PART I

Foundations of Systems Engineering

Part I provides a multi-dimensional framework that interrelates the basic principles of systems engineering, and helps to organize the areas of knowledge that are required to master this subject. The dimensions of this framework include:

a) A hierarchical model of the structure of complex systems
b) A set of commonly occurring functional and physical system building blocks
c) A systems engineering life cycle, integrating the features of the DoD, ISO/IEC and NSPE models
d) Four basic steps of the systems engineering method that are iterated during each phase of the life cycle
e) Three capabilities differentiating project management, design specialization and systems engineering
f) Three different technical orientations of a scientist, a mathematician and an engineer, and how they combine in the orientation of a systems engineer
g) A concept of "materialization" that measures the degree of transformation of a system element from a requirement to a fully implemented part of a real system.

The origins and characteristics of modern complex systems, and systems engineering as a profession are the main subjects of Chapter 1. The chapter also defines the "systems engineering viewpoint" and how it differs from the viewpoints of technical specialists and project managers.

The hierarchical model of a complex system and the key building blocks from which it is constituted are developed in Chapter 2. This framework is used to define the breadth and depth of the knowledge domain of systems engineers in terms of the system hierarchy.

The concept of the systems engineering life cycle, which sets the framework for the evolution of a complex system from a perceived need to operation and disposal, is derived in Chapter 3. This framework is systematically applied throughout Parts II, III, and IV of the book, each part addressing the key responsibilities of system engineering in the corresponding phase of the life cycle.

The key parts that system engineering plays in the management of systems development projects are described in Chapter 4. It defines the basic organization and the planning documents of a system development project, with a major emphasis on the management of program risks.

Chapter 1

Systems Engineering and the World of Modern Systems

1.1 WHAT IS SYSTEMS ENGINEERING?

There are many ways in which to define systems engineering. For the purposes of this book, we will use the following definition:

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

The words in this definition are used in their conventional meanings, as described further below.

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

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

The above definitions of "systems engineering" and "system" are not represented as being unique or superior to those used in other textbooks, each of which defines them somewhat differently; there is not even unanimity whether the former is spelled "system engineering" or "systems engineering." In fact, Eberhardt Rechtin (1997), in his book *Systems Architecting—Creating and Building Complex Systems*, uses the term "systems architecting" in virtually the same context as "systems engineering." For these reasons, in order to avoid any potential misunderstanding, the meaning of these terms **as used in this book** is defined at the very outset, before going on to the more important subjects of the responsibilities, problems, activities, and tools of systems engineering.

Systems Engineering and Traditional Engineering Disciplines

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

1. Systems engineering is focused on the system as a whole—it emphasizes its total operation. It looks at the system from the outside, that is, at its interactions with other systems and the environment, as well as from the inside. It is concerned not only with the engineering design of the system but also with external factors, which can significantly constrain the design. These include the identification of customer needs, the system operational environment, interfacing systems, logistic support requirements, the capabilities of operating personnel and such other factors as must be correctly reflected in system requirements documents and accommodated in the system design.

2. While the primary purpose of systems engineering is to **guide**, this does not mean that systems engineers do not themselves play a key role in system design. On the contrary, they are responsible for leading the formative (Concept Development) stage of a new system development, which culminates in the functional design of the system reflecting the needs of the user. Important design decisions at this stage cannot be based entirely on quantitative knowledge, as they are for the traditional engineering disciplines, but rather must often rely on qualitative judgments balancing a variety of incommensurate quantities and utilizing experience in a variety of disciplines, especially when dealing with new technology.

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

Systems Engineering and Project Management

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

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

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

1.2 ORIGINS OF SYSTEMS ENGINEERING

No particular date can be associated with the origins of systems engineering. Systems engineering principles have been practiced at some level since the building of the pyramids and probably before. (The Bible records that Noah's Ark was built to a system specification.)

The recognition of systems engineering as a distinct activity is often associated with the effects of World War II, and especially the 1950s and 1960s when a number of textbooks were published that first identified systems engineering as a distinct discipline and defined its place in the engineering of systems. More generally, the recognition of systems engineering as a unique activity evolved as a necessary corollary to the rapid growth of technology, and its application to major military and commercial operations during the second half of the twentieth century.

The global conflagration of World War II provided a tremendous spur to the advancement of technology in order to gain a military advantage for one side or the other. The development of high performance aircraft, military radar, the proximity fuse, the German V1 and V2 missiles, and especially the atomic bomb required revolutionary advances in the application of energy, materials, and information. These systems were complex, combining multiple technical disciplines, and their development posed engineering challenges significantly beyond those that had been presented by their more conventional predecessors. Moreover, the compressed development time schedules imposed by wartime imperatives necessitated a level of organization and efficiency that required new approaches in program planning, technical coordination, and engineering management. Systems engineering, as we know it today developed to meet these challenges.

During the Cold War of the 1950s, 1960s, and 1970s, military requirements continued to drive the growth of technology in jet propulsion, control systems, and materials. However, another development, that of solid-state electronics, has had perhaps a more profound effect on technological growth. This to a large extent made possible the still evolving "information age," in which computing and communications are extending the power and reach of systems far beyond their previous limits. Particularly significant in this connection is the development of the digital computer and the associated software technology driving it, which increasingly is leading to the replacement of human control of systems by automation. Computer control is qualitatively increasing the complexity of systems, and is a particularly important concern of systems engineering.

The relation of modern systems engineering to its origins can be best understood in terms of three basic factors:

1. **Advancing technology**, which provides opportunities for increasing system capabilities, but introduces development risks that require systems engineering management.
2. **Competition**, whose various forms require seeking superior (and more advanced) system solutions through the use of system-level trade-offs among alternative approaches.

3. **Specialization**, which requires the partitioning of the system into building blocks corresponding to specific product types that can be designed and built by specialists, and strict management of their interfaces and interactions.

These factors are discussed in the following paragraphs.

Advancing Technology: Risks

The explosive growth of technology in the latter half of the twentieth century has been the single largest factor in the emergence of systems engineering as an essential ingredient in the engineering of complex systems. Advancing technology has not only greatly extended the capabilities of earlier systems, such as aircraft, telecommunications, and power plants, but has created entirely new systems such as those based on jet propulsion, satellite communications and navigation, and a host of computer-based systems for manufacturing, finance, transportation, entertainment, and other products and services. Advances in technology have not only affected the nature of products, but have fundamentally changed the way they are engineered, produced, and operated.

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

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

The systems engineering approach to the early application of new technology is embodied in the practice of "risk management." Risk management is a process of dealing with calculated risks through a process of analysis, development, test, and engineering oversight. It is described more fully in Chapter 4.

An excellent example of dealing with risk was the U.S. program to put a man on the Moon. To reach this goal, it was necessary to extend the limits of technology in many areas, such as rocket propulsion, life support, automatic navigation, flight control, atmospheric re-entry and recovery, and many others. In particular, the reliability of the total system throughout its operating modes had to be orders of magnitude better than the prior state of the art.

The program succeeded because of an emphasis on safety far beyond any prior practice, using parallel development approaches, multiple levels of backup, intensive training, special failure analysis methods, and exhaustive testing of components and procedures. The result was that not only was the mission spectacularly successful, but that no lives were lost on any of the space flights and Moon landings. It was the reliability/safety problem that forced the Soviets to stop pursuing their own Moon mission.

Dealing with risks is one of the essential tasks of systems engineering, requiring a broad knowledge of the total system and its critical elements. In particular, systems engineering is central to the decision of how to achieve the best balance of risks, that is, which system elements should best take advantage of new technology and which should be based on proven components, and how the risks incurred should be reduced by development and testing.

The Growth of Automation The development of the digital computer and software technology noted earlier deserves special mention. This development has led to an enormous increase in the automation of a wide array of control functions for use in factories, offices, hospitals, and throughout society. Automation, most of it being concerned with information processing hardware and software, is the fastest growing and most powerful single influence on the engineering of modern systems.

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

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

Competition: Trade-offs

Competitive pressures on the system development process occur at several different levels. In the case of defense systems, a primary drive comes from the increasing military capabilities of potential adversaries, which correspondingly decrease the effectiveness of systems designed to defeat them. Such pressures eventually force a development program to redress the military balance with a new and more capable system or a major upgrade of an existing one.

Another source of competition comes with the use of competitive contracting for the development of new system capabilities. Throughout the competitive period, which may last through the initial engineering of a new system, each contractor seeks to devise the most cost-effective program to provide a superior product.

In developing a commercial product, there are nearly always other companies that compete in the same market. In this case, the objective is to develop a new market or obtain an increased market share by producing a superior product ahead of the competition, with an edge that will maintain a lead for a number of years. The above approaches nearly always apply the most recent technology in an effort to gain a competitive advantage.

Securing the large sums of money needed to fund the development of a new complex system also involves competition on quite a different level. In particular, both government agencies and industrial companies have many more calls on their resources than they can accommodate, and hence must carefully weigh the relative payoff of proposed programs. This is a primary reason for requiring a phased approach in new system development efforts, through the requirement for justification and formal approval to proceed with the increasingly expensive later phases. The results of each phase of a major development must convince decision makers that the end objectives are highly likely to be attained within the projected cost and schedule.

On a still different basis, the competition among the essential characteristics of the system is always a major consideration in its development. For example, there is always competition between performance, cost, and schedule, and it is impossible to optimize all three at once. Many programs have failed by striving to achieve levels of performance that proved unaffordable. Similarly, the various performance parameters of a vehicle, such as speed and range, are not independent of one another—efficiency of most vehicles, and hence their operating range, decreases at higher speeds. Thus, it is necessary to examine alternatives in which these characteristics are allowed to vary, and select the combination that best balances their values for the benefit of the user.

All of the forms of competition exert pressure on the system development process to produce the best performing, most affordable system, in the least possible time. The process of selecting the most desirable approach requires the examination of numerous potential alternatives and the exercise of a breadth of technical knowledge and judgment that only experienced systems engineers possess. This is often referred to as "trade-off analysis" and forms one of the basic practices of systems engineering.

Specialization: Interfaces

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

Chapter 2 describes the kind of functional and physical building blocks that make up most modern systems.

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

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

The convenience of subdividing complex systems into individual building blocks has a price—that of integrating these disparate parts into an efficient, smoothly operating system. Integration means that each building block fits perfectly with its neighbors and with the external environment with which it comes into contact. The "fit" must be not only physical, but also functional, that is, its design will both affect the design characteristics and behavior of other elements, and will be affected by them, to produce the exact response that the overall system is required to make to inputs from its environment. The physical fit is accomplished at inter-component boundaries called **interfaces**. The functional relationships are called **interactions**.

The task of analyzing, specifying, and validating the component interfaces with each other and with the external environment is beyond the expertise of the individual design specialists and is the province of the systems engineer. Chapter 2 discusses further the importance and nature of this responsibility.

A direct consequence of the subdivision of systems into their building blocks is the concept of modularity. Modularity is a measure of the degree of mutual independence of the individual system components. An essential goal of systems engineering is to achieve a high degree of modularity—to make interfaces and interactions as simple as possible for efficient manufacture, system integration, test, operational maintenance, reliability, and ease of in-service upgrading. The process of subdividing a system into modular building blocks is called "functional allocation" and is another basic tool of systems engineering.

1.3 EXAMPLES OF SYSTEMS REQUIRING SYSTEMS ENGINEERING

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

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

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

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

Examples of Complex Engineered Systems

To illustrate the types of systems that fit within the above definition, Tables 1-1 and 1-2 list 10 modern systems and their principal inputs, processes, and outputs.

It has been noted that a system consists of a multiplicity of elements, some of which may well themselves be complex and deserve to be considered as

TABLE 1-1 Examples of Engineered Complex Systems: Signal and Data Systems

System	Inputs	Process	Outputs
Weather satellite	Images	Data storage Transmission	Encoded images
Terminal air traffic control system	Aircraft beacon responses	Identification Tracking	Identity Air tracks Communications
Truck location system	Cargo routing requests	Map tracing Communication	Routing info Delivered cargo
Airline reservation system	Travel requests	Data management	Reservations Tickets
Clinical information system	Patient ID Test records Diagnoses	Information management	Patient status History Treatment

systems in their own right. For example, a telephone-switching substation can well be considered as a system, with the telephone network considered as a "supersystem." Such issues will be discussed more fully in Chapter 2, to the extent necessary for the understanding of systems engineering.

TABLE 1-2 Examples of Engineered Complex Systems: Material and Energy Systems

System	Inputs	Process	Outputs
Passenger aircraft	Passengers Fuel	Combustion Thrust Lift	Transported passengers
Modern harvester combine	Grain field Fuel	Cutting Threshing	Harvested grain
Oil refinery	Crude oil Catalysts Energy	Cracking Separation Blending	Gasoline Oil products Chemicals
Auto assembly plant	Auto parts Energy	Manipulation Joining, Finishing	Assembled auto
Electric power plant	Fuel Air	Power generation, regulation	Electric AC power

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

An automobile is also an example of a large class of systems that require active interaction (control) by a human operator. To some degree all systems require such interaction, but in this case continuous control is required. In a very real sense, the operator (driver) functions as an integral part of the overall automobile system, serving as the steering feedback element that detects and corrects deviations of the car's path on the road. The design must therefore address as a critical constraint the inherent sensing and reaction capabilities of the operator, in addition to a range of associated human–machine interfaces such as the design and placement of controls and displays, seat position, and so on. Also, while the passengers may not function as integral elements of the auto steering system, their associated interfaces (e.g., weight, seating and viewing comfort, safety, etc.) must be carefully addressed as part of the design process. Nevertheless, since automobiles are developed and delivered without the human element, for purposes of systems engineering they may be addressed as systems in their own right.

1.4 SYSTEMS ENGINEERING VIEWPOINT

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

The essence of the systems engineering viewpoint is exactly what it implies—making the central objective the system as a whole and the success of its mission. This, in turn, means the subordination of individual goals and attributes in favor of those of the overall system. The systems engineer is always the advocate of the total system in any contest with a subordinate objective.

A Successful System

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

Successful system development requires the use of a consistent well-understood systems engineering approach within the organization, which involves the exercise of systematic and disciplined direction, with extensive planning, analysis, reviews, and documentation. Just as important, however, is a side of systems engineering that is often overlooked, namely, innovation. For a new complex system to compete successfully in a climate of rapid technological change and to retain its edge for many years of useful life, its key components must use some of the latest technological advances. These will inevitably introduce risks, some known and others as yet unknown, which in turn will entail a significant development effort to bring each new design approach to maturity and later to validate the use of these designs in system components. Selecting the most promising technological approaches, assessing the associated risks, rejecting those for which the risks outweigh the potential payoff, planning critical experiments, and deciding on potential fallbacks are all primary responsibilities of systems engineering. Thus, the systems engineering viewpoint includes a combination of risk-taking and risk-mitigation.

The "Best" System

In characterizing the systems engineering viewpoint, two oft-stated maxims are "the best is the enemy of the good" and "systems engineering is the art of the good enough." These statements may be misleading if they are interpreted to imply that systems engineering means settling for second best. On the contrary, systems engineering does seek the "best" possible system, which, however, is often not the one that provides the best performance. The seeming inconsistency comes from what is referred to by "best." The popular maxims use the terms "best" and "good enough" to refer to system performance, whereas systems engineering views performance as only one of several critical attributes; equally important ones are affordability, timely availability to the user, ease of maintenance, and adherence to an agreed-upon development completion schedule. Thus, the systems engineer seeks the **best balance** of the critical system attributes from the standpoint of the success of the development program and of the value of the system to the user.

The interdependence of performance and cost can be understood in terms of the law of diminishing returns. Assuming a particular technical approach to the achievement of a given performance attribute of a system under development, Figure 1-1a is a plot of a typical variation in the level of performance of a

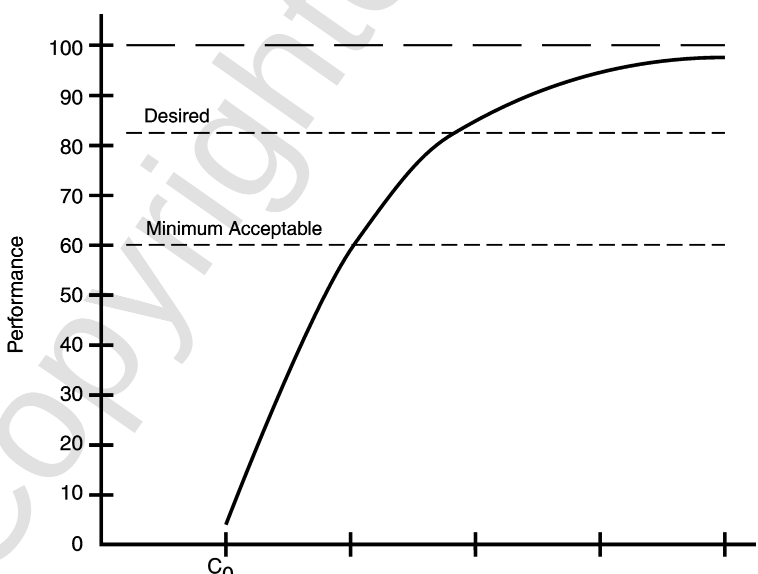

Fig. 1-1a Performance vs. cost.

hypothetical system component as a function of the cost of the expended development effort. The upper horizontal line represents the theoretical limit in performance inherent in the selected technical approach. A more sophisticated approach might produce a higher limit, but at a higher cost. The dashed horizontal lines represent the minimum acceptable and the desirable performance levels.

The curve of Figure 1-1a originates at C_0, which represents the cost of just achieving any significant performance. The slope is steep at first, becoming less steep as the performance asymptotically approaches the theoretical limit. This decreasing slope, which is a measure of the incremental gain in performance with an increment of added cost, illustrates the law of diminishing returns that applies to virtually all developmental activities.

An example of the above general principle is the development of an automobile with a higher maximum speed. A direct approach to such a change would be to use an engine that generates greater power. Such an engine would normally be larger, weigh more, and use gas less efficiently. Also, an increase in speed will result in greater air drag, which would require a disproportionately large increase in engine power to overcome. If it was required to maintain fuel economy and retain vehicle size and weight as nearly as possible, it would be necessary to consider using or developing a more advanced engine, improving body streamlining, using special lightweight materials, and otherwise seeking to offset the undesirable side effects of increasing vehicle speed. All of the above factors would escalate the cost of the modified automobile, with the incremental costs increasing as the ultimate limits of the several technical approaches are approached. It is obvious, therefore, that a balance must be struck well short of the ultimate limit of any performance attribute.

An approach to establishing such a balance is illustrated in Figure 1-1b. This figure plots performance divided by cost against cost (i.e., y/x vs. x from Fig. 1-1a). This performance-to-cost ratio is equivalent to the concept of cost-effectiveness. It is seen that this curve has a maximum, beyond which the gain in effectiveness diminishes. This shows that the performance of the "best" overall system is likely to be close to that where the performance/cost ratio peaks, provided this point is significantly above the minimum acceptable performance.

A Balanced System

One of the dictionary definitions of the word "balance" that is especially appropriate to system design is "a harmonious or satisfying arrangement or proportion of parts or elements, as in a design or a composition." An essential function of systems engineering is to bring about a balance among the various components of the system, which, it was noted earlier, are designed by engineering specialists, each intent on optimizing the characteristics of a particular component. This is often a daunting task, as illustrated in

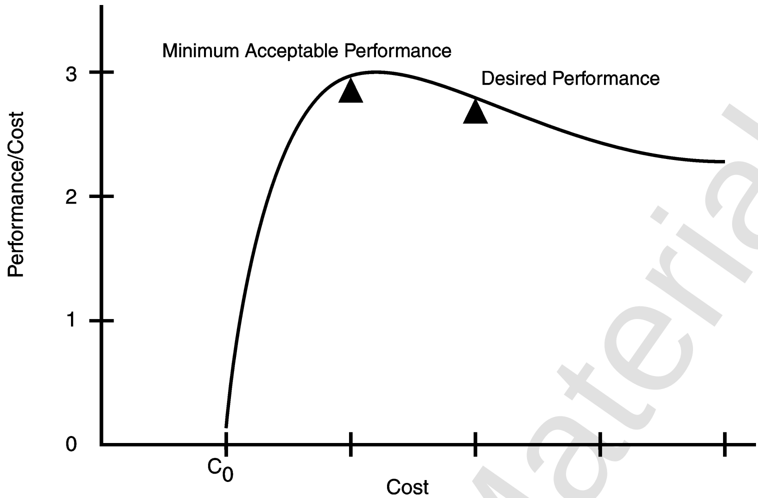

Fig. 1-1b Performance/Cost vs. cost.

Figure 1-2. The figure is an artist's conception of what a guided missile might look like if it were designed by a specialist in one or another guided missile component technology. While the cartoons may seem fanciful, they reflect a basic truth, that is, that design specialists will seek to optimize the particular aspect of a system that they best understand and appreciate. In general it is to be expected that, while the design specialist does understand that the system is a group of components that in combination provide a specific set of capabilities, during system development the specialist's attention is necessarily focused on those issues that most directly affect his or her own area of technical expertise and assigned responsibilities.

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

A Balanced Viewpoint

A system view thus connotes a focus on "balance"—ensuring that no system attribute is allowed to grow at the expense of an equally important or more important attribute, for example, greater performance at the expense of

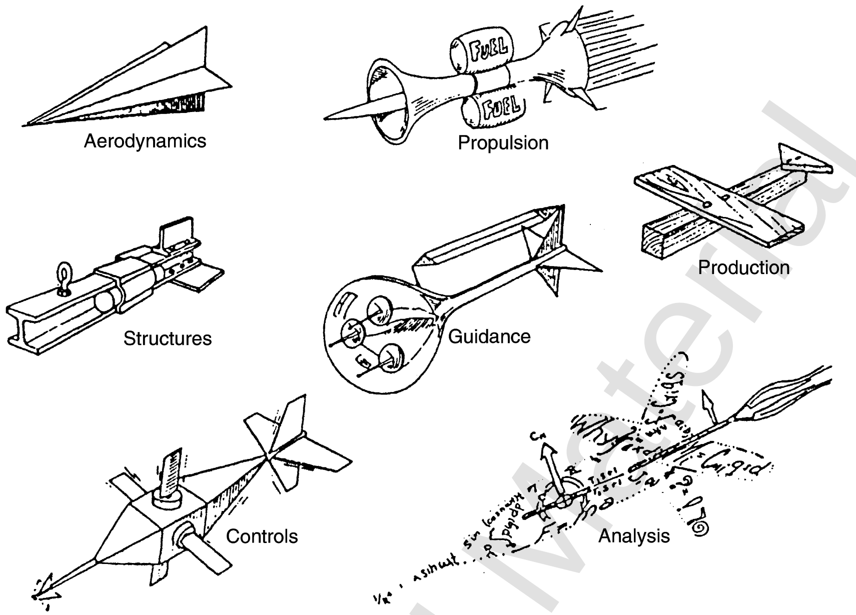

Fig. 1-2 The ideal missile design from the viewpoint of various specialists.

acceptable cost, high speed at the expense of adequate range, or high throughput at the expense of excessive errors. Since virtually all critical attributes are interdependent, a proper balance must be struck in essentially all system design decisions. These characteristics are typically incommensurable, as in the above examples, so that the judgment of how they should be balanced must come from a deep understanding of how the system works. It is such judgment that systems engineers have to exercise every day, and they must be able to think at a level that encompasses all of the system characteristics.

The viewpoint of the systems engineer calls for a different combination of skills and areas of knowledge than those of a design specialist or a manager. Figure 1-3 is intended to illustrate the general nature of these differences. Using the three dimensions to represent technical depth, technical breadth, and management depth, respectively, it is seen that the design specialist may have limited managerial skills but has a deep understanding in one or a few related areas of technology. Similarly, a project manager needs to have little depth in any particular technical discipline, but must have considerable breadth and capability to manage people and technical effort. A systems engineer, on the other hand, requires significant capabilities in all three compo-

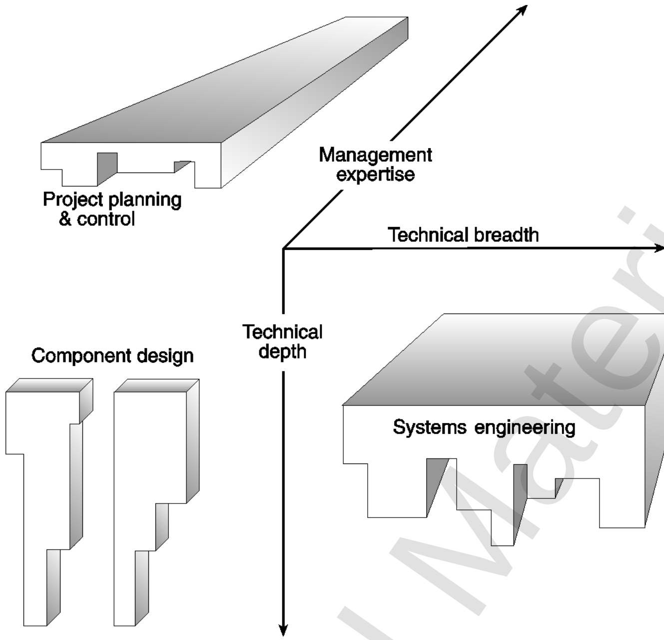

Fig. 1-3 The dimensions of design, systems engineering, and project planning and control.

nents, representing the balance needed to span the needs of a total system effort. In that sense the systems engineer operates in more dimensions than do his or her co-workers.

1.5 SYSTEMS ENGINEERING AS A PROFESSION

Despite the increasing prevalence of complex systems in modern society, and the essential role of systems engineering in the development of systems, systems engineering as a profession has not been widely recognized. Its primary recognition has come in companies specializing in the development of large systems. A number of these have established departments of systems engineering, and have classified those engaging in the process as systems engineers.

Perhaps the main reason for the slowness of recognition of systems engineering as a career is the fact that it does not correspond to the traditional academic engineering disciplines. Engineering disciplines are built on quantitative relationships, obeying established physical laws, and measured properties of materials, energy, or information. Systems engineering, on the other hand, deals mainly with problems for which there is incomplete knowledge, whose variables do not obey known equations, and where a balance must be made among conflicting objectives involving incommensurate attributes. The absence of a quantitative knowledge base has effectively inhibited the establishment of systems engineering as a unique discipline.

Despite those obstacles, the recognized need for systems engineering in industry and government has spurred the establishment of a number of academic programs offering master's degrees in system(s) engineering, mainly as components of part-time continuing education. A few universities are offering undergraduate degrees in systems engineering as well.

There has also been a relatively recent recognition of systems engineering as a profession in the formation of a professional society, the International Council on Systems Engineering (INCOSE), one of whose primary objectives is the promotion of systems engineering education, and the recognition of systems engineering as a professional career.

Orientation of Technical Professionals

The special relationship of systems engineers with respect to other disciplines can be better understood when it is realized that technical people not only engage in widely different professional specialties, but their intellectual objectives, interests, and attitudes, which represent their technical orientations, can also be widely divergent. The typical scientist is dedicated to understanding the nature and behavior of the physical world. The scientist asks the questions "Why?" and "How?" The mathematician is usually primarily concerned with deriving the logical consequences of a set of assumptions, which may be quite unrelated to the real world. The mathematician develops the proposition "If A, then B." Usually, the engineer is mainly concerned with creating a useful product. The engineer exclaims "Voila!"

These orientations are quite different from one another, which accounts for why technical specialists are focused on their own aspects of science and technology. However, in most professionals those orientations are not absolute; in many cases the scientist may need some engineering to construct an apparatus, and the engineer may need some mathematics to solve a control problem. So, in the general case the orientation of a technical professional might be modeled by a sum of three orthogonal vectors, each representing the extent of the individual's orientation being in science, mathematics, or engineering.

To represent the above model, it is convenient to use a diagram designed to show the composition of a mixture of three components. Figure 1-4a is such a diagram in which the components are science, mathematics, and engineering. A point at each vertex represents a mixture with 100% of the corresponding component. The composition of the mixture marked by the small triangle in the figure is obtained by finding the percentage of each component by projecting a line parallel to the baseline opposite each vertex to the scale radiating from the vertex. This process gives intercepts of 70% science, 20% mathematics, and 10% engineering for the orientation marked by the triangle.

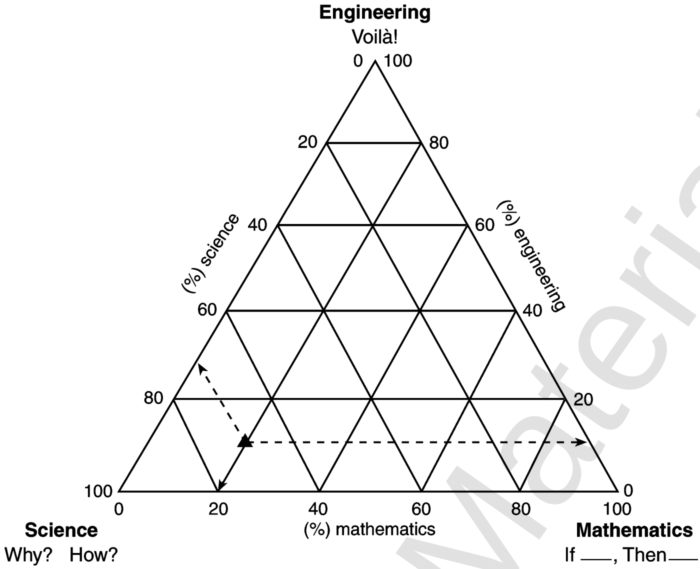

Fig. 1-4a Technical orientation phase diagram.

Because the curricula of technical disciplines tend to be concentrated in specialized subjects, most students graduate with limited general knowledge. In Figure 1-4b, the circles representing the orientation of individual graduates are seen to be concentrated in the corners, reflecting their high degree of specialization.

The tendency of professional people to polarize into diverse specialties and interests tends to be accentuated after graduation, as they seek to become recognized in their respective fields. Most technical people resist becoming generalists for fear they will lose or fail to achieve positions of professional leadership and the accompanying recognition. This specialization of professionals inhibits technical communication between them; the language barrier is bad enough, but the differences in basic objectives and methods of thought are even more serious. The solution of complex interdisciplinary problems has had to depend on the relatively rare individuals who, for one reason or another, after establishing themselves in their principal profession, have become interested and involved in solving system problems and have learned to work jointly with specialists in various other fields.

The occasional evolution of technical specialists into systems engineers is symbolized in Figure 1-4b by the arrows directed from the vertices toward the center. The small black triangle corresponds to such an evolved individual whose orientation is 30% science, 50% engineering, and 20% mathematics, a balance that would be effective in the type of problem solving with which

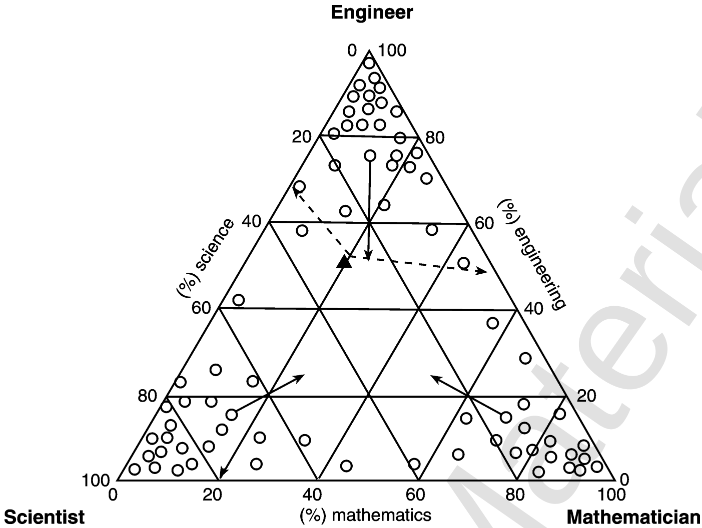

Fig. 1-4b Technical orientation population density distribution.

a systems engineer is typically involved. It is the few individuals who evolve into systems engineers or system architects who become the technical leaders of system development programs.

The Challenge of Systems Engineering

An inhibiting factor in becoming a professional systems engineer is that it represents a deviation from a chosen established discipline to a more diverse, complicated and uncertain professional practice. It requires the investment of time and effort to an extensive broadening of the engineering base, as well as learning communication and management skills, a much different orientation from the individual's original professional choice.

For the above reasons, an engineer considering a career in systems engineering may come to the conclusion that the road is difficult, not obviously rewarding, and altogether not very attractive. It is clear that a great deal must be learned and that the educational experience in a traditional engineering discipline will be of only limited use; that there are few tools and few quantitative relationships to help make decisions. Instead, the issues are ambiguous and abstract, defying definitive solutions. There may appear to be little opportunity for individual accomplishment and even less for individual recognition. For a systems engineer, success is measured by the apparent absence of program difficulties rather than by spectacular successes.

What then is the Attraction of Systems Engineering? Why Do Very Good People Devote Their Lives to this Pursuit?

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

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

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

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

Attributes and Motivations of Systems Engineers

In order to identify candidates for systems engineering careers, it is useful to examine the characteristics that may be useful to distinguish people with a talent for systems engineering from those who are not likely to be interested or successful in that discipline. Those likely to become talented systems engineers would be expected to have done well in mathematics and science in college. In fact, as demonstrated during World War II, many physics or chemistry graduates have developed into excellent systems engineers.

A systems engineer will be required to work in a multidisciplinary environment and grasp the essentials of related disciplines. It is here that an aptitude for science and engineering helps a great deal, because it makes it much easier and less threatening for individuals to learn the essentials of new disciplines. It is not so much that they require knowledge of higher mathematics, but rather those who have a limited mathematical background tend to lack confidence in their ability to grasp subjects that inherently contain mathematical concepts.

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

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

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

1.6 THE POWER OF SYSTEMS ENGINEERING

If power is measured by authority over people or money, then systems engineers would appear to have little power as members of the system development team. However, if power is measured by the influence over the design of the system and its major characteristics, and over the success or failure of the system development, then systems engineers can be more powerful than project managers. The sources of this power come from their knowledge, skills, and attitude. Each of these is discussed in the following paragraphs.

The Power of Multidisciplinary Knowledge

A major system development project is a veritable "Tower of Babel." There are literally dozens of specialists in different disciplines whose collective efforts are necessary to develop and produce a successful new system. Each group of specialists has its own language, making up for the imprecision of the English language with a rich set of acronyms, which convey a very specific meaning but are unintelligible to those outside the specialty. The languages, in turn, are backed up by knowledge bases, which the specialists use to ply their trade. These knowledge bases contain descriptions of the different materials peculiar to each discipline, as well as bodies of relationships, many of them expressed in mathematical terms, that enable the specialists to compute various characteristics of their components on the basis of design assumptions. These knowledge bases are also foreign to those outside the discipline.

Such a collection of multi-tongued participants could never succeed in collectively developing a new system by themselves, just as the citizens of

Babylon could never build their tower. It is the systems engineers who provide the linkages that enable these disparate groups to function as a team. The systems engineers accomplish this feat through the power of multidisciplinary knowledge. This means that they are sufficiently literate in the different disciplines involved in their system that they can understand the languages of the specialists, appreciate their problems, and are able to interpret the necessary communications for their collective endeavor. Thus, they are in the same position as a linguist in the midst of a multinational conference, with people speaking in their native tongues. Through the ability to understand different languages comes the capability to obtain cooperative effort from people who would otherwise never be able to achieve a common objective. This capability enables systems engineers to operate as leaders and troubleshooters, solving problems that no one else is capable of solving. It truly amounts to a power that gives systems engineers a central and decisive role to play in the development of a system.

It is important to note that the depth of interdisciplinary knowledge, which is required to interact effectively with specialists in a given field, is a very small fraction of the depth necessary to work effectively in that field. The number of new acronyms that one has to learn in a given technical area is nearer to a dozen of the more frequently used ones than to a hundred. It also turns out that once one gets past the differences in semantics, there are many common principles in different disciplines and many similar relationships. For instance, the equation used in communications, connecting signal, noise, antenna gain, receiver sensitivity, and other factors, is directly analogous to a similar relationship in acoustics.

These facts mean that a systems engineer does not need to spend a lifetime becoming expert in associated disciplines, but rather can accumulate a working knowledge of related fields through selected readings, and more particularly, discussion with colleagues knowledgeable in each field. The important thing is to know which principles, relationships, acronyms, and the like are important at the system level and which are details. The power of multidisciplinary knowledge is so great that to a systems engineer the effort required to accumulate it is well worth the learning time.

The Power of Approximate Calculation

The practice of systems engineering requires another talent besides multidisciplinary knowledge. The ability to carry out "back of the envelope" calculations to obtain a "sanity check" on the result of a complex calculation or test is of inestimable value to the systems engineer. In a few cases, this can be done intuitively on the basis of past experience, but more frequently it is necessary to make a rough estimate to ensure that a gross omission or error has not been committed. Most successful systems engineers have the ability, using first principles, to apply basic relationships, such as the communications equation or other simple calculation, to derive an order of magnitude result to serve as a check. This is particularly important if the results of the calculation or experiment turn out very differently from what had been originally expected.

When the "sanity check" does not confirm the results of a simulation or experiment, it is appropriate to go back to make a careful examination of the assumptions and conditions on which the latter were based. As a matter of general experience, more often than not such examinations reveal an error in the conditions or assumptions under which the simulation or experiment was conducted.

The Power of Skeptical Positive Thinking

The above seemingly contradictory title is meant to capture an important characteristic of successful systems engineering. The skeptical part is important to temper the traditional optimism of the design specialist regarding the probability of success of a chosen design approach. It is the driving force for the insistence of validation of the approach selected at the earliest possible opportunity.

The other dimension of skepticism, which is directly related to the characteristic of positive thinking, refers to the reaction in the face of failure or apparent failure of a selected technique or design approach. Many design specialists who encounter an unexpected failure are plunged into despair. The systems engineer on the other hand cannot afford the luxury of hand wringing, but must have first of all a healthy skepticism of the conditions under which the unexpected failure occurred. Often it is found that these conditions did not properly test the system. When the test conditions are shown to be valid, the systems engineer must set about finding ways to circumvent the cause of failure. The conventional answer that the failure must require a new start along a different path, which in turn will lead to major delays and increases in program cost, is simply not acceptable unless heroic efforts to find an alternative solution do not succeed. This is where the power of multidisciplinary knowledge permits the systems engineer to look for alternative solutions in other parts of the system, which may take the stress off the particular component whose design proved to be faulty.

The characteristic of positive thinking is absolutely necessary in both the systems engineer and project manager so that they are able to generate and sustain the confidence of the customer and of company management, as well as the members of the design team. Without the "can-do" attitude, the esprit de corps and productivity of the project organization is bound to suffer.

1.7 SUMMARY

Systems engineering has the function of guiding the engineering of a complex system.

A system is a set of interrelated components working together toward a common objective.

A complex engineered system (as defined in this book) is:

Composed of a multiplicity of intricately interrelated diverse elements.
Requires systems engineering to lead its development.

Systems engineering differs from traditional disciplines in that it:

Is focused on the system as a whole
Is concerned with customer needs and operational environment
Leads system conceptual design
Bridges traditional engineering disciplines and gaps between specialties.

Systems engineering is an integral part of project management that:

Plans and guides the engineering effort.

Modern systems engineering originated because:

Advancing technology brought risks and complexity
Competition required expert risk-taking
Specialization required bridging disciplines and interfaces.

Examples of engineered complex systems include:

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

The systems engineering viewpoint is focused on producing a successful system and:

Understands user's needs and focuses on their satisfaction
Balances superior performance with affordability and timeliness
Applies new technology and manages resulting risks
Seeks the best overall balance among conflicting objectives

Bridges specialized disciplines and components, focusing on the total system

Requires a consistent systems engineering approach in the organization.

Design is one-dimensional: it has great technical depth, but little technical breadth and little management expertise.

Planning and control is two-dimensional: it has great management expertise, but moderate technical breadth and small technical depth.

Systems engineering is three-dimensional: it has great technical breadth, as well as moderate technical depth and management expertise.

Systems engineering is now recognized as a profession, and has:

An increasing role in government and industry

Numerous graduate (and some undergraduate) degree programs

The International Council on Systems Engineering (INCOSE).

Technical professionals have specific technical orientations:

Technical graduates tend to be highly specialized

Only a few become interested in interdisciplinary problems—it is these individuals who often become systems engineers.

The systems engineering profession is difficult but rewarding, featuring:

The solution of abstract and ambiguous problems

The attractions of technical challenge and pivotal program role.

A successful systems engineer should be:

A good problem solver, and should welcome challenges

Well grounded technically, with broad interests

Analytical and systematic, but also creative

A superior communicator, with leadership skills.

Systems engineering is a powerful discipline, requiring:

A multidisciplinary knowledge, integrating diverse system elements

The ability to perform approximate calculations of complex phenomena, thereby providing ‘‘sanity checks’’

Skeptical positive thinking is a prerequisite to prudent risk taking.

PROBLEMS

1.1 Write a paragraph explaining what is meant by the statement "Systems engineering is focused on the system as a whole." State what characteristics of a system you think this statement implies, and how they apply to systems engineering.

1.2 Discuss the difference between engineered complex systems and complex systems that are not engineered. Give three examples of the latter. Can you think of systems engineering principles that can also be applied to non-engineered complex systems?

1.3 For each of four of the following areas, list and explain how at least two major technological advances/breakthroughs occurring since 1970 that have radically changed them. In each case explain how the change was effected.

- **(a)** Transportation
- **(b)** Communication
- **(c)** Financial management
- **(d)** Manufacturing
- **(e)** Distribution and sales
- **(f)** Entertainment
- **(g)** Medical care

1.4 What characteristics of an airplane would you attribute to the system as a whole rather than to a collection of its parts? Explain why.

1.5 List four pros and cons (two of each) of incorporating some of the latest technology into the development of a new complex system. Give a specific example of each.

1.6 What is meant by the term "modularity?" What characteristics does a modular system possess? Give a specific example of a modular system and identify the modules.

1.7 Figure 1-1 illustrates the law of diminishing returns in seeking the optimum system (or component) performance and hence the need to "balance" the performance against the cost. Give examples of two pairs of characteristics other than performance vs. cost where optimizing one frequently competes with the other, and briefly explain why they do.

1.8 The section on the Orientation of Technical Professionals uses three components to describe this characteristic: science, mathematics, and engineering. Using this model, describe what you think your orientation is in terms of x% science, y% mathematics, and z% engineering. Note that your "orientation" does not measure your knowledge or expertise, but rather your interest and method of thought. Consider your relative interest in discovering new truths, finding new relationships, or building new things and making them work. Also, try to remember what your orientation was when you graduated from college, and explain how and why it has changed.

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