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INTRODUCTION TO SYSTEM ENGINEERING

This text deals with "system engineering," or the orderly process of bringing a system into being. A "system" comprises a complex combination of resources (in the form of human beings, materials, equipment, software, facilities, data, information, services, etc.), integrated in such a manner as to fulfill a designated need. A system is developed to accomplish a specific function, or series of functions, and may be classified as a *natural system, human-made system, physical system, conceptual system, closed-loop system, open-loop system, static system, dynamic system,* and so on. This text addresses primarily human-made systems that are physical, dynamic, and open-loop in structure.

A system may vary in form, fit, and/or function. One may be dealing with a group of aircraft accomplishing a mission at a specific geographical location, a communication network for distributing information on a worldwide basis, a power distribution capability involving waterways and electrical power generating units, a manufacturing facility that produces x products in a designated time frame, a health care network serving a given community, or a small vehicle providing the transportation of certain cargo from one location to another. A system may be contained within some form of hierarchy and may be broken down into subsystems and various smaller components, the level of detail being dependent on the function(s) to be performed.

This objectives of this chapter are to address the subject of "systems" in general, to define some terms and the characteristics of systems, to identify the need for and the basic requirements for initially bringing systems into being and for later evaluating systems in terms of their effectiveness in a user's environment, and to provide an introduction to "system engineering" and the associated management activities inherent in the system engineering process.

1.1 THE CURRENT ENVIRONMENT

Having a good understanding of the overall "environment" is certainly a prerequisite to the successful implementation of system engineering principles and concepts. Although individual perceptions will differ, depending on what various people observe, there are a number of trends that appear to be significant. These trends, presented in Figure 1.1, are all interrelated and need to be addressed "in total" and as an integrated set in determining the requirements for systems and in the implementation of the system engineering process:

1. *Constantly changing requirements.* The requirements for new systems are frequently changing because of the dynamic conditions worldwide, changes in mission thrusts and priorities, and the continuous introduction of new technologies.

2. *More emphasis on "systems."* There is greater emphasis on total *systems* versus the *components* of a system. One must look at the system "in total," and throughout its entire life cycle, to ensure that the functions that need to be performed are being accomplished in an effective and efficient manner.

3. *Increasing system complexities.* It appears that the structures of many systems are becoming more complex with the introduction of evolving new technologies. It will be necessary to design systems so that changes can be incorporated quickly, efficiently, and without causing a significant impact on the overall configuration of the system.

4. *Extended system life cycles—shorter technology life cycles.* The life cycles of many of the systems in use today are being extended for one reason or another while, at the same time, the life cycles of most technologies are relatively much shorter. It will be necessary to design systems with an *open-architecture* approach in mind so that the incorporation of a new technology can be accomplished easily and efficiently (this trend, of course, closely relates to item 3).

5. *Greater utilization of commercial off-the-shelf (COTS) products.* With current goals pertaining to lower initial costs and shorter and more efficient procurement and acquisition cycles, there has been a greater emphasis on the utilization of best commercial practices, processes, and commercial off-the-shelf (COTS) equipment and software. As a result, there is a greater need for a good definition of requirements from the beginning, and there is a greater emphasis on the design of systems (and their major subsystems) versus the design of components.

6. *Increasing globalization.* The "world is becoming smaller" (as they say), and there is more trading and dependency on different countries (and manufacturers) throughout the world than ever before. This trend, of course, is being facilitated through the introduction of rapid and improved communications practices, the availability of quicker and more efficient packaging and transportation methods, the application of electronic commerce (EC) methods for expediting procurement and related processes, and so on.

7. *Greater international competition.* Along with the noted trends toward increasing globalization, there is more "international" competition than ever before.

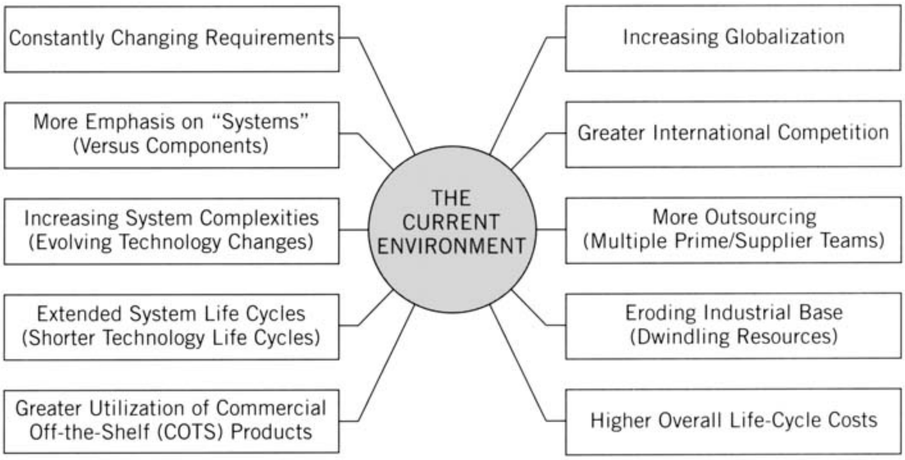

Figure 1.1 The current environment.

This, of course, is facilitated not only through improvements in communications and transportation methods, but through the greater utilization of COTS items and the establishment of effective partnerships worldwide.

8. *More outsourcing.* There is more "outsourcing" and procurement of COTS items (equipment, software, processes) from external sources of supply than ever before. Thus, there are more suppliers associated with any given program. This trend, in turn, requires greater emphasis on the early definition and allocation of system-level requirements, the development of a good and complete set of specifications, and a closely coordinated and integrated level of activity throughout the system development and acquisition process.

9. *Eroding industrial base.* The aforementioned trends (increasing globalization, more outsourcing, and greater international competition), combined with some decline in available resources worldwide, have resulted in a decrease in the number of available manufacturers of many products. In the design of systems, it is necessary to take care to select and utilize components for which there are stable and reliable sources of supply for at least the duration of the life cycle for the system in question.

10. *Higher overall life cycle costs.* In general, experience indicates that the life-cycle costs of many of the systems in use today are increasing. Although a great deal of emphasis has been placed on minimizing the costs associated with the procurement and acquisition of systems, little attention has been paid to the costs of system operation and support. In the design of systems, it is important to view *all* decisions in the context of *total cost* if one is to properly assess the risks associated with the decision in question.

Although these and related trends have evolved over time and have had a direct impact on our day-to-day activities, we often tend to ignore some of the changes that have taken place and continue with a business-as-usual approach by implementing some past practices that ultimately have had a negative impact on the systems we have developed. From past experience, it is clear that many of the problems noted have been the direct result of not applying a *disciplined* "systems approach" to meet the desired objectives. The overall requirements for the system in question were not well defined from the beginning; the perspective in terms of responding to a consumer (user) need was a relatively "short-term" focus; and, in many instances, the approach followed was to *design it now and fix it later!* In essence, the system design and development process has suffered somewhat from a lack of good early planning and the subsequent definition and allocation of requirements in a complete and methodical manner.

In regard to *requirements,* the trend has been to keep things "loose" in the beginning by developing a system-level specification that is very general in content, providing an opportunity for the introduction of the "latest and greatest" in technology developments just prior to going into the construction/production stage. Traditionally, many engineers do not want to be forced into design-related commitments any earlier than necessary, and the basis for defining lower-level requirements is often very "fluid" from the beginning. Thus, there are a lot of last-minute changes in design, and many of these late changes are introduced in haste and without concern for any form of configuration management. Furthermore, sometimes these changes are actually incorporated at a later stage. In any event, the introduction of late changes and the lack of good configuration control can be rather costly. Figure 1.2 provides a comparison of the cost impact due to the incorporation of changes early in the design process versus those incorporated later.[1]

These and related past practices have had a great impact on the overall costs of systems. In fact, in recent years and for many systems, there has been an *imbalance* between the "cost" side of the spectrum and the "effectiveness" side, as illustrated in Figure 1.3. Many systems have grown in complexity, and although there has been an increase in emphasis on some *performance* factors, the resultant reliability and quality have been decreasing. At the same time, the overall long-term costs have been increasing. Thus, there is a need to provide the proper balance in the development of systems in the future, as any specific design decision will have an impact on both sides of the balance and the interaction effects can be significant.

In addressing the aspect of economics, one often finds that there is a lack of total *cost visibility,* as illustrated by the "iceberg" in Figure 1.4. For many systems, design and development costs (and production costs) are relatively well known; however, the costs associated with system operation and maintenance are somewhat hidden. In essence, the design community has been successful in dealing with the short-term aspects of cost, but has not been very responsive to the long-term effects. At the same time, experience has indicated that a large segment of the life-cycle cost for a given system is associated with the operational and maintenance support activities accomplished downstream in the life cycle (e.g., up to 75% of the total cost in some in-

[1]Referring to Figure 1.2, it should be noted that the curves show the relative costs of actually incorporating the changes in design and not the "downstream" costs resulting from the impact of these changes over the life cycle.

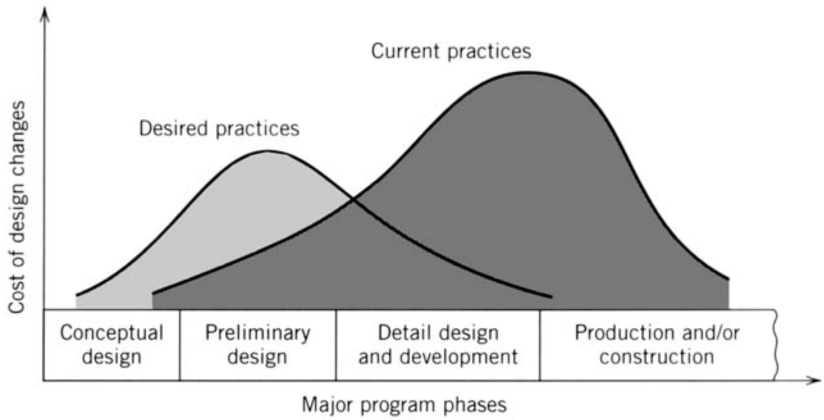

Figure 1.2 The cost impact due to changes.

stances). Thus, although our budgeting and current practices tend to heed the short-term cost impacts, we cannot adequately assess the risks associated with the ongoing decision-making process without projecting these decisions in the context of the entire system life cycle. In other words, we may wish to make a design decision based on some short-term aspect of cost, but it is important to address the life-cycle implications prior to finalizing the decision.

Moreover, in considering cause-and-effect relationships, it has been determined that a major portion of the projected life-cycle cost for a given system stems from the

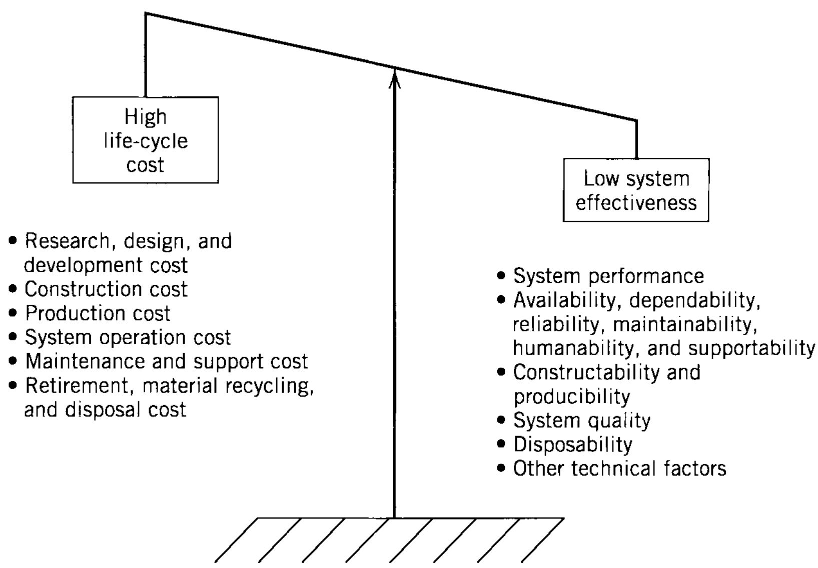

Figure 1.3 The imbalance between system cost and effectiveness factors.

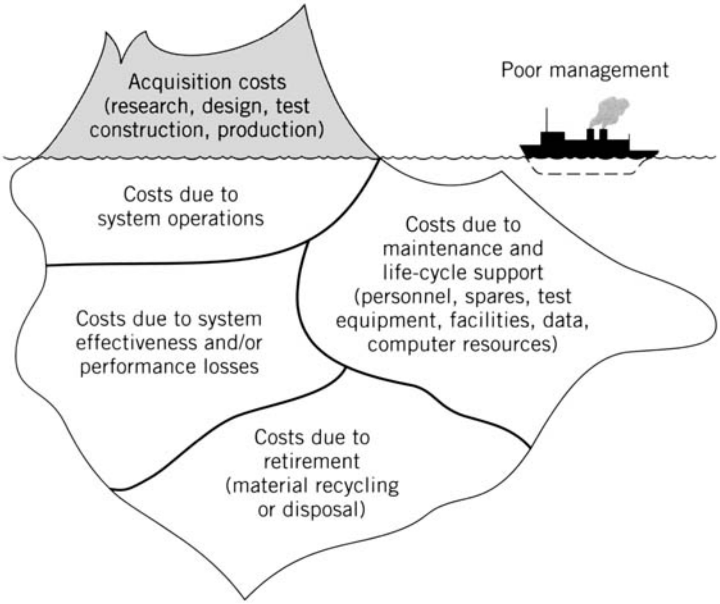

Figure 1.4 Total cost visibility.

consequences of decisions made during the early stages of advance planning and system conceptual design. Such decisions, which can have a significant impact on downstream costs, relate to the definition of operational requirements (the number of consumer sites assumed, the selection of a given mission profile, specified utilization factors, the assumed life cycle), maintenance and support policies (two versus three levels of maintenance, levels of repair, in-house versus third-party maintenance support), allocations associated with manual versus automation applications, equipment packaging schemes and diagnostic routines, hardware versus software applications, the selection of materials, the selection of a manufacturing process, whether a COTS item should be selected versus the pursuit of a new design approach, and so on. In Figure 1.5 it can be seen that the greatest opportunity for influencing life-cycle cost can be realized in the early stages of system design and development. In other words, early design decisions should be evaluated on the basis of *total life-cycle cost.*

Given the current environment of constantly changing requirements, greater utilization of COTS items, increased globalization and more outsourcing, and so forth, there is an ever-increasing need to review our current practices for bringing new systems into being. A highly disciplined approach must be pursued in the design and development of new systems, with the objective of providing the consumer (user) with a high-quality system that is cost-effective, considering the proper balance among the factors identified in Figure 1.3. In addition, there must be more emphasis on *systems,* from a life-cycle perspective, which must be established from the beginning, as illustrated in Figure 1.5. For systems already in use, it is critical that we establish a sys-

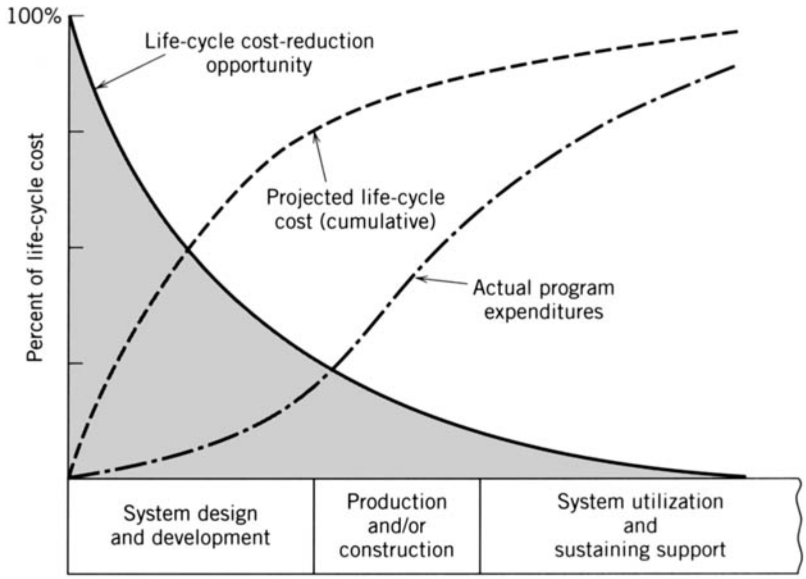

Figure 1.5 Commitment of life-cycle cost.

tematic approach to reviewing their requirements and subsequently implementing an effective *evaluation and continuous product/process improvement methodology.* In any event, the current environment, as highlighted herein, is certainly conducive to the implementation of the principles and concepts discussed throughout this text.

1.2 THE NEED FOR SYSTEM ENGINEERING

The trends and concerns conveyed in Section 1.1 are only a sample of the major issues that need to be addressed. The challenge is to be more effective and efficient in the development and acquisition of new systems, as well as in the operation and support of those systems already in use. This can be accomplished through the implementation of system engineering concepts, principles, and methods.

In exploring topics such as *systems, system engineering, system analysis,* and the like, one will find a variety of approaches in existence. These terms may be defined somewhat differently, depending on individual backgrounds, experiences, and the organizational interests of practitioners in the field. Thus, with the objective of providing clarification relative to the material included throughout this text, it seems appropriate to consider a few key concepts and definitions.[2]

[2]The bibliography presented in Appendix A includes a variety of publications covering system engineering and related areas.

1.2.1 Definition of *System*

The term *system* is used in many different contexts, and the variations pertaining to the elements are numerous. For this reason, there is often a communications problem from the beginning as to what one wishes to include (or not to include) when attempting to define the end product. A clarification of the basics may be worthwhile at this point.

The term *system* stems from the Greek *systēma,* meaning an "organized whole." *Merriam-Webster's Collegiate Dictionary* defines a system as "a regularly interacting or interdependent group of items forming a unified whole."[3] One of the early Military Standards on the subject, MIL-STD-499, defines a system as "a composite of equipment, skills, and techniques capable of performing and/or supporting an operational role. A complete system includes all equipment, related facilities, material, software, services, and personnel required for its operation and support to the degree that it can be considered a self-sufficient unit in its intended environment."[4] A more recent document, EIA/IS-632, defines a system as "an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective."[5]

Given the variations in the basic definition of a "system," the leadership of INCOSE (International Council on Systems Engineering) assigned the current Fellows of the Council to develop a consensus definition. After a few iterations the following definition evolved:

> A "system" is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behavior, and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected.[6]

In essence, a system constitutes a set of interrelated components working together with the common objective of fulfilling some designated need.

Although the preceding definitions reflect a good initial overview, a greater degree of detail and precision is required to provide a good working definition acceptable for describing the principles and concepts of system engineering. To facilitate this objective, a "system" may be defined further in terms of the following general characteristics:

[3] *Merriam-Webster's Collegiate Dictionary.* 10th ed. Springfield, MA: Merriam-Webster, Inc., 1998.
[4] Military Standard, MIL-STD-499. *System Engineering Management.* (Department of Defense, July 17, 1969).
[5] EIA/IS-632, Processes for Engineering a System, Electronic Industries Association (EIA), Washington, DC., December 1994.
[6] INCOSE, 2150 N. 107th Street, Suite 205, Seattle, WA 98133. This definition was developed in the fall of 2001.

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1. A system constitutes a *complex combination of resources* in the form of human beings, materials, equipment, software, facilities, data, money, and so on. To accomplish many functions often requires large amounts of personnel, equipment, facilities, and data (e.g., an airline or a manufacturing capability). Such resources must be combined in an *effective* manner, as it is too risky to leave this to chance alone.

2. A system is contained within some form of *hierarchy.* An airplane may be included within an airline, which is part of an overall transportation capability, which is operated in a specific geographic environment, which is part of the world, and so on. As such, the system being addressed is highly influenced by the performance of the higher-level system, and these external factors must be evaluated.

3. A system may be broken down into *subsystems* and related components, the extent of which depends on complexity and the function(s) being performed. Dividing the system into smaller units allows for a simpler approach relative to the initial allocation of requirements and the subsequent analysis of the system and its functional interfaces. A system is made up of many different components, these components *interact* with each other, and these interactions must be thoroughly understood by the system designer and/or analyst. Because of these interactions among components, it is impossible to produce an effective design by considering each component separately. One must view the system as a whole, break down the system into components, study the components and their interrelationships, and then put the system back together.

4. A system must have a *purpose.* It must be functional, able to respond to some identified need, and able to achieve its overall objective in a cost-effective manner. There may be a conflict of objectives, influenced by the higher-level system in the hierarchy, and the system must be capable of meeting its stated purpose in the best way possible.

As a point of emphasis, a system must respond to an identified *functional need.* Thus, the elements of a system must include not only those items that relate directly to the accomplishment of a given scenario or mission profile, but must also include those elements of logistics and the maintenance and support infrastructure that have to be available and in place should a failure of a prime element(s) occur. In other words, if one is to ensure the successful completion of a mission, all of the supporting elements must be available, in place, and ready to respond to a given need.[7]

1.2.2 Categories of Systems

In defining systems in terms of the general characteristics presented, it readily becomes apparent that some degree of further classification is desirable. There are many

[7]In many instances, the logistics and maintenance support infrastructure is not addressed or included as an element of the system, or as a major subsystem, but treated separately and "after the fact." The approach assumed throughout this text is that this is included in the context of a major subsystem and addressed as an inherent part of the whole.