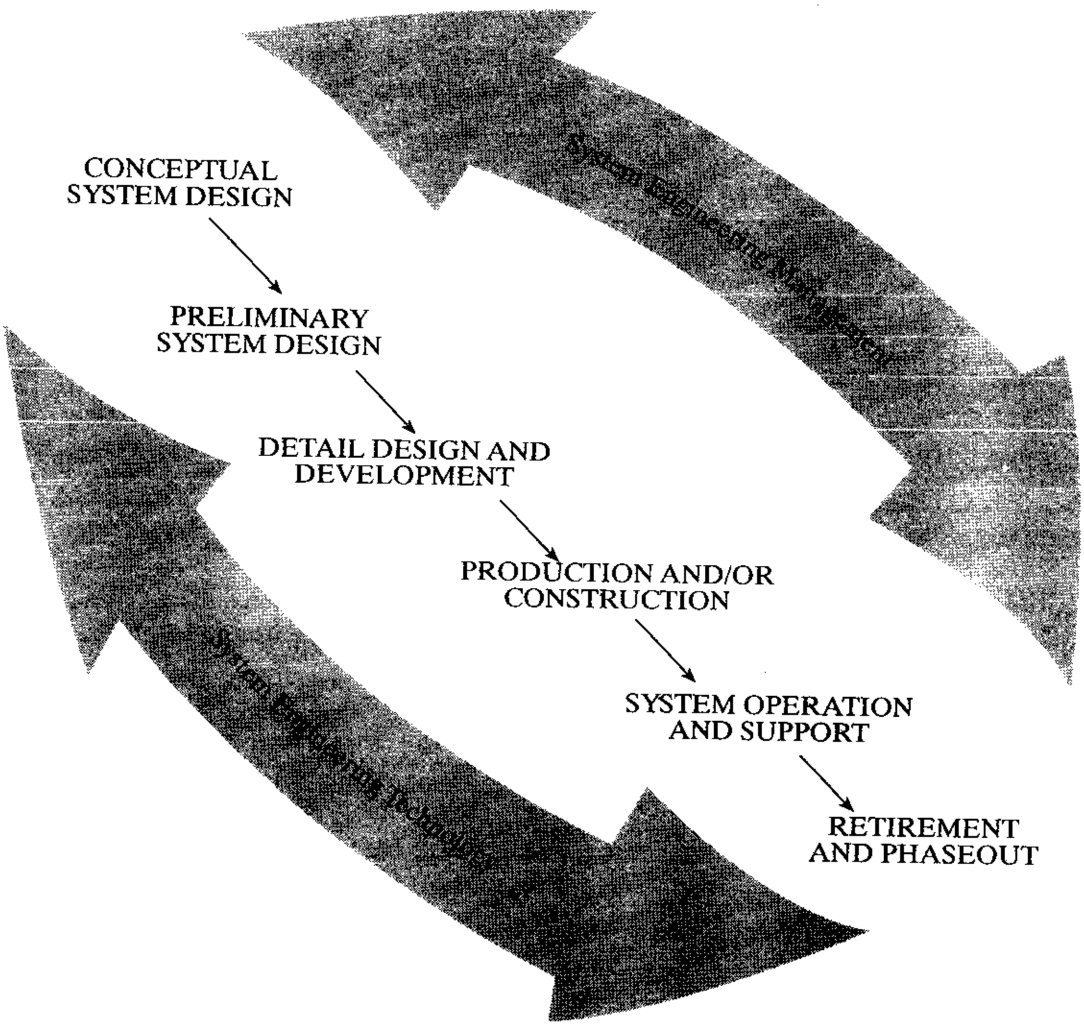


Figure 2.16 Application of technology and management activities to systems engineering.

Without the proper organizational emphasis from the top down, 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 will not occur. Thus, systems engineering must be addressed in terms of both *technology* and *management* as conveyed in Figure 2.16

Potential Benefits From Systems Engineering

Some of the benefits associated with application of the concepts and principles of systems engineering have been implied throughout this chapter, but it may be worthwhile 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 good engineering effort is initiated from the beginning. Additionally, experience indicates that the early emphasis in 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 technologies, such as the use of CAD methods) should help to promote greater design maturity earlier. Changes can be incorporated at an early stage before the 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.

The implementation of systems engineering is the responsibility of systems engineering management. Part V of this text is devoted to this important activity.

QUESTIONS AND PROBLEMS

1. Describe some of the interfaces between the natural world and the human-made world as they pertain to the process of bringing systems, products, and structures into being.
2. What are some of the problems for producers in today's competitive economic environment? How can the application of system engineering preclude some of these problems in the future?
3. What does system life-cycle thinking add to engineering as practiced traditionally? What are the expected benefits to be gained (if any)?
4. Various phases of the system life cycle are shown in Figure 2.1. Describe how the system engineering process can be effectively applied to each phase (if at all).
5. Refer to Figure 2.3 and describe some of the interrelationships between the three life cycles.
6. Select a system of your choice and describe the system life cycle and the activities in each phase as appropriate (the description should be "tailored" for the system that you have selected).
7. Describe some of the main goals and objectives for implementing the system engineering process in the design and development of the system you selected in Question 6.
8. One of the first steps in the system engineering process is the definition of systems requirements. Based on your own experience, how is this accomplished and why is it important?

9. What are the major systems engineering functions in conceptual design, preliminary system design, detail design and development, production and/or construction, system operation, maintenance and support, system retirement, and material disposal/recycling?
10. What is the significance of the "feedback" process illustrated in Figure 2.5? Relate it to feedback in Figure 2.2.
11. What is meant by "tailoring," and why is it important in the engineering of a system?
12. Describe your understanding of the interfaces between synthesis, analysis, and evaluation.
13. Relate the activities of Figure 2.7 to the elements of Figure 2.8; that is, map one on the other.
14. Design decisions at the system level are multicriteria in nature. Pick a hypothetical system, and classify the essential cost and effectiveness measures to be considered.
15. Describe some of the application categories of the system engineering process. Give specific examples from your own experience.
16. What are some of the impediments (as you see them) to the successful implementation of systems engineering?
17. Describe some of the management requirements necessary for the successful implementation of the system engineering process.
18. What are the differences (or similarities) between "systems engineering" and some of the more traditional disciplines, such as civil engineering, electrical engineering, industrial engineering, or mechanical engineering?
19. Describe some of the benefits that may result from the proper implementation of the system engineering process.

THE SYSTEM DESIGN PROCESS

PART II

3 CONCEPTUAL SYSTEM DESIGN

Conceptual design is the first step in the overall process of system design and development, as introduced in Chapter 2. The system engineering process evolves from an identified need to the definition of system requirements in functional terms, establishment of design criteria, and development of a system to meet customer needs in an effective and efficient manner. Thus, systems engineering is concerned with the transition from a need and requirements definition to a fully defined system configuration ready for production and subsequent use.

Conceptual design is the foundation on which the life-cycle phases of preliminary system design, detail design and development, and so forth are based (refer to Figure 2.2, Block 1). Within the conceptual design phase are activities related to the identification of customer need and the several steps involved in the definition of system design requirements (refer to Figure 2.4, Block 0.1). This chapter primarily addresses customer needs and requirements and their conversion to design criteria as a basis for the topics presented in Chapters 4 to 6.

3.1 IDENTIFICATION OF NEED

The systems engineering process begins with the identification of a "need," "want," or "desire" for one or more new entities, or for a new or improved capability. It should be based on a real (or perceived) deficiency. For example, a current system may not be adequate in meeting certain performance goals, may not be available when needed, cannot be properly supported, is too costly to operate, and so on. Or there is a lack of capability to communicate between point A and point B, at a desired bit rate X, with a reliability of Y, and within a specified cost of Z. Accordingly, a new system requirement may be defined along with the priority for its realization, the date when the new capability is to be introduced for use, and an estimate of the resources needed for its acquisition. The statement of need should be presented in specific qualitative and quantitative terms and in enough detail to justify proceeding to the next step.

To identify the need seems to be basic or self-evident. However, a design project is often initiated as a result of a personal interest or a political whim, without first having adequately defined the requirement. Defining the problem is the most difficult part of the system engineering process. However, a complete description of the current deficiency and the real need is necessary. It is essential that the results truly reflect a requirement. This objective can be met best by involving the customer, or ultimate "user," in the process from the beginning.[1]

3.2 ACCOMPLISHMENT OF FEASIBILITY ANALYSIS

Having a definition of need, it is then necessary to (1) identify possible system-level design approaches that can be pursued to meet that need; (2) evaluate the most likely approaches in terms of performance, effectiveness, maintenance and logistic support, and economic criteria; and (3) recommend a preferred course of action. There may be many possible alternatives; however, the number must be narrowed down to a few feasible ones, consistent with the availability of resources (i.e. personnel, materials, and money).

In considering alternative design approaches, different technology applications are investigated. For instance, in the design of a communications system, should one use fiber optics technology or the conventional twisted-wire approach? In aircraft design, to what extent should the use of composite materials be considered? In automobile design, should one incorporate high-speed electronic circuitry in a certain control application, or should an electromechanical approach be taken? In the design of a data communications capability, should a digital or conventional format be used? In the design of a process, to what extent should embedded computer capabilities be incorporated, or artificial intelligence be used? Included in the evaluation process are considerations pertaining to the type and maturity of the technology, its stability and growth potential, the anticipated life of the technology, the number of supplier sources, and so forth.

It is at this early stage in the life cycle (i.e., the conceptual design phase) that major decisions are made relative to adapting a specific design approach, and it is at this stage that the results of such decisions can have a great impact on the ultimate characteristics and life-cycle cost of a system. Technology applications are evaluated and, in some instances where there is not enough information available, research may

[1] The application of Quality Function Deployment (QFD), or equivalent methods, can be useful in helping to estabilish necessary communications between the customer and producer and in identifying and ranking design goals. Two good references are Y. Akao, (ed.), *Quality Function Deployment: Integrating Customer Requirements Into Product Design*, translated into English (Portland: Productivity Press, 1990); and L. Cohen, *Quality Function Deployment: How To Make QFD Work for You* (Reading, Mass.: Addison-Wesley Publishing Co., 1995). The QFD method was developed at the Kobe Shipyard, Mitsubishi Heavy Industries, Japan, in the late 1960s and has been applied in many situations since.

be initiated with the objective of developing new knowledge for specific applications. Finally, the "need" should drive the "technology" and not vice versa.

The results of a feasibility analysis will significantly impact the operational characteristics of the system including its producibility, supportability, disposability, and similar characteristics. The selection (and application) of a given technology has reliability and maintainability implications, may affect manufacturing operations in terms of the processes required, may significantly impact the requirements for test equipment and spare parts, and will certainly affect life-cycle cost. Thus, it is essential that life-cycle considerations be an inherent aspect of the feasibility analysis activity.

3.3 ADVANCE SYSTEM PLANNING

Given an identified need for a feasible new system, advance planning activities are initiated that will establish a project for the conceptual design of that system. Advance planning activities most often included in the conceptual design phase are highlighted in Figure 3.1. These include (1) communication with the customer (consumer) to

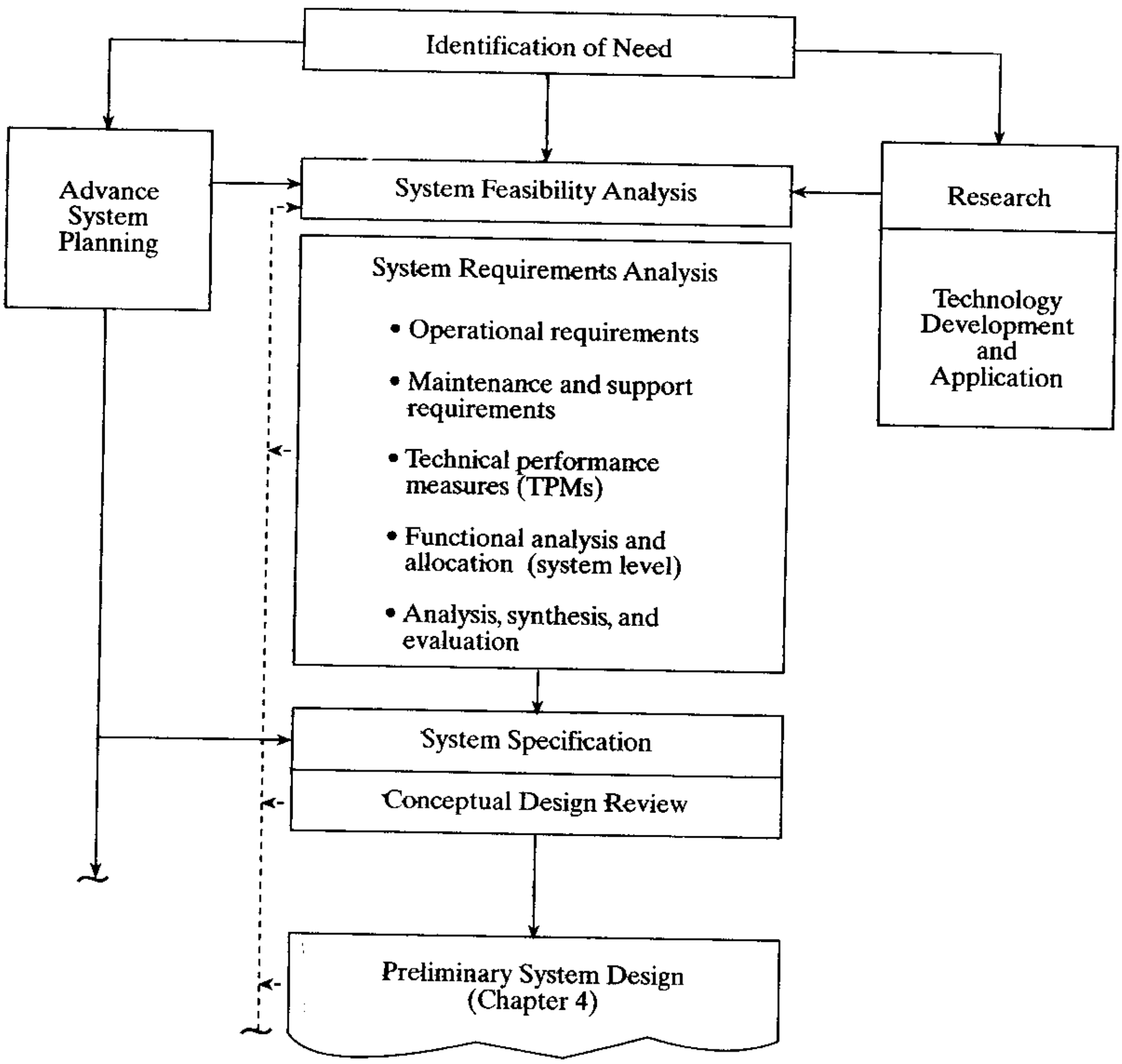


Figure 3.1 System requirements definition process (example).

obtain an in-depth delineation of the need, (2) completion of a feasibility analysis to determine the availability of technologies applicable to the need (i.e., the "technical" approach to design), (3) definition of system operational requirements, (4) development of the system maintenance and support concept, (5) identification and prioritization of technical performance measures (and other design dependent "metrics"), (6) completion of a top-level functional analysis, (7) preparation of a system specification, and (8) conduct of a conceptual design review.

The results from advance system planning may be classified in terms of the *technical* requirements, included in specifications, and the *management* requirements provided in program planning documentation. Of particular significance are the System Specification (type A) and the System Engineering Management Plan (SEMP), both shown in Figure 2.4. It is these documents that initiate the requirements for the implementation of a given program. The relationships between these documents are shown in Figure 3.2, and it is essential that they complement each other.

The system specification provides the design requirements for the system as an entity. It usually includes such information as a general description of the system, operational requirements and the maintenance concept, top-level functional analysis and the allocation of requirements to the subsystem level, performance and effectiveness factors (technical performance measures), physical characteristics, design characteristics, design data requirements, materials and manufacturing processes, logistic support provisions, test and evaluation requirements, and quality assurance provisions. The System Specification leads to lower-level development, product, process, or material specifications as illustrated in Figure 3.2.

In preparing specifications, it is important to recognize that requirements should be stated in terms of the "whats" versus the "hows." There has been a tendency to "overspecify" by telling suppliers how to do something versus defining the overall performance-related requirements in functional terms. This can be costly, particularly if the specifications are not written well in the first place.

Systems engineering requirements, from a program management perspective, are initiated through the SEMP. This plan includes a description of the tasks to be accomplished, the program organizational structure showing the interfaces with various design and supporting disciplines, customer-supplier relationships, the Work Breakdown Structure (WBS), task schedules, cost projections, data and documentation needs, program reporting requirements, design reviews, a risk management plan, and so on. A sample outline and discussion pertaining to systems engineering planning and organization is presented in Part V (Chapter 18).

3.4 SYSTEM REQUIREMENTS ANALYSIS

The activities of requirements analysis, functional analysis, requirements allocation, and so on are iterative in nature. They lead from an identified need to the definition of a system in functional terms, as shown in Figure 2.4. Within each block, there is some degree of iteration. For example, trade-off studies are accomplished at all levels. But it is difficult to convey graphically every iteration that occurs in system engineering.

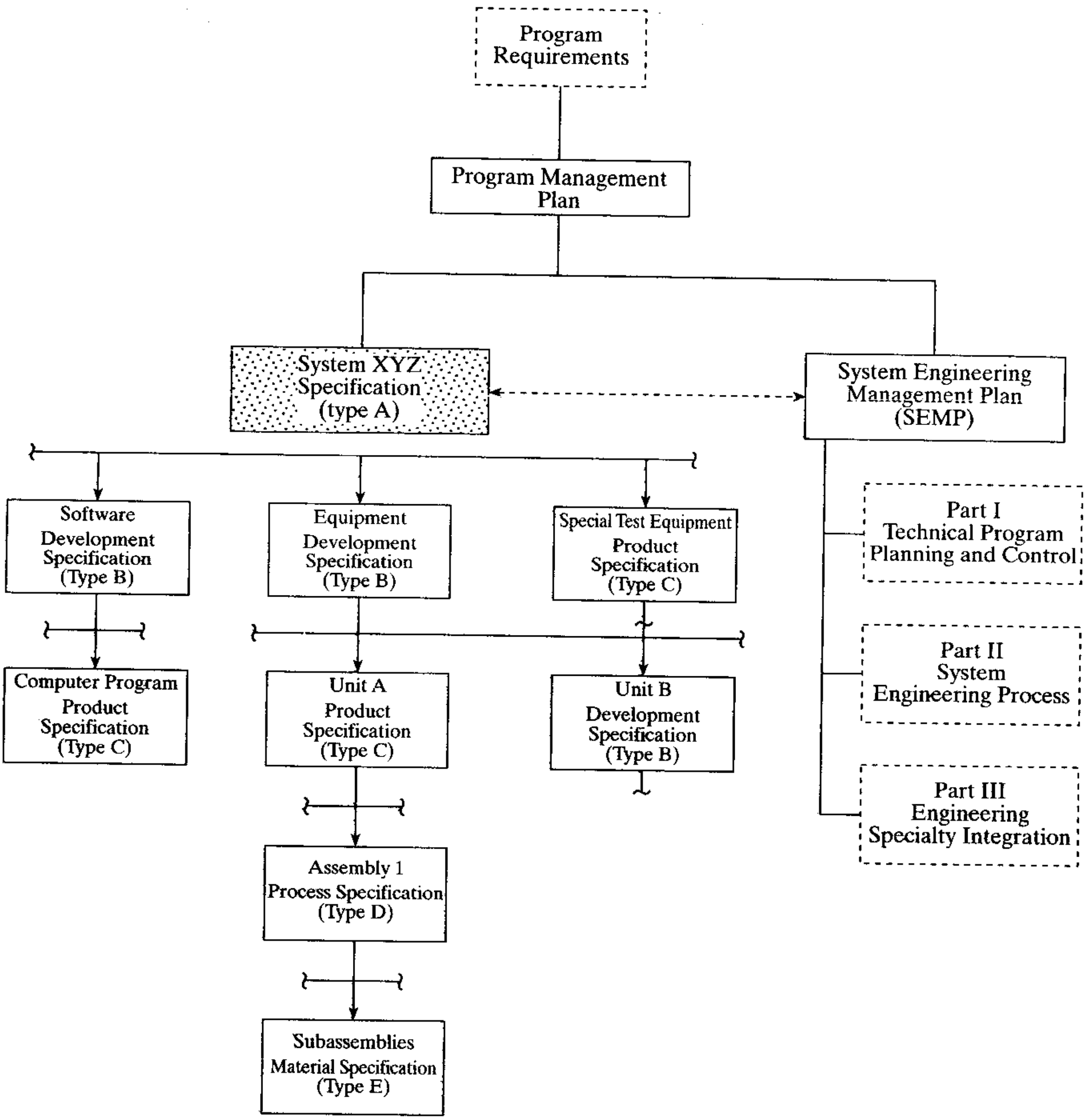


Figure 3.2 Program documentation tree.

Thus, the format presented in Figure 2.4 serves only as a basis for highlighting some of the key activities that must occur.

In any event, the process is initially top down and evolutionary in nature, leading from definition at the system level, to the subsystem level, and to major components of the system. The objective is to describe *requirements* at each level in the system hierarchy; i.e., to describe the "whats (not the "hows" in terms of specific hardware, software, facilities, people, data, etc.). The resources supporting the "hows" will ultimately evolve from the functional analysis and allocation process. Requirements must be complete and fully describe the user's need; they should be objective and designable into the system, must be measurable and demonstrable, and so on.

The important ingredient in the implementation of the requirements analysis and definition process (which is also iterative in nature), is the necessary communications that must exist between the customer and the producer or contractor.

Definition of Operational Requirements

After the needs analysis is combined with the selection of a feasible technical approach, one is ready to project the relevant information to derive anticipated operational requirements. These requirements include the following considerations:

1. *Operational distribution or deployment*—the number of customer sites where the system will be used, the geographical distribution and deployment schedule, and the type and number of system components at each location. This responds to the question—where is the system to be used? Figure 3.3 presents a hypothetical worldwide distribution pattern.
2. *Mission profile or scenario*—identification of the prime mission for the system, and its alternative or secondary missions. What is the system to accomplish and what functions must be performed in responding to the need? This may be defined through a series of operational profiles, illustrating the "dynamic" aspects required in accomplishing a mission. An aircraft flight path between two cities, an automobile or a shipping route, and the number of products to be produced in a factory are examples. Figure 3.4 presents a simple illustration of possible profiles.
3. *Performance and related parameters*—definition of the basic operating characteristics or functions of the system. This refers to parameters, such as range, accuracy, rate, capacity, throughput, power output, size, and weight. What are the

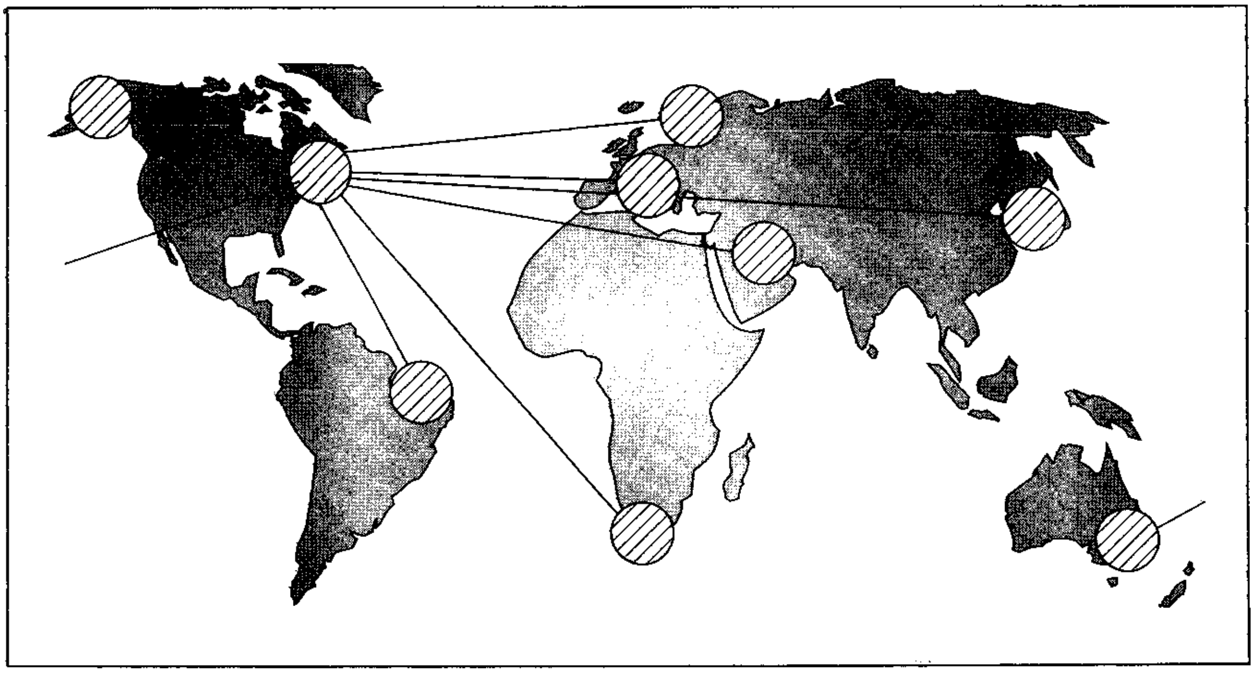


Figure 3.3 Operational requirements (geographical distribution).

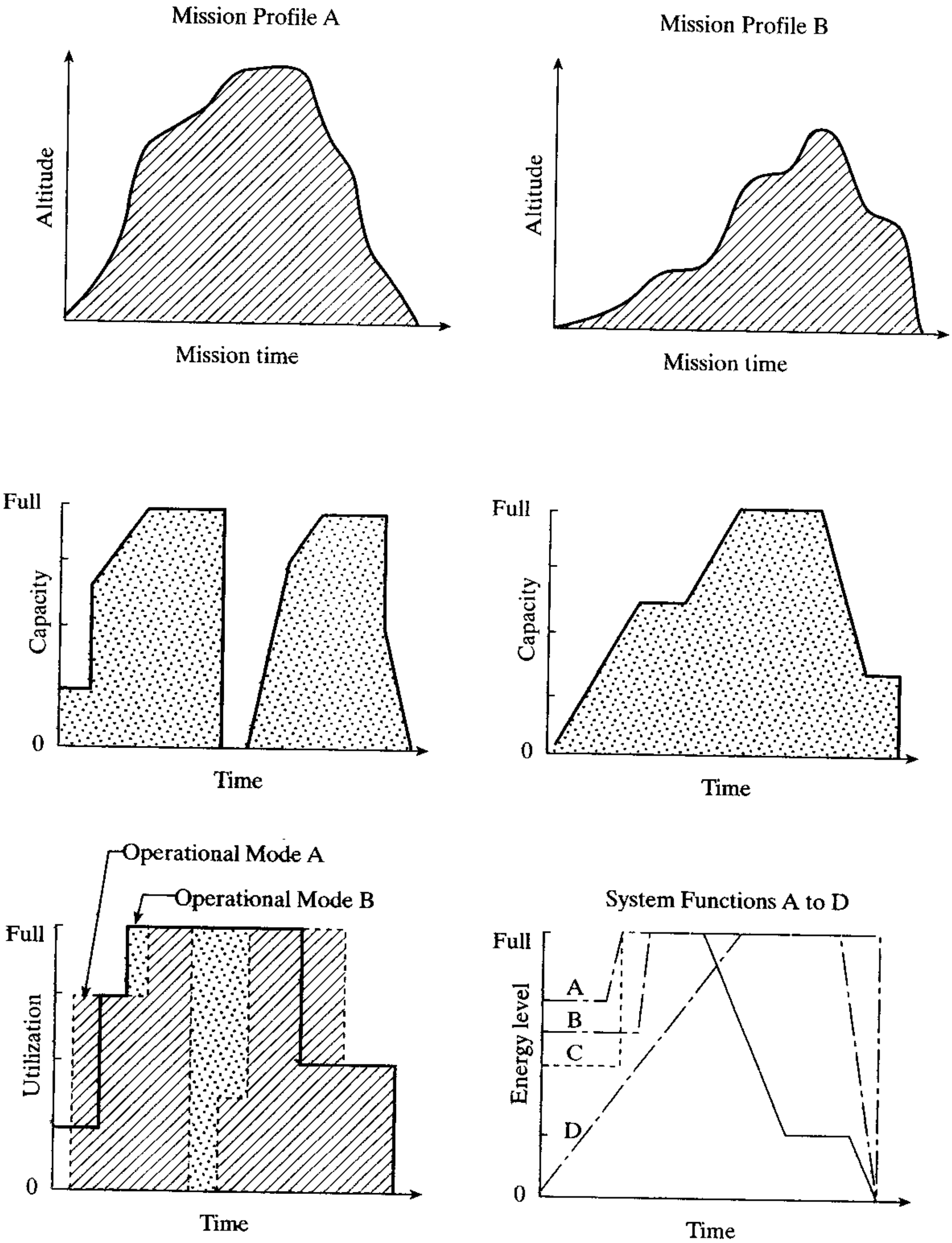


Figure 3.4 System operational profiles (examples).

critical system performance parameters needed to accomplish the mission at the various sites? How do these parameters relate to the mission profiles(s)?

4. *Utilization requirements*—anticipated usage of the system (and its components), in accomplishing its mission. This refers to hours of equipment operation per day, the duty cycle, on-off cycles per months, percentage of total capacity used, facility loading, and so forth. To what extent will the various system components be

used? This leads to a determination of some of the stresses imposed on the system by the operator.

5. *Effectiveness requirements*—system requirements (specified quantitatively as applicable) to include cost/system effectiveness, operational availability, dependability, reliability mean time between failure (MTBF), failure rate (λ), readiness rate, maintenance downtime (MDT), mean time between maintenance (MTBM), facility use (percentage), personnel quantities and skill levels, cost, and so on. Given that the system will perform, how effective or efficient must it be?
6. *Operational life cycle (horizon)*—the anticipated time duration that the system will be operational. How long will the system be in use by the consumer? What is the total inventory profile for units of the system and its components, and where is this inventory to be located? One needs to define the system life cycle. Although this may change (i.e., the life cycle of a system may be extended or reduced), a "baseline" needs to be established at the beginning.
7. *Environment*—definition of the environment in which the system is expected to operate in an effective manner. Examples are temperature, shock and vibration, noise, humidity, arctic or tropics, mountainous or flat terrain, airborne, ground, and shipboard. Following a set of mission profiles may result in specifying a range of values. To what will the system be subjected during its operational use and for how long? In addition to system operations, environmental considerations should address transportation, handling, and storage modes. It is possible that the system (or some of its components) will be subjected to a more rigorous environment when being transported than during operation.

The establishment of operational requirements forms the basis for system design. Obviously, one needs answers to the following questions before proceeding further:

a. *What* function(s) will the system perform?
b. *When* will the system be required to perform its intended function and for how long?
c. *Where* will the system be used?
d. *How* will the system accomplish its objective?

In responding to these questions, a baseline must be established. Although conditions may change, some initial assumptions are required. For example, system components will be used differently at different locations, the distribution of system components may vary as the need changes, or the length of the life cycle may change as a result of obsolescence or the effects of competition. Nevertheless, the information presented earlier must be available so that system design may proceed.

Maintenance and Support Requirements

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" (i.e., prime equipment, operator personnel, operational software, and associated data).

There is usually little attention given to system maintenance and support. In general, emphasis in the past has been directed to only part of the system and not the entire system as defined earlier.

To meet the overall objectives of systems engineering, it is essential that all aspects of the system be considered on an integrated basis from the beginning. This includes not only the prime mission-oriented elements of the system but the support capability as well. The prime system elements must be designed in such a way that they can be effectively and efficiently supported throughout the planned life cycle. The overall support capability must be responsive to this requirement. This, in turn, means that one should also address the characteristics of design as they pertain to the supply support network (i.e., spares, repair parts, and operating inventories), test and support equipment, transportation and handling equipment, computer resources (i.e., software), personnel and training, facilities, and technical data. It is essential that a system "maintenance and support concept" be developed during the conceptual design phase.[2]

The maintenance concept evolves from the definition of system operational requirements and includes the activities illustrated in Figure 3.5. It constitutes a before-the-fact series of illustrations and statements on how the system is to be designed for supportability, whereas the "maintenance plan" defines the follow-on requirements for system support based on the results of the supportability or logistic support analysis, or some equivalent analysis of a given configuration. The maintenance concept ultimately evolves into a detailed maintenance plan.

Referring to Figure 3.5, one must deal with the flow of activities and materials from design, through production, and to the operational sites for customer use. A maintenance flow exists when items are returned from the operational site to the intermediate and suppliers or depot levels of maintenance. By reviewing the network in total, one should address issues, such as the levels of maintenance, the responsibilities and functions to be performed at each level, design criteria pertaining to the various elements of support (e g., type of spares and levels of inventory, reliability of the test equipment, personnel numbers and skill levels), and the effectiveness factors for the overall support capability. Although design of the prime elements of a system may appear to be adequate, the overall ability of the system to successfully fulfill its mission objective is highly dependent on the effectiveness of the support infrastructure.

While there are some variations that arise as a function of the nature and type of system, the maintenance concept generally includes the following information:

1. *Levels of maintenance*—corrective and preventive maintenance may be accomplished on the system itself (or an element thereof) at the site where the system is being used, in an intermediate shop near the consumer/user site, or at a depot or manufacturer's plant 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, and so on, dictate, to a great extent, the specific maintenance functions to be accomplished at each level. Depending on the nature and

[2] B. S. Blanchard, *Logistics Engineering and Management*, 5th ed., (Upper Saddle River, N. J.: Prentice Hall, 1998).

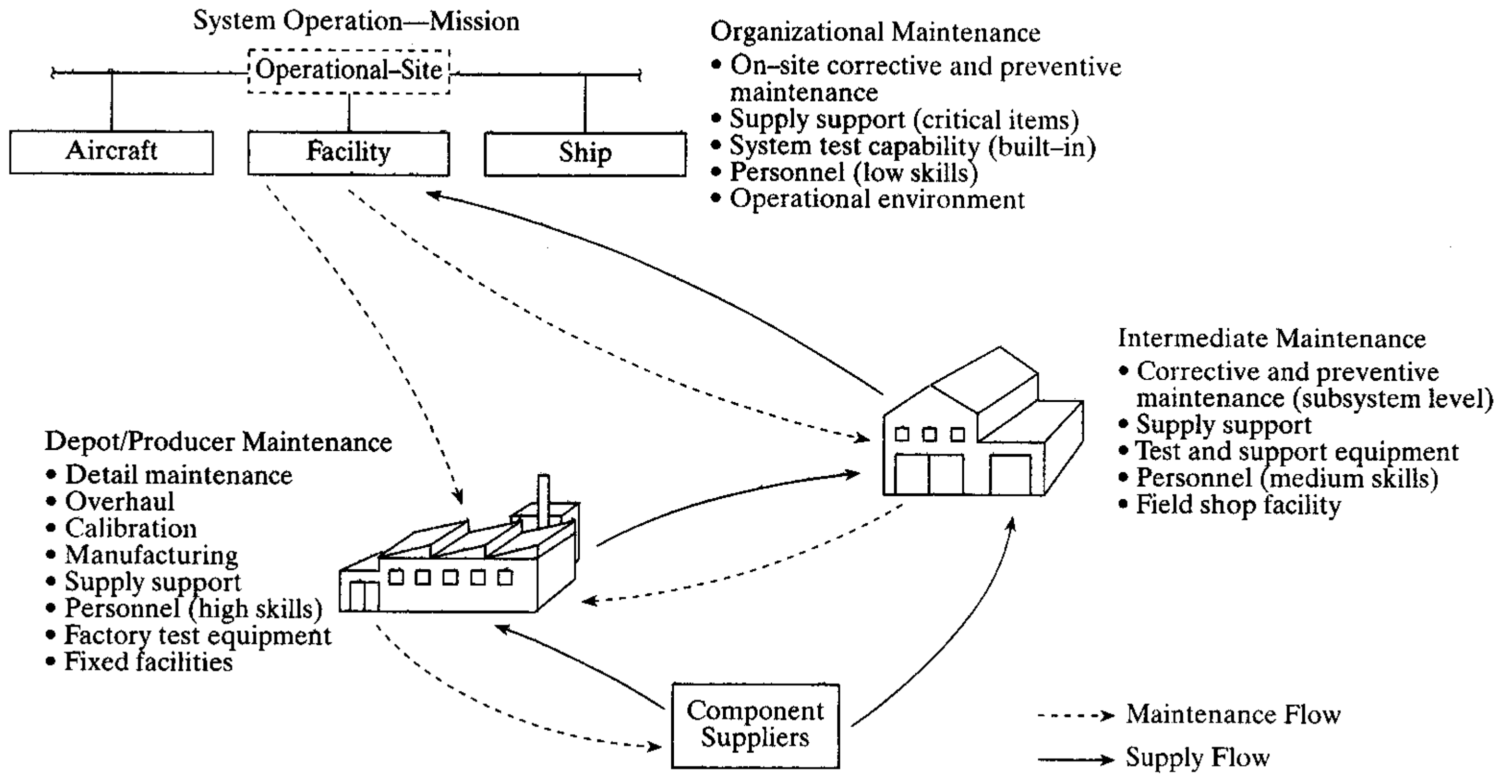


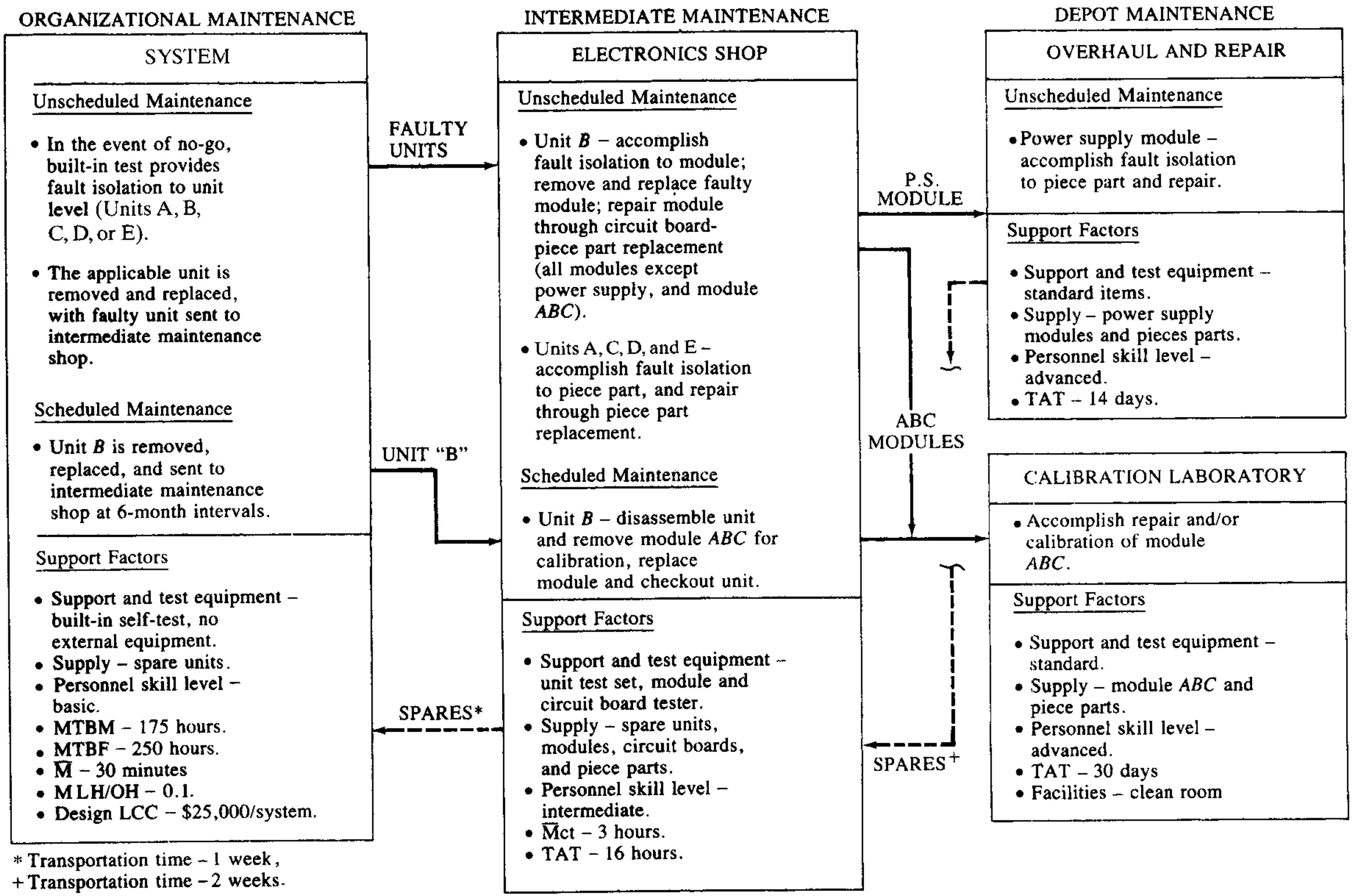
Figure 3.5 System operational and maintenance flow.

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 3.6 Major levels of maintenance.

mission of the system, there may be two to four levels of maintenance. However, for the purposes of further discussion, maintenance may be classified as "organizational," "intermediate," and "supplier/depot." Figure 3.6 describes the basic differences between these levels.

2. *Repair policies*—within the constraints illustrated in Figures 3.5 and 3.6, there may be several possible policies specifying the extent to which repair of a system component will be accomplished (if at all). A repair policy may dictate that an item should be designed to be nonrepairable, partially repairable, or fully repairable. Repair policies are initially established (through accomplishing a repair level analysis), criteria are developed, and system design progresses within the bounds of the repair policy that is selected. An example of a repair policy for System XYZ, developed as part of the maintenance concept during conceptual design, is illustrated in Figure 3.7.
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. The responsibilities may vary, not only with different components of the system but as one progresses in time through the operational use and system support phase. Decisions pertaining to organizational responsibilities may impact system design from the diagnostic and packaging standpoint, as well as dictating repair policies, contract warranty provisions, and the like. Although conditions may change, some initial assumptions are required.
4. *Logistic support elements*—as part of the definition of the initial maintenance concept, criteria must be established relating to the various elements of logistic support. These elements include supply support (spare and repair parts, associated inventories, provisioning data), test and support equipment, personnel and



* Transportation time – 1 week,
+ Transportation time – 2 weeks.

Figure 3.7 System maintenance and repair policy.

training, transportation and handling equipment, facilities, data, and computer resources. Such criteria, as an input to design, may involve self-test provisions, built-in versus external test requirements, packaging and standardization factors, personnel quantities and skill levels, transportation and handling factors and constraints, and so on. The maintenance concept provides some initial system design criteria pertaining to the activities illustrated in Figure 3.5. The final determination of specific logistic, support requirements will occur through the completion of the maintenance or supportability analysis, to be accomplished as design progresses.

5. *Effectiveness requirements*—this constitutes the effectiveness factors associated with the support capability. In the supply support area, this may include a spare part demand rate, the probability of a spare part being available when required, the probability of mission success given a designated quantity of spares, 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 processing time, and the test equipment reliability are key factors. In transportation, transport rates, transportation times, the reliability of transportation, and transportation costs are of significance. For personnel and training, one should be interested in personnel numbers and skill levels, training rates, training times, and training equipment reliability. In software, the number of errors per module or hundred lines of code may be an important measure. These factors, as related to a specific system-level requirement, must be addressed. It is meaningless to specify a tight quantitative requirement applicable to the repair of prime elements of the system when it takes months to acquire a needed spare part. The effectiveness requirements applicable to the support capability must complement the requirements for the overall system.
6. *Environment*—definition of the environment as it pertains to maintenance and support. This includes temperature, shock and vibration, humidity, noise, arctic versus tropical, mountainous versus flat terrain, shipboard versus ground, and so on, as applicable to maintenance activities and related transportation, handling, and storage functions.

In summary, the maintenance concept provides the basis for the establishment of maintenance and supportability requirements in system design. Not only do these requirements impact the prime mission-oriented elements of the system, but they provide guidance in the design or procurement of the necessary elements of maintenance and logistic support. Additionally, the maintenance concept forms the baseline for the development of the detailed maintenance plan, to be prepared during detail design and development.

3.5 TECHNICAL PERFORMANCE MEASURES (TPMs)

Evolving from the operational requirements and the maintenance and support concept is the development of qualitative and quantitative design-to *criteria*, as conveyed in Figure 2.8. Of particular interest are the quantitative factors or *metrics* associated with the system being developed. These metrics, or *technical performance measures* (TPMs), lead to the identification of *design-dependent parameters* (DDPs) and the desired characteristics that should be incorporated into the design (refer to Figure 2.9), and must be established initially as part of the requirements definition process during conceptual design.

In defining the quantitative requirements for a particular system, it is essential that the correct factors be established along with their respective priorities in terms of degrees of importance as viewed by the customer. These prioritized factors must then be translated into the appropriate design criteria and reflected by the DDPs as an input into the design process. Accomplishing this objective requires a good continuous communications link between the consumer (customer) and the producer (contractor).

A good method for facilitating the early consumer-producer communications process is through the use of the Quality Function Deployment (QFD) technique. QFD constitutes a "team" approach to help ensure that the "voice of the customer" is reflected in the ultimate design. The purpose is to establish the necessary *requirements* and to translate those requirements into technical solutions. Customer requirements and preferences are categorized as *attributes*, which are then weighted based on the degree of importance. The QFD method provides the design team an understanding of customer desires, forces the customer to prioritize those desires, and enables a relatively complete comparison of one design approach with another. Each customer attribute is then satisfied by a technical solution.[3]

The QFD process involves constructing one or more matrices, the first of which is often referred to as the "House of Quality" (HOQ).[4] A modified version of the HOQ is presented in Figure 3.8. Starting on the left side of the structure is the identification of customer needs and the ranking of those needs in terms of priority, the levels of importance being specified quantitatively. This reflects the "whats" that must be addressed. A team, with representation from both customer and design organizations, determines the priorities through an iterative process of review, evaluation, revision, re-evaluation, and so on. The top part of the HOQ identifies the designer's *technical* response relative to the attributes that must be incorporated into the design to respond to the needs (i.e., the "voice of the customer"). This constitutes the "hows," and there should be at least one technical solution for each identified customer need. The interrelationships among attributes (or technical correlations) are identified, as well as possible areas of conflict. The center part of the HOQ conveys the strength or impact of the proposed technical response on the identified requirement. The bottom part allows for a comparison between possible alternatives, and the right side of the HOQ is used for planning purposes.

The QFD method is used to facilitate the translation of a prioritized set of subjective customer requirements into a set of *system-level* requirements during conceptual design. A similar approach may be used to subsequently translate system-level requirements into a more detailed set of requirements at each stage in the design and development process. Referring to Figure 3.9, the "hows" from one house become the

[3] See footnote 1 for Akao and Cohen. Also, refer to the bibliography in Appendix F.

[4] J. R. Hauser, and D. Clausing, "The House Of Quality," *Harvard Business Review*, May-June 1988.

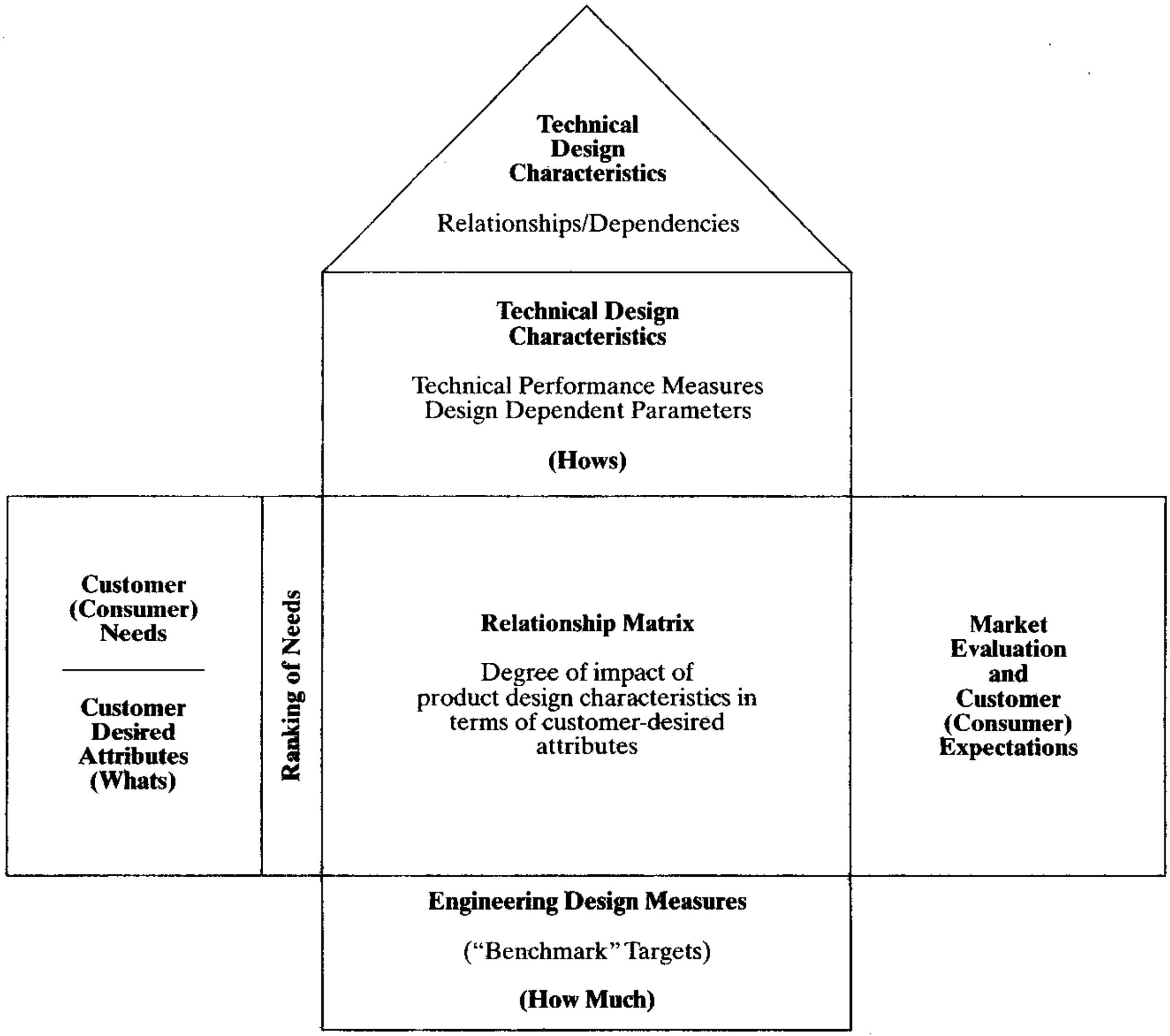


Figure 3.8 Modified "house of quality."

"whats" for a succeeding house. Requirements may be developed for the system, subsystem, component, the manufacturing process, the support infrastructure, and so on. The objective is to ensure the required justification and traceability of requirements from the top down. Further, requirements should be stated in *functional* terms.

Although the QFD method may not be the only approach used in helping to define the requirements for system design, it does constitute an excellent tool for creating the necessary visibility from the beginning. One of the largest contributors to "risk" is the lack of a good set of requirements and an adequate system specification. Inherent within the system specification should be the identification and prioritization of TPMs, as illustrated in Figure 3.10. The TPM, its associated measure (i.e., "metric"), its relative importance, and "benchmark" objective and of what is currently available will provide the designer with the necessary guidance for accomplishing his or her task. This is essential for establishing the appropriate levels of design emphasis, defining the criteria as an input to the design, and identifiying the levels of possible risk should the requirements not be met.

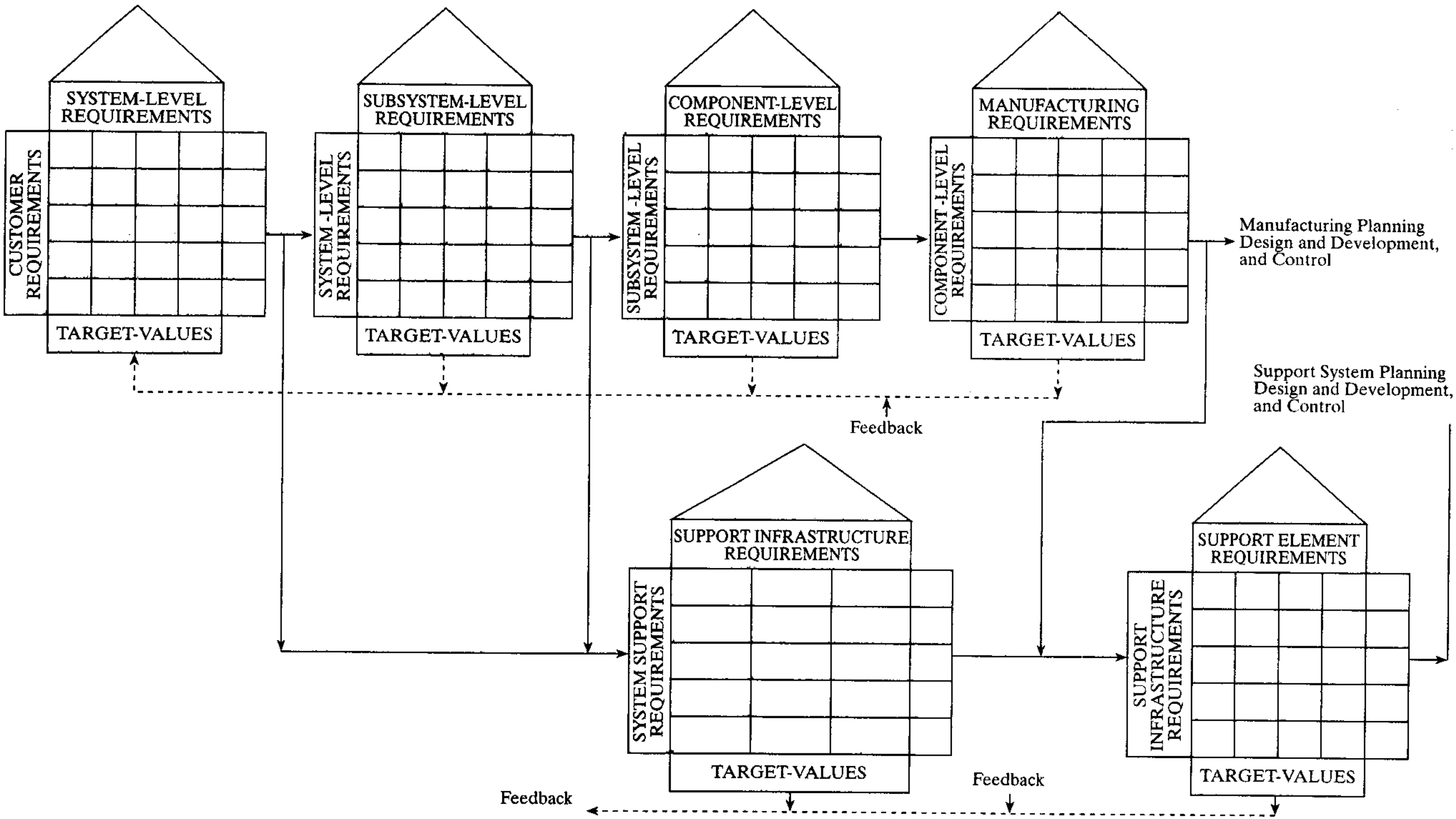


Figure 3.9 Family of houses (traceability of requirements). Source: Blanchard, B.S., *System Engineering Management*, 2nd ed. New York: John Wiley & Sons, 1998.

Technical performance measure	Quantitative requirement ("metric")	Current "benchmark" (competing systems)	Relative importance (customer desires) (%)
Process time (days)	30 days (maximum)	45 days (system M)	10
Velocity (MPH)	100 mph (minimum)	115 mph (system B)	32
Availability (operational)	98.5% (minimum)	98.9% (system H)	21
Size (feet)	10 feet long 6 feet wide 4 feet high (maximum)	9 feet long 8 feet wide 4 feet high (system M)	17
Human factors	Less than 1% error rate per year	2% per year (system B)	5
Weight (pounds)	600 pounds (maximum)	650 pounds (system H)	6
Maintainability (MTBM)	300 miles (minimum)	275 miles (system H)	9
			100

Figure 3.10 Prioritization of technical performance measures.

3.6 FUNCTIONAL ANALYSIS AND ALLOCATION

Functional analysis is the process of translating system requirements into detailed design criteria, along with the identification of specific resource requirements at the subsystem level and below. One starts with an abstraction of the needs of the customer and works down to identify the requirements for hardware, software, people, facilities, data, or combinations thereof. The initial step in this process results in the definition of system requirements (refer to Figure 2.4, Block 0.1). The results may also be specified as part of the overall *system architecture*, a term sometimes used the literature to address "requirements" and "structure" at a top level.[5]

[5] E. Rechtin, *System Architecting: Creating and Building Complex Systems* (Upper Saddle River, N. J.: Prentice Hall, 1991).

Functional Analysis

Although Figure 2.4 appears to show a sequential approach, the functional analysis actually begins with the initial identification of the "functions" that the proposed system is to accomplish (defined as part of the definition of need as explained in Section 3.1). A function refers to a specific or discrete action that is necessary to achieve a given objective (e.g., an operation that the system must perform to accomplish its purpose or a maintenance action that is necessary to restore the system to operational use).

Functions may ultimately be accomplished through the actions of equipment, software, people, and the like. However, the objective is to specify the "whats" and not the "hows" (i.e., *what* is needed to be accomplished versus *how* it should be done). No piece of equipment, item of software, data item or element of logistic support should be identified and purchased without first being justified through a functional analysis. As obvious as this may seem, the design practice often followed is to acquire an item of equipment or software and then attempt to justify its need.

Functional analysis is the iterative process of breaking down, or decomposing, requirements from the system level, to the subsystem level, and as far down the hierarchical structure as necessary to identify specific resources and components of the system. The result represents a definition of the system in *functional* terms and includes system design functions, production functions, distribution and transportation functions, operating functions, maintenance and support functions, disposal functions, and so on.

The functional analysis (as it evolves from the system to the subsystem level and below and applied during the preliminary system design phase) is covered further in Chapter 4, Section 4.1. The specific mechanics for the development of functional block diagrams are discussed in Appendix A, Section A.1.

Functional Flow Block Diagrams

Accomplishment of the functional analysis is often facilitated through the use of functional flow block diagrams. Figure 3.11 shows a simplified flow diagram with some decomposition. Top-level functions are broken down into second-level functions, operational functions lead to maintenance functions, and block numbering is used for the purposes of initially providing top-down traceability of requirements (and later a bottom-up justification of resources in terms of these requirements).[6]

Figure 3.12 shows an expansion of the functional block diagram, identifying several levels and showing operational functions leading into maintenance functions. Note that the words in each block are "action-oriented." Each block can be expanded (through a further downward iteration) and then evaluated in terms of inputs, out-

[6] The preparation of functional block diagrams may be accomplished through the use of any one of a number of graphical methods to include the Integrated DEFinition (IDEF) modeling method, the Behavioral Diagram method, and the N-Squared Charting method. Although the graphical descriptions are different, the ultimate objective is similar. These methods are compared and discussed (within the context of the functional analysis) in B. S. Blanchard, D. Verma, and E. L. Peterson, *Maintainability: A Key to Effective Serviceability and Maintenance Management* (New York: John Wiley & Sons, Inc., 1995).

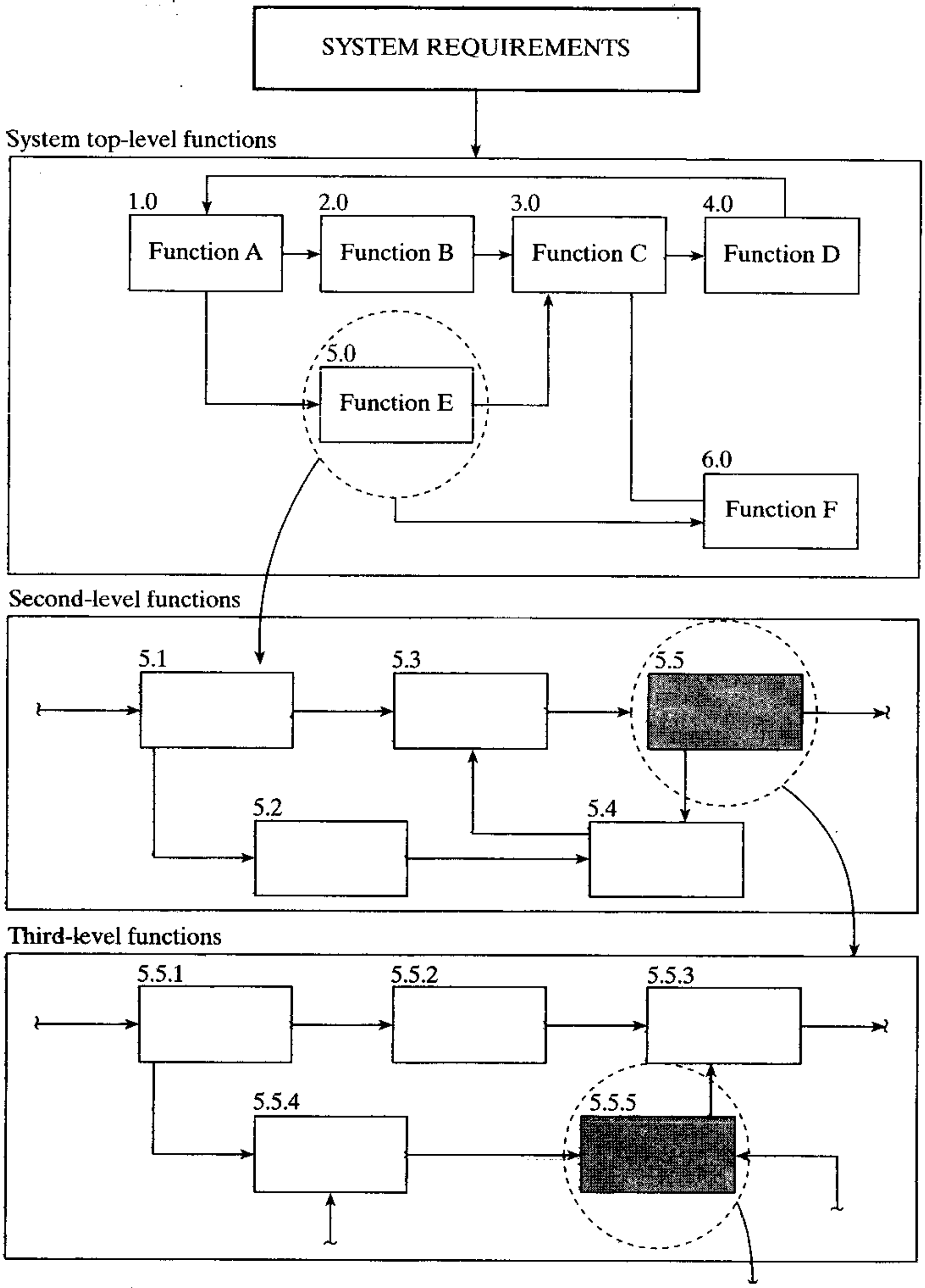


Figure 3.11 System functional breakdown.

puts, controls and/or constraints, and enabling mechanisms. Basically, the "mechanisms" lead to identification of the specific resources necessary to accomplish the function; i.e., equipment, an item of software, a design analysis tool, a facility, people, data, and so forth.

Functional block diagrams are developed for the primary purpose of structuring system requirements into functional terms. They serve to illustrate system organization and to identify major functional interfaces. The functional analysis is initiated during

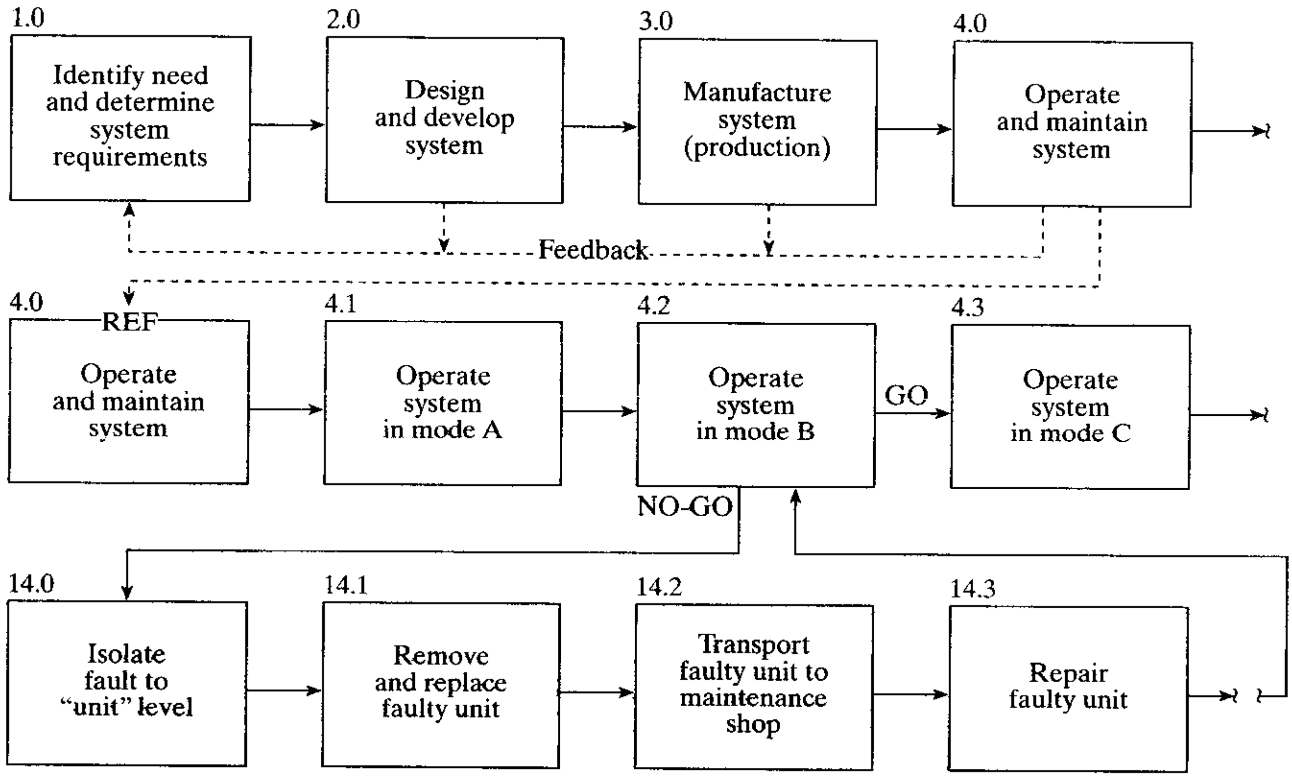


Figure 3.12 Functional block diagram expansion (partial).

the latter stages of conceptual design and is intended to enable the completion of the system design and development process in a comprehensive and logical manner. More specifically, the functional approach helps to ensure that

1. All facets of system design and development, production, operation, and support are considered (i.e., all significant activities within the system life cycle).
2. All elements of the system are fully recognized and defined (i.e., prime equipment, spare/repair parts, test and support equipment, facilities, personnel, data, and software).
3. A means is provided for relating system packaging concepts and support requirements to specific system functions (i.e., satisfying the requirements of good functional design).
4. The proper sequences of activity and design relationships are established along with critical design interfaces.

Functional Allocation

Given a top-level description of the system in functional terms, the next step is to combine, or group, similar functions into logical subdivisions, identifying major subsystems and lower-level elements of the overall system (i.e., the development of a functional packaging scheme for the system). An "open-system architecture" approach is used where the functions (and the functional interfaces) are well defined. At the same time, the "whats" are converted into "hows," and the system is broken down into components as illustrated in Figure 3.13.

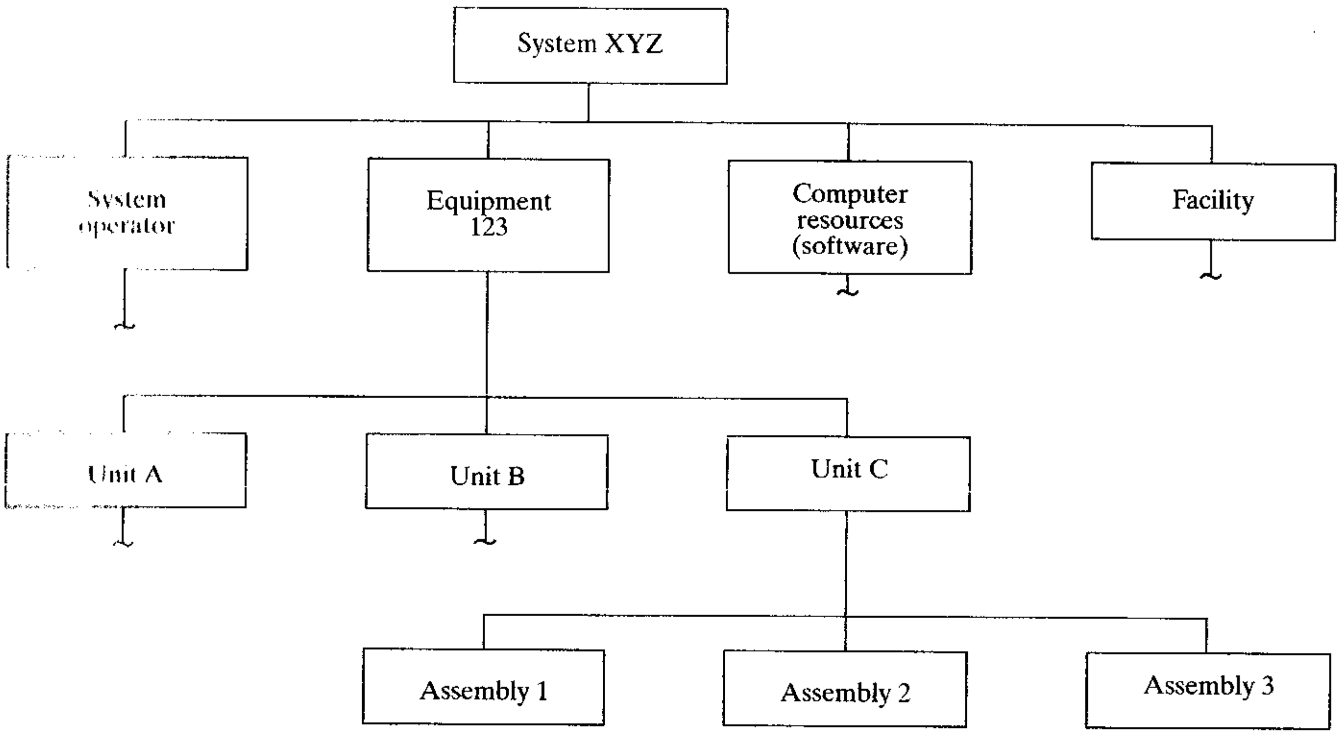


Figure 3.13 The function breakdown of the system into components.

With this structure as a framework for preliminary system design, the qualitative and quantitative requirements evolving from development of the TPMs and DDPs can be allocated to the appropriate system element (i.e., the criteria dictating the design requirements for "Equipment 123," or "Computer Resources (Software)," or "System Operator," or "Facility"). These requirements, developed through the allocation process identified in Block 0.3 of Figure 2.4, may be included in the appropriate lower-level *development, product, process,* or *material* specifications (refer to Figures 2.4 and 3.2).

Through the process of functional packaging and allocation, trade-off studies are conducted in evaluating the different design approaches that can be followed in responding to a given functional requirement (i.e., the "how!"). It may be appropriate to accomplish a designated function through the use of equipment (hardware), software, facilities, people, or combinations thereof. The proper mix is established, and the respective system elements are either developed or procurred as required. At this stage, a plan is generated covering the steps necessary for the acquisition of the system elements that have been justified. Figure 3.14 presents an example of the evolution of hardware, software, and human requirements from the functional analysis and the steps required for acquisition. From a systems engineering perspective, it is essential that the requirements for equipment, software, people, facilities, and so on, be justified by responding to some *functional need.* Further, it is critical that the appropriate coordination and integration of the activities shown in Figure 3.14 be initiated from the beginning.[7]

[7]Referring to Figure 3.14, it is not uncommon for hardware engineers, software engineers, facility engineers, and other specialists to each proceed through a given series of steps without the appropriate level of communications between these activities. Further, the human element is often left out. This often results in significant problems being detected and numerous modifications being required during the final system

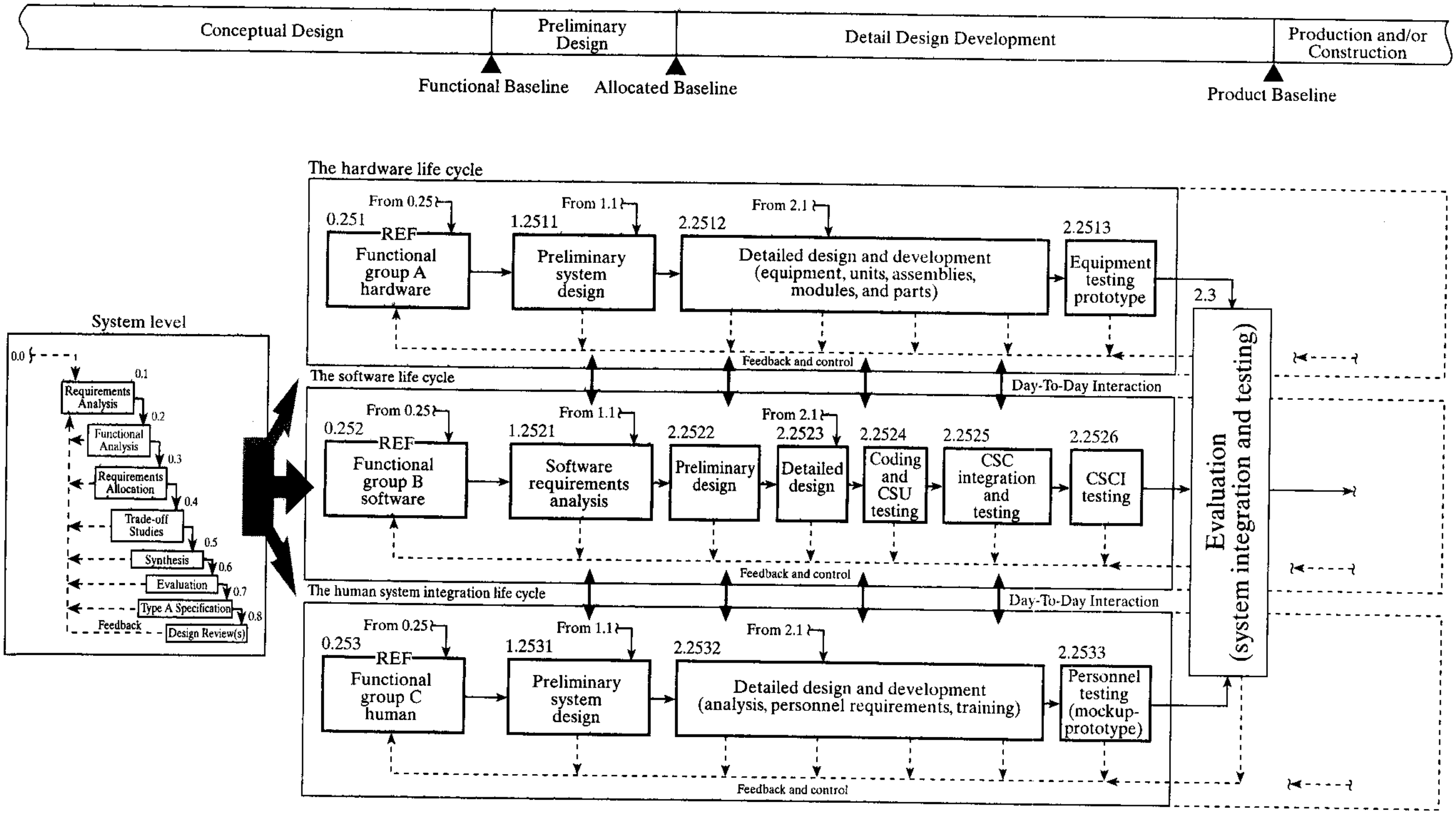


Figure 3.14 The evolution of hardware, software, and human requirements from the functional analysis (refer to Figure 2.4).

3.7 SYNTHESIS, ANALYSIS, AND EVALUATION

As the system design progresses, there are many possible trade-offs involving such issues as the evaluation and selection of different technologies, different materials, alternative system packaging schemes, alternative diagnostic routines, the evaluation and selection of COTS items, alternative maintenance and support policies, the incorporation of automation versus the accomplishment of functions by human means, and so on. Later, there may be alternative manufacturing processes, detailed maintenance plans, alternative logistic support structures, and/or alternative methods of material disposal that require evaluation. In general, the approach followed in the accomplishment of almost any trade-off study (or evaluation) is illustrated in Figure 3.15. One must first define the problem, identify the specific design criteria or measures against which the various alternatives will be evaluated (i.e., the applicable TPMs and DDPs), select the appropriate evaluation techniques, select or develop a model to facilitate the evaluation process, acquire the necessary input data, evaluate each of the candidates being considered, perform a sensitivity analysis and identify the potential areas of risk and finally recommend a course of action. This process can be "tailored" and applied at any point in the life cycle as illustrated in Figures 2.2 and 2.4. Inherent within this process is the application of the design evaluation morphology illustrated in Figure 2.10. Only the depth of the analysis and evaluation effort will vary, depending on the nature of the problem at hand.

The trade-off analysis leads into *synthesis*. Synthesis refers to the combining and structuring of components in such a way as to represent a feasible system configuration. The basic requirements have been established, some trade-off studies have been completed, and a baseline configuration is developed to demonstrate the concepts presented earlier.

Synthesis is *design*. Initially, synthesis is used in the development of preliminary concepts and to establish relationships among the various components of the system. Later, when sufficient functional definition and decomposition have occurred, synthesis is used to further define the "hows" at a lower level. Synthesis involves the creation of a configuration which could be representative of the form that the system will ultimately take (although a final configuration is certainly not to be assumed at this point in the process).

Given a synthesized configuration, one needs to evaluate the characteristics of that configuration in terms of the requirements initially specified. Changes are incorporated as required, leading to a preferred design configuration. This iterative process of analysis, synthesis, evaluation, and design refinement leads initially to the establishment of the "functional baseline," then the "allocated baseline," and finally the "product baseline" (refer to Figure 2.4). A good description of these configuration baselines, combined with a *disciplined* approach to baseline management, is essential for the successful implementation of the system engineering process.

integration and test task when it is discovered that the various elements do not fit (refer to Block 2.3)! The objective is to provide the proper day-to-day coordination (with the appropriate feedback) as one proceeds through Blocks 0.251, 0.252, 0.253, and so on, identifying potential problems as early in the life cycle as possible.

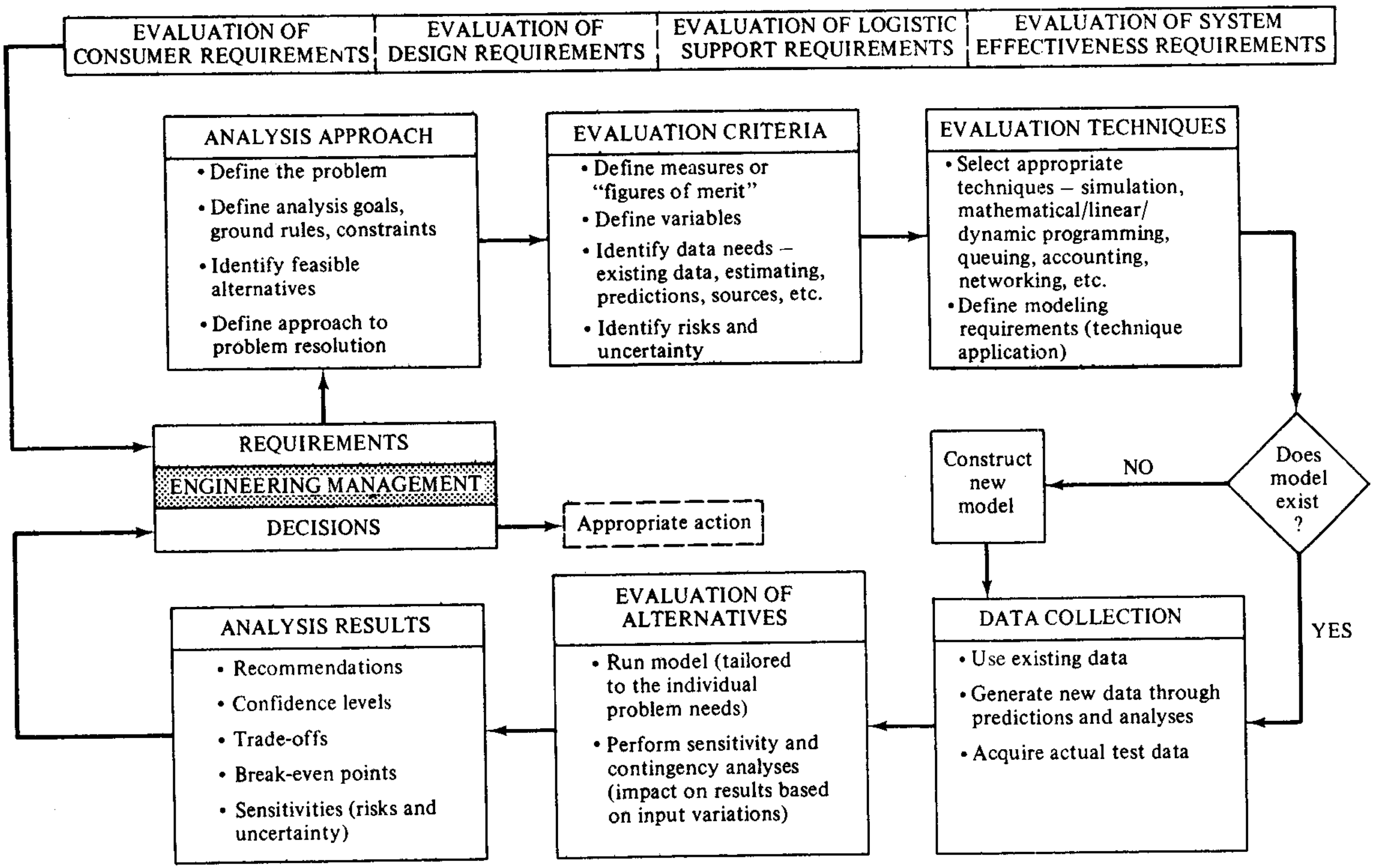


Figure 3.15 A generic systems analysis process.

3.8 SYSTEM SPECIFICATION

The *technical* requirements for the system and its elements are documented through a series of specifications, as conveyed in Figure 2.4. Of significance at this stage in the life cycle is the *System Specification* (type A). This is the single most important engineering *design* document, defining the system functional baseline and including the results from the needs analysis, feasibility analysis, operational requirements and the maintenance concept, top-level functional analysis, and identifying the critical TPMs and DDPs. This top-level specification leads into one or more subordinate specifications, as shown in Figure 3.2, covering applicable subsystems, configuration items, equipment, software, and other components of the system. Although the individual specifications for a given program may assume a different set of designations, a generic approach is used here. Further, the different categories of specifications are described subsequently.[8]

1. *System specification* (type A)—includes the technical, performance, operational and support characteristics for the system as an entity. It includes the allocation of requirements of functional areas, and it defines the various functional-area interfaces. The information derived from the feasibility analysis, operational requirements, maintenance concept, and the functional analysis is covered.
2. *Development specification* (type B)—includes the technical requirements for any item below the system level where research, design, and development are accomplished. This may cover an equipment item, assembly, computer program, facility, critical item of support, and so on. Each specification must include the performance, effectiveness, and support characteristics that are required in the evolving of design from the system level and down.
3. *Product specification* (type C)—includes the technical requirements for any item below the top system level that is currently in the inventory and can be procured "off the shelf." This may cover standard system components (equipment, assemblies, units, cables), a specific computer program, a spare part, a tool, and so on.
4. *Process specification* (type D)—includes the technical requirements that cover a service that is performed on any component of the system (e.g., machining, bending, welding, plating, heat treating, sanding, marking, packing, and processing).
5. *Material specification* (type E)—includes the technical requirements that pertain to raw materials, mixtures (e.g., paints, chemical compounds), or semifabricated materials (e.g., electrical cable, piping) that are used in the fabrication of a product.

The System Specification (type A) provides the *technical baseline* for the system as an entity, must be written in "performance-related" terms, and must describe design requirements in terms of the "whats" (i.e., the functions that the system is to perform and the associated metrics). Although the individual content should be "tailored" to the particular system in question, Figure 3.16 shows an example of what might be

[8] These categories were initially developed for application in the defense sector and are used in a "generic" sense throughout this text.

System Specification

1.0 Scope
2.0 Applicable Documents
3.0 Requirements
- 3.1 System Definition
  - 3.1.1 General Description
  - 3.1.2 Operational Requirements (Need, Mission, Use Profile, Distribution, Life Cycle)
  - 3.1.3 Maintenance Concept
  - 3.1.4 Functional Analysis and System Definition
  - 3.1.5 Allocation of Requirements
  - 3.1.6 Functional Interfaces and Criteria
- 3.2 System Characteristics
  - 3.2.1 Performance Characteristics
  - 3.2.2 Physical Characteristics
  - 3.2.3 Effectiveness Requirements
  - 3.2.4 Reliability
  - 3.2.5 Maintainability
  - 3.2.6 Usability (Human Factors)
  - 3.2.7 Supportability
  - 3.2.8 Transportability/Mobility
  - 3.2.9 Flexibility
  - 3.2.10 Other
- 3.3 Design and Construction
  - 3.3.1 CAD/CAM Requirements
  - 3.3.2 Materials, Processes, and Parts
  - 3.3.3 Mounting and Labeling
  - 3.3.4 Electromagnetic Radiation
  - 3.3.5 Safety
  - 3.3.6 Interchangeability
  - 3.3.7 Workmanship
  - 3.3.8 Testability
  - 3.3.9 Economic Feasibility
- 3.4 Documentation/Data
- 3.5 Logistics
  - 3.5.1 Maintenance Requirements
  - 3.5.2 Supply Support
  - 3.5.3 Test and Support Equipment
  - 3.5.4 Personnel and Training
  - 3.5.5 Facilities and Equipment
  - 3.5.6 Packaging, Handling, Storage, and Transportation
  - 3.5.7 Computer Resources (Software)
  - 3.5.8 Technical Data
  - 3.5.9 Customer Services
- 3.6 Producibility
- 3.7 Disposability
- 3.8 Affordability

4.0 Test and Evaluation
5.0 Quality Assurance Provisions
6.0 Distribution and Customer Service

Figure 3.16 Type A system specification format (example).

included for a large system. It is essential that a good comprehensive well-written specification be prepared from the beginning.[9]

3.9 CONCEPTUAL DESIGN REVIEW

Design progresses from an abstract notion to something that has form and function, is fixed, and can ultimately be reproduced in designated quantities to satisfy a need. Initially, a need is identified. From this point, a design evolves through a series of stages (i.e., conceptual design, preliminary system design, detail design and development). In each major stage of the design process, an evaluative function is accomplished to ensure that the design is correct at that point before proceeding with the next stage. The evaluative function includes both the informal day-to-day project coordination and data review, and the formal design review. Design information is released and reviewed for compliance with the basic system-equipment requirements (i.e., performance, reliability, maintainability, usability, etc., as defined by the system specification). If the requirements are satisfied, the design is approved as is. If not, recommendations for corrective action are initiated and discussed as part of the formal design review.

The formal design review constitutes a coordinated activity (including a meeting or series of meetings) directed to satisfy the interests of the design engineer and the technical discipline support areas (reliability, maintainability, human factors, logistics, manufacturing, industrial engineering, quality assurance, and program management). The purpose of the design review is to formally and logically cover the proposed design from the total system standpoint in the most effective and economical manner through a combined integrated review effort. The formal design review serves a number of purposes.

1. It provides a formalized check (audit) of the proposed system/subsystem design with respect to specification requirements. Major problem areas are discussed and corrective action is taken.
2. It provides a common baseline for all project personnel. The design engineer is provided the opportunity to explain and justify his or her design approach, and representatives from the various supporting organizations (e.g., maintainability, logistic support) are provided the opportunity to hear the design engineer's problems. This serves as an excellent communication medium and creates a better understanding among design and support personnel.

[9] It is not uncommon for the *system specification* to be written in very vague terms, with the objective of keeping the requirements "loose" in the beginning in order to provide for as much flexibility in design as possible (i.e., to allow for innovation on the part of the designer). Without a good foundation on which to build, the follow-on *B*, *C*, *D*, and *E* specifications, which are usually stated in rather *specific* terms, may not properly reflect what is ultimately desired by the customer in terms of system performance. Further, these lower-level specifications may not be mutually supportive or compatible if there is a poor description of the system upon which to base requirements. Thus, it is essential that a well-written *performance-based* specification be prepared in the beginning.

3. It provides a means for solving interface problems and promotes the assurance that all system elements will be compatible.
4. It provides a formalized record of what design decisions were made and the reasons for making them. Analyses, predictions, and trade-off study reports are noted and are available to support design decisions. Compromises to performance, reliability, maintainability, human factors, cost, and logistic support are documented and included in the trade-off study reports.
5. It promotes a higher probability of mature design, as well as the incorporation of the latest techniques (where appropriate). Group review may identify new ideas, possibly resulting in simplified processes and ultimate cost savings.

The formal design review, when appropriately scheduled and conducted in an effective manner, causes a reduction in the producer's risk relative to meeting specification requirements and results in improvement of the producer's methods of operation. Also, the customer often benefits through receipt of a better product.

Design reviews are generally scheduled before each major evolutionary step in the design process, as illustrated in Figure 2.4. In some instances, this may entail a single review toward the end of each stage (i.e., conceptual, preliminary system design, and detail design and development). For the other projects, where a large system is involved and the amount of new design is extensive, a series of formal reviews may be conducted on designated elements of the system. This may be desirable to allow for the early processing of some items while concentrating on the more complex, high-risk items.

Although the number and type of design reviews scheduled may vary from program to program, four basic types are readily identifiable and are common to most programs. They include the conceptual design review (i.e., system requirements review), the system design review, the equipment/software design review, and the critical design review. Of particular interest relative to the activities discussed in this chapter is the *conceptual design review.* The conceptual design review may be scheduled during the early part of a program (preferably not more than 4 to 8 weeks after program start) when operational requirements and the maintenance concept have been defined. Feasibility studies justifying preliminary design concepts should be reviewed. Logistic support requirements at this point are generally included in the maintenance-concept definition.

QUESTIONS AND PROBLEMS

1. In accomplishing a needs analysis in response to a given deficiency, what type of information would you include? Describe the process that you would use in developing the necessary information.
2. What is the purpose of the feasibility analysis? What considerations should be addressed in the completion of such an analysis?
3. Through a review of the literature, describe the QFD approach and how it could be applied in helping to define the requirements for a given system design.
4. Why is the definition of system operational requirements important? What type of information is included?

5. Why is it important to define specific mission scenarios (or operational profiles) within the context of the system operational requirements?
6. What information should be included in the system maintenance concept? How is it developed (describe the steps), and at what point in the system life cycle should it be developed?
7. How do system operational requirements influence the maintenance concept (if at all)?
8. How does the maintenance concept affect system/product design? Give some specific examples.
9. Select a system of your choice and develop the operational requirements for that system. Based on the results, develop the maintenance concept for the system. Construct the necessary operational and maintenance flows, identify repair policies, and apply quantitative effectiveness factors as appropriate.
10. In evaluating whether or not a two or three-level maintenance concept should be specified, what factors would you consider in the evaluation process?
11. In developing the maintenance concept, it is essential that all levels of maintenance be considered on an integrated basis. Why?
12. Why is the development of technical performance measures (TPMs) important?
13. Refer to Figure 3.10. Describe the steps that you would complete in developing the information included in the figure. Be specific.
14. Given the information provided in Figure 3.10, how would you apply this information in the system design process (if at all)?
15. What is meant by functional analysis? When in the system life cycle is it accomplished? What purpose does it serve? Identify some of the benefits derived. Can a functional analysis be accomplished for any system?
16. How does the functional analysis lead into the definition of specific resource requirements in the form of hardware, software, people, data, facilities, and so on? Briefly describe the steps in the process, and include an example. What is the purpose of the block numbering shown in Figures 3.11 and 3.12?
17. What is the purpose of allocation? To what depth in the system hierarchical structure should allocation be accomplished? How does it impact system design (if at all)?
18. Briefly define "synthesis," "analysis," and "evaluation." How are they related (if at all)?
19. Describe what is meant by a "design dependent parameter" (DDP). How are DDP's determined?
20. What is the purpose of the formal design review? What are some of the benefits derived from the conduct of design reviews? Describe some of the negative aspects.