2

SYSTEMS ENGINEERING LANDSCAPE

2.1 SYSTEMS ENGINEERING VIEWPOINT

The origins of the systems engineering section in Chapter 1 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, it was initially filled by engineers and scientists who acquired through experience the ability to lead successfully complex system development programs. To do so, they had to acquire a greater breadth of technical knowledge and, more importantly, to 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.

Systems Engineering Principles and Practice, Second Edition. Alexander Kossiakoff, William N. Sweet, Samuel J. Seymour, and Steven M. Biemer

Successful Systems

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

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

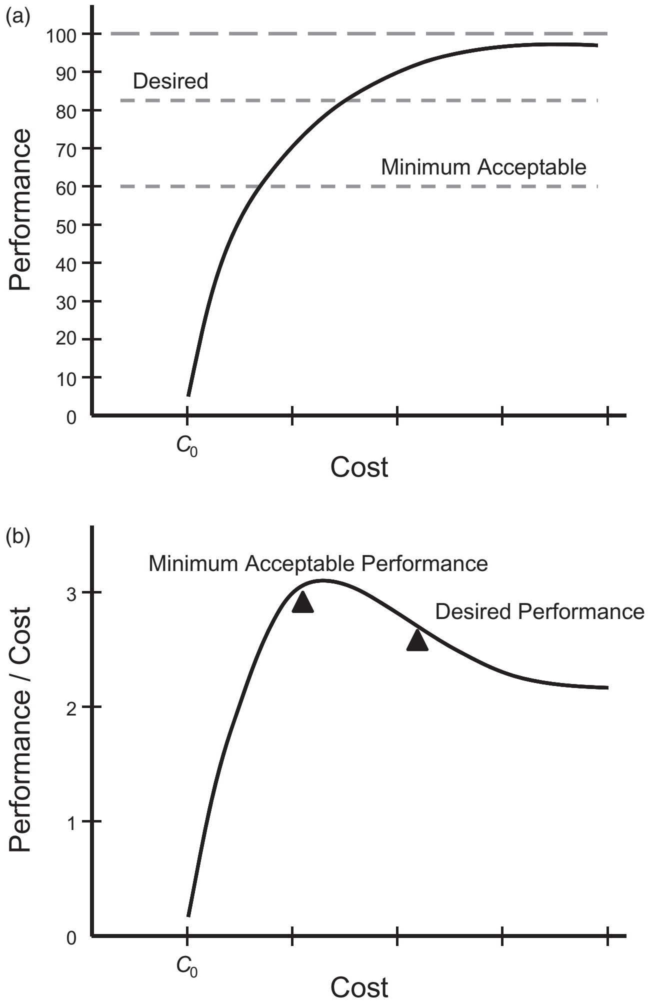

Figure 2.1. (a) Performance versus cost. (b) Performance/cost versus cost.

ment of a given performance attribute of a system under development, Figure 2.1a is a plot of a typical variation in the level of performance of a 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 desirable performance levels.

The curve of Figure 2.1a 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 to 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 2.1b. This figure plots performance divided by cost against cost (i.e., y/x vs. x from Fig. 2.1a). 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 Figure 2.2. 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

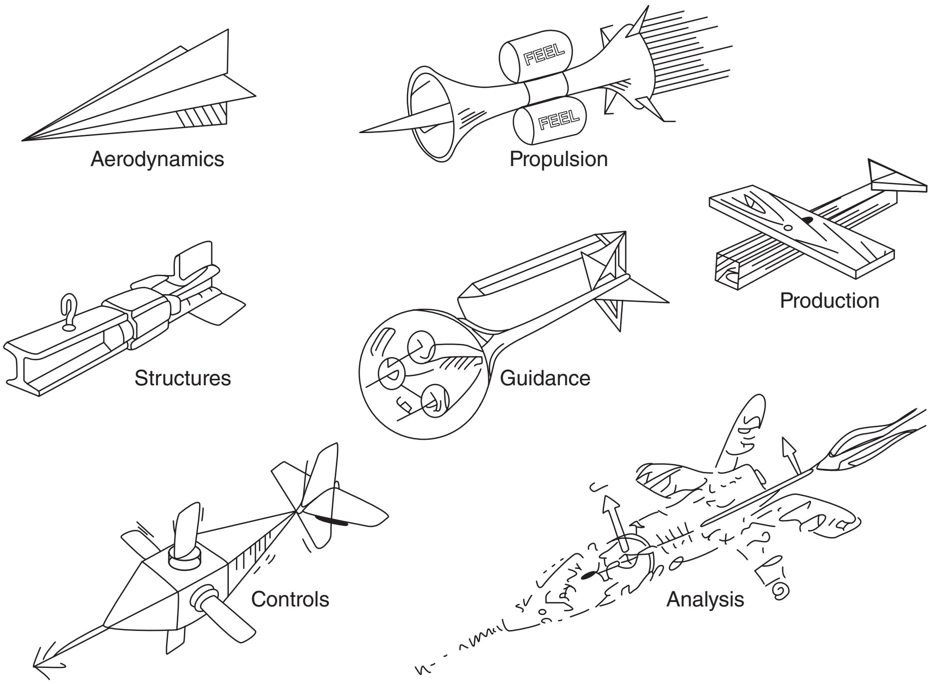

Figure 2.2. The ideal missile design from the viewpoint of various specialists.

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 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 2.3 is

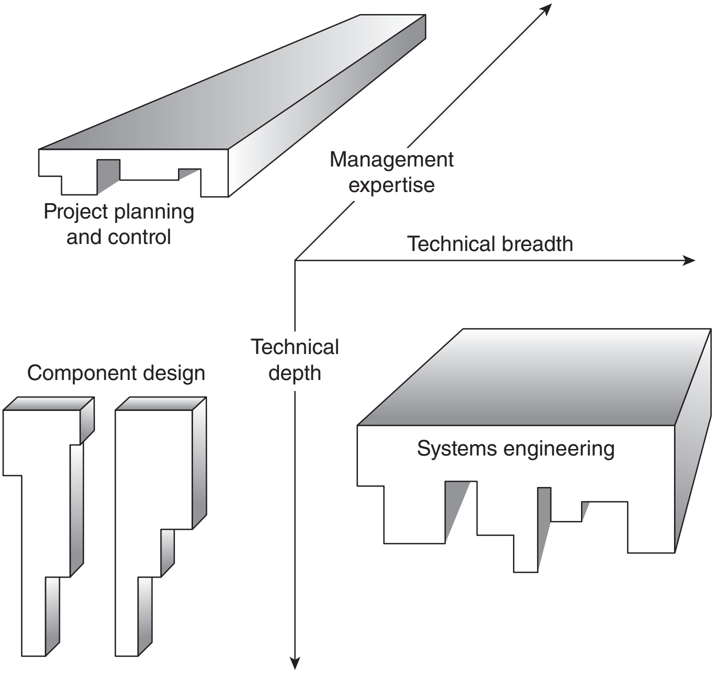

Figure 2.3. The dimensions of design, systems engineering, and project planning and control.

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 components, 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 coworkers.

2.2 PERSPECTIVES OF SYSTEMS ENGINEERING

While the field of systems engineering has matured rapidly in the past few decades, there will continue to exist a variety of differing perspectives as more is learned about the potential and the utility of systems approaches to solve the increasing complex problems around the world. The growth of systems engineering is evidenced in the number of academic programs and graduates in the area. Some surveys note that systems engineering is a favored and potentially excellent career path. Employers in all sectors, private and government, seek experienced systems engineering candidates. Experts in workforce development look for ways to encourage more secondary school

TABLE 2.1. Comparison of Systems Perspectives

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

and college students to pursue degrees in science, technology, engineering, and mathematics (STEM). With experience and additional knowledge, these students would mature into capable systems engineers.

Since it often requires professional experience in addition to education to tackle the most complex and challenging problems, developing a systems mindset—to "think like a systems engineer"—is a high priority at any stage of life. A perspective that relates a progression in the maturity of thinking includes concepts of systems thinking, systems engineering, and engineering systems (see Table 2.1) An approach to understanding the environment, process, and policies of a systems problem requires one to use systems thinking. This approach to a problem examines the domain and scope of the problem and defines it in quantitative terms. One looks at the parameters that help define the problem and then, through research and surveys, develops observations about the environment the problem exists in and finally generates options that could address the problem. This approach would be appropriate for use in secondary schools to have young students gain an appreciation of the "big picture" as they learn fundamental science and engineering skills.

The systems engineering approach discussed in this book and introduced in Chapter 1 focuses on the products and solutions of a problem, with the intent to develop or build a system to address the problem. The approach tends to be more technical, seeking from potential future users and developers of the solution system, what are the top level needs, requirements, and concepts of operations, before conducting a functional and physical design, development of design specifications, production, and testing of a system solution for the problem. Attention is given to the subsystem interfaces and the need for viable and tangible results. The approach and practical end could be applied to many degrees of complexity, but there is an expectation of a successful field operation of a product. The proven reliability of the systems engineering approach for product development is evident in many commercial and military sectors.

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

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

2.3 SYSTEMS DOMAINS

With a broad view of system development, it can be seen that the traditional approach to systems now encompasses a growing domain breadth. And much like a Rubik's Cube, the domain faces are now completely integrated into the systems engineer's perspective of the "big (but complex) picture." The systems domain faces shown in Figure 2.4 include not only the engineering, technical, and management domains but

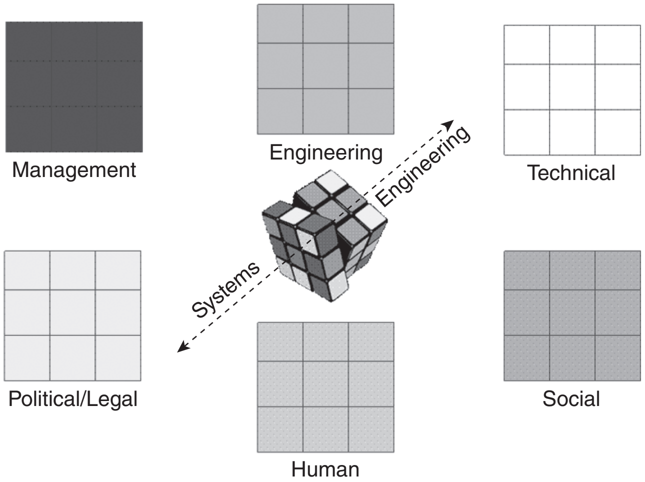

Figure 2.4. Systems engineering domains.

also social, political/legal, and human domains. These latter softer dimensions require additional attention and research to fully understand their impact and utility in system development, especially as we move to areas at the enterprise and global family of systems levels of complexity.

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

2.4 SYSTEMS ENGINEERING FIELDS

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

These perceptions are illustrated in Figure 2.5, and additional fields that represent a few of the traditional areas associated with systems engineering methods and practices are also shown. An example is the area of operations research whose view of systems engineering includes provision of a structure that will lead to a quantitative analysis of

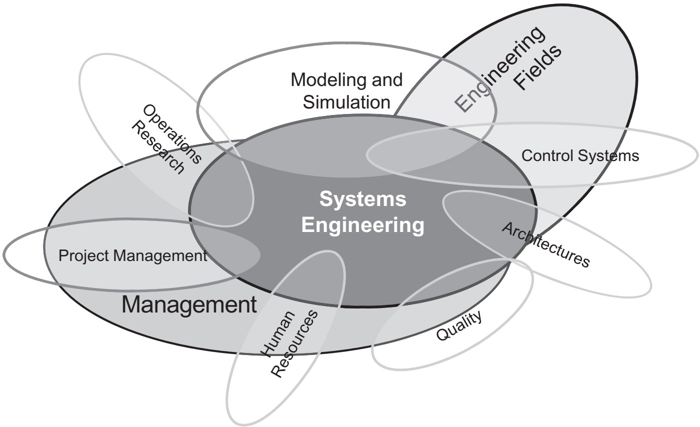

Figure 2.5. Examples of systems engineering fields.

alternatives and optimal decisions. The design of systems also has a contingency of professionals who focus on the structures and architectures. In diverse areas such as manufacturing to autonomous systems, another interpretation of systems engineering comes from engineers who develop control systems, who lean heavily on the systems engineering principles that focus on management of interfaces and feedback systems. Finally, the overlap of elements of modeling and simulation with systems engineering provides a perspective that is integral to a cost-effective examination of systems options to meet the requirements and needs of the users. As systems engineering matures, there will be an increasing number of perspectives from varying fields that adopt it as their own.

2.5 SYSTEMS ENGINEERNG APPROACHES

Systems engineering can also be viewed in terms of the depictions of the sequence of processes and methodologies used in the execution of the design, development, integration, and testing of a system (see Figure 2.6 for examples). Early graphics were linear

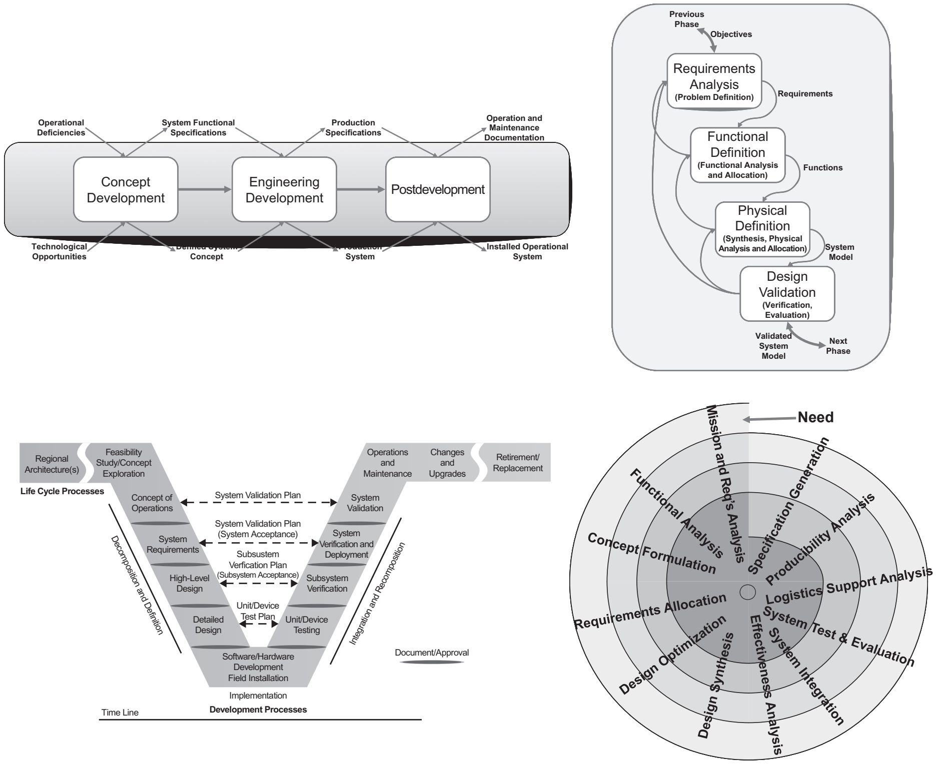

Figure 2.6. Examples of systems engineering approaches.

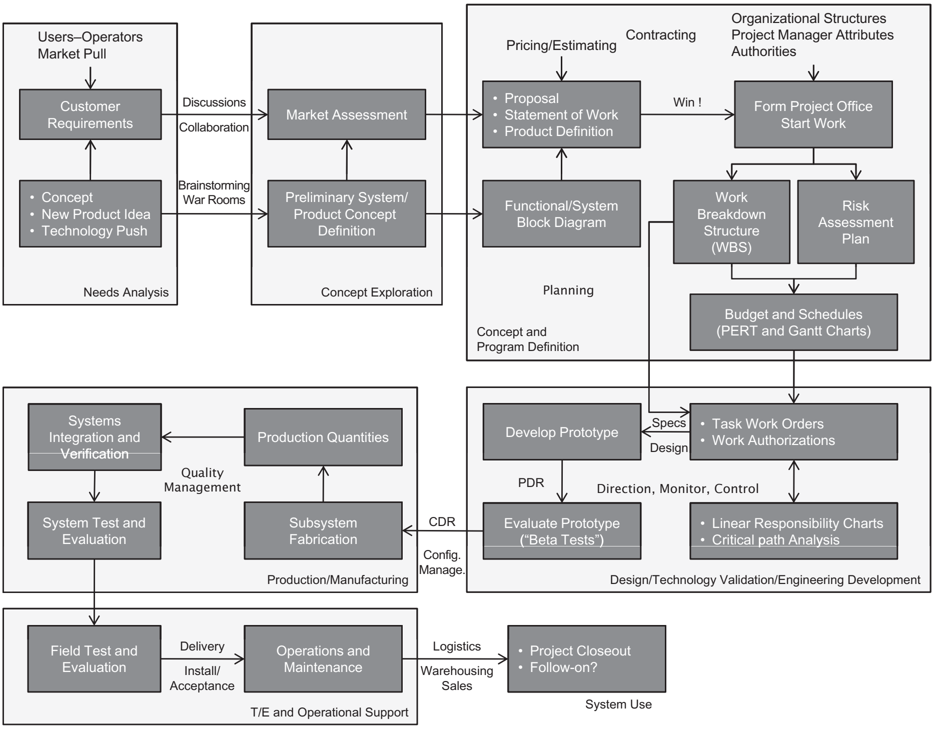

Figure 2.7. Life cycle systems engineering view. PERT, Program Evaluation and Review Technique; PDR, Preliminary Design Review; CDR, Critical Design Review.

in the process flow with sequences of steps that are often iterative to show the logical means to achieve consistency and viability. Small variations are shown in the waterfall charts that provide added means to illustrate interfaces and broader interactions. Many of the steps that are repeated and dependent on each other lead to the spiral or loop conceptual diagrams. The popular systems engineering "V" diagram provides a view of life cycle development with explicit relationships shown between requirements and systems definition and the developed and validated product.

A broader perspective shown in Figure 2.7 provides a full life cycle view and includes the management activities in each phase of development. This perspective illustrates the close relationship between management planning and control and the systems engineering process.

2.6 SYSTEMS ENGINEERING ACTIVITIES AND PRODUCTS

Sometimes followed as a road map, the life cycle development of a system can be associated with a number of systems engineering and project management products or outputs that are listed in Table 2.2. The variety and breadth of these products reflect

TABLE 2.2. Systems Engineering Activities and Documents

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

the challenges early professionals have in understanding the full utility of engaging in systems engineering. Throughout this book, these products will be introduced and discussed in some detail to help guide the systems engineer in product development.

2.7 SUMMARY

Systems Engineering Viewpoint

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

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

Perspectives of Systems Engineering

A spectrum of views exist in understanding systems engineering, from a general systems thinking approach to problems, to the developmental process approach for systems engineering, to the broad perspective of engineering systems.

Systems Domains

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

Systems Engineering Fields

Systems engineering encompasses or overlaps with many related fields including engineering, management, operations analysis, architectures, modeling and simulation, and many more.

Systems Engineering Approaches

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

Systems Engineering Activities and Products

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

PROBLEMS

2.1 Figure 2.1 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 versus cost where optimizing one frequently competes with the other, and briefly explain why they do.

2.2 Explain the advantages and disadvantages of introducing system concepts to secondary students in order to encourage them to pursue STEM careers.

2.3 Select a very large complex system of system example and explain how the engineering systems approach could provide useful solutions that would have wide acceptance across many communities.

2.4 Referring to Figure 2.5, identify and justify other disciplines that overlap with systems engineering and give examples how those disciplines contribute to solving complex systems problems.

2.5 Discuss the use of different systems engineering process models in terms of their optimal use for various system developments. Is one model significantly better than another?

FURTHER READING

B. Blanchard. *Systems Engineering Management*, Third Edition. John Wiley & Sons, 2004.

H. Eisner. *Essentials of Project and Systems Engineering Management*, Second Edition. John Wiley & Sons, 2002.