Chapter 1

Introduction

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> To be consistent, you have to have systems. You want systems, and not rules. Rules create robots. Systems are predetermined ways to achieve a result. The emphasis is an achieving the results, not the system for the system's sake... Systems give you a floor, not a celling.
>
> —Ken Blanchard and Sheldon Bowles

1.1 PURPOSE

This is the first chapter in a foundational book on a technical field. It serves two purposes. First, it introduces the key terms and concepts of the discipline and their relationships with one another. Second, it provides an overview of the major topics of the book. All technical fields have precisely defined terms that provide a foundation for clear thinking about the discipline. Throughout this book we will use the terms and definitions recognized by the primary professional societies informing the practice of contemporary systems engineering:

The International Council on Systems Engineering (INCOSE) (1) is a not-for-profit membership organization founded in 1990. INCOSE is an international authoritative body promoting the application of an interdisciplinary approach and means to enable the realization of successful systems.

The American Society for Engineering Management (ASEM) (2) exists to assist its members in developing and improving their skills as practicing managers

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of engineering and technology and to promote the profession of engineering management.

The Institute for Operations Research and the Management Sciences (INFORMS) (3) is the largest professional society in the world for professionals in the fields of operations research and the management sciences. The INFORMS annual conference is one of the major forums where systems engineers present their work.

The Operational Research Society (ORS) (4) is the oldest professional society of operations research professionals in the world with members in 53 countries, provides training, conferences, publications, and information to those working in operations research. Members of the ORS were among the first systems engineers to embrace systems thinking as a way of addressing complicated modeling and analysis challenges.

Figure 1.1 shows the concept map for this chapter. This concept map relates the major sections of the chapter, and of the book, to one another. The concepts shown in round-edge boxes are assigned as major sections of this chapter. The underlined items are introduced within appropriate sections. They represent ideas and objects that link major concepts. The verbs on the arcs are activities that we describe briefly in this chapter. We use a concept map diagram in each of the chapters to help identify the key chapter concepts and make explicit the relationships between key concepts

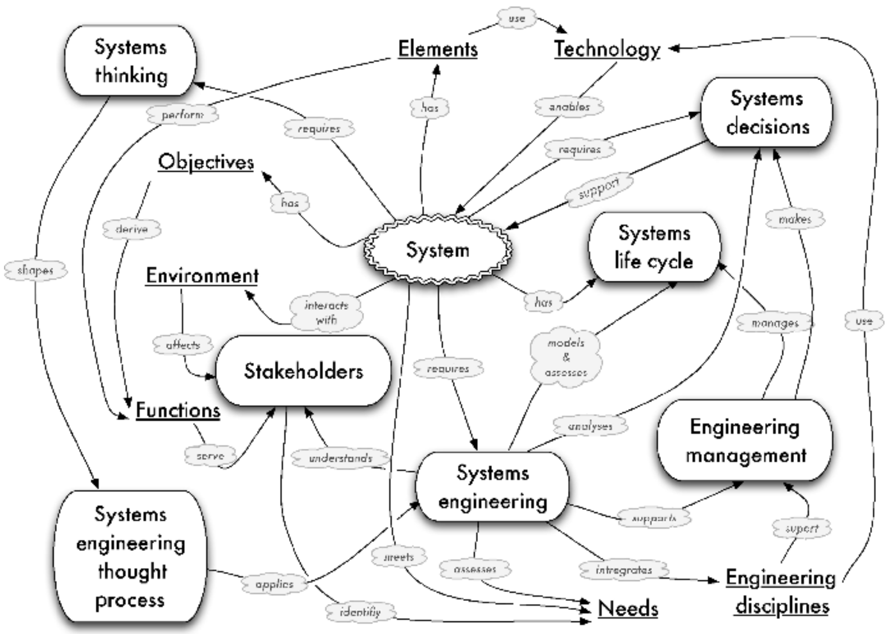

Figure 1.1 Concept map for Chapter 1.

we explore. This book addresses the concepts of systems, system life cycles, systems decisions, systems thinking, systems engineering, and engineering management.

1.2 SYSTEM

There are many ways to define the word *system*. The Webster Online Dictionary defines a system as "a regularly interacting or interdependent group of items [elements] forming a unified whole" (5). We will use the INCOSE definition:

> A system is "an integrated set of elements that accomplishes a defined objective. These elements include products (hardware, software, firmware), processes (policies, laws, procedures), people (managers, analysts, skilled workers), information (data, reports, media), techniques (algorithms, inspections, maintenance), facilities (hospitals, manufacturing plants, mail distribution centers), services (evacuation, telecommunications, quality assurance), and other support elements." (1)

As we see in Fig. 1.1, a system has several important attributes:

- Systems have interconnected and interacting elements that perform systems functions to meet the needs of consumers for products and services.
- Systems have objectives that are achieved by system functions.
- Systems interact with their environment thereby creating effects on stakeholders.
- Systems require systems thinking that uses a systems engineering thought process.
- Systems use technology that is developed by engineers from all engineering disciplines.
- Systems have a system life cycle containing elements of risk that are managed throughout this life cycle by engineering managers.
- Systems require systems decisions, analysis by systems engineers, and decisions made by engineering managers.

Part I of this book discusses systems and systems thinking in detail.

1.3 STAKEHOLDERS

The primary focus of any systems engineering effort is on the stakeholders of the system. A stakeholder is a person or organization that has a vested interest in any system or its outputs. It is this vested interest that establishes their importance within any systems decision process. Sooner or later, for any systems decision problem, stakeholders will care about the decision reached, because it will in one way or another affect them, their systems, or the success of what they are engaged in. Consequently, it is prudent and wise to consider and integrate their needs, wants, and desires in any possible candidate solution. In the systems decision process

(SDP) that we introduce Chapter 9, we do this by constructing value models based on stakeholder input. Their input as a group impacts system functions and establishes screening criteria used to eliminate various alternatives failing to meet these criteria.

Notice that this notion of a stakeholder makes no distinction based on the motivation of stakeholder vested interest. We should allow for the possibility that for any system of reasonable presence in its surrounding environment there exists a subset of stakeholders who are not interested in the success and well-being of the system under study. On the contrary, they might have a vested interest in its demise, or at the very least the stagnation or reduction in the growth of the system, its outputs, and linkages. Market competitors, advocates of opposing political ideologies, members of hostile biological systems, and the like are obvious examples of groups that might typify this malevolent category of stakeholders.

More complex and challenging to identify are the nonobvious stakeholders; those persons and organizations that are once, twice, and further removed from direct interaction with the system under study but nonetheless have a vested interest that needs to be considered in a systems decision problem. A once removed stakeholder could be described as one whose direct vested interest lies in the output of a system that is dependent on output of the system under study. A similar relationship exists for further removed stakeholders. The environmental factors shown in the SDP of Fig. 1.5 are very helpful in this regard. They are frequently used as memory cues during stakeholder identification.

For our purposes, the simplest complete taxonomy of stakeholders contains five types. These are, listed in their typical order of importance:

1. *Decision Authority*. The stakeholder(s) with ultimate decision gate authority to adopt and implement a system solution.
2. *Client*. The person or organization that solicited systems decision support for a project; the source of project compensation; the stakeholder that principally defines system requirements.
3. *Owner*. The person or organization responsible for proper and purposeful system operation.
4. *User*. The person or organization accountable for proper and purposeful system operation.
5. *Consumer*. The person(s) or organization(s) that have created intentional dependencies on the products or services output from the system.

For any given systems decision problem, it is perhaps easiest to identify the Client first, then the Decision authority, followed by the others in any convenient order. For example, on a recent rental car system re-design, the Client solicited assistance in identifying creative alternatives for marketing non-recreational vehicle rental in his region. When asked, the Client stated that although he would be making the intermediate gate decisions to move the project forward, any solutions would have to be approved by his regional manager prior to implementation. His regional manager is therefore the Decision authority.

An example will help to distinguish between a User and an Owner. A technology company purchases computer systems for its engineers to use for computer aided design. The company owns the computers and is held responsible for maintaining proper accountability against loss. The engineers use the computers and typically sign hand receipts acknowledging that they have taken possession of the computers. If, on a particularly bad Friday, one of the engineers (User) tosses her computer out the window and destroys it, she will be held accountable and have to pay for the damages or replacement. The managing supervisor of the engineer, as the company's representative (Owner), is held responsible that all proper steps were taken to protect and safeguard the system against its loss or damage.

This taxonomy can then be further divided into an *active* set and a *passive* set of stakeholders. The active set contains those stakeholders who currently place a high enough priority on the systems decision problem to return your call or participate in an interview, focus group, or survey in order to provide the design team with relevant information. The passive set contains those who do not. Membership in these two sets will most likely change throughout the duration of a systems decision project as awareness and relevance either rises or falls.

1.4 SYSTEM LIFE CYCLE

Systems are dynamic in the sense that the passage of time affects their elements, functions, interactions, and value delivered to stakeholders. These observable effects are commonly referred to as system maturation effects. A system life cycle is a conceptual model that is used by system engineers and managers to describe how a system matures over time. It includes each of the stages in the conceptualization, design, development, production, deployment, operation, and retirement of the system.

A system's performance level, its supportability, and all associated costs are important considerations in any systems decision process. The systems decision process we use is fundamentally life cycle centered. All systems decisions are made in the context of a life cycle. In each stage of a system's useful life, systems owners make decisions that influence the well-being of their system and determine whether the system will continue to the next stage of its life cycle.

The performance of a system will degrade if it is not maintained properly and maintaining a system consumes valuable resources. At some point, system owners are faced with critical decisions of whether to continue to maintain the current system, modify the system to create new functionality with new objectives in mind, or to retire the current system and replace it with a new system design. These decisions should be made taking into consideration of the entire system life cycle and its associated costs, such as development, production, support, and "end of life" disposal costs, because it is in this context that some surprising costs, such as energy and environmental costs, become clearly visible.

Consider, for example, the life cycle costs associated with a washing machine (6) in terms of percentage of its overall contributions to energy and water consumption, air and water pollution, and solid waste. One might suspect that the largest solid waste

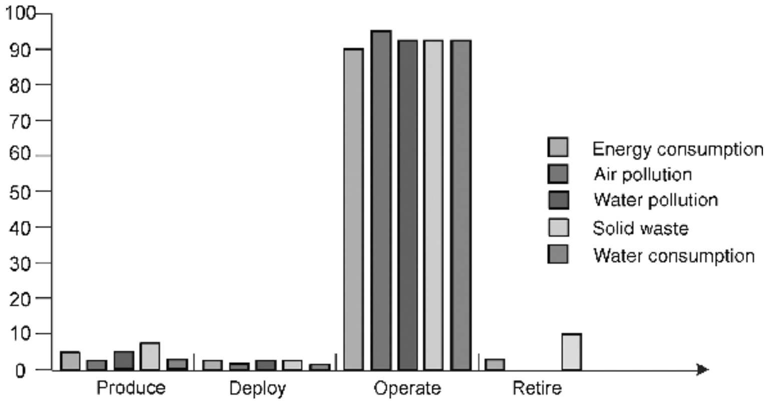

Figure 1.2 Life cycle assessment of environmental costs of a washing machine (6).

costs to the environment would be in the two life cycle stages at the beginning of its life cycle (packaging material is removed and discarded) and at the end (the machine is disposed of). However, as can be seen in Fig. 1.2, the operational stage dominates these two stages as a result of the many packets of washing detergent and other consumables that are discarded during the machine's life. It is just the opposite case with the environmental costs associated with nuclear power facilities. The disposal (long-term storage) costs of spent nuclear fuel have grown over time to equal the development and production costs of the facility (7).

We use the system life cycle shown in Fig. 1.3 throughout the book. Chapter 3 develops the life cycle in detail so that it can be used to assess any system in support of systems decisions. This system life cycle is composed of *stages* that are aligned with how a system matures during its lifetime, and *decision gates* through which the system can only pass by satisfying some explicit requirements. These requirements are usually set by system owners. For example, a system typically will not be allowed to proceed from the design and development stage to the production stage without clearly demonstrating that the system design has a high likelihood of efficiently delivering the value to stakeholders that the design promises. Decision gates are used by engineering managers to assess system risk, both in terms of what it promises to deliver in future stages and threats to system survivability once deployed.

Risk appears throughout: business risk (does it make sense for the project team to undertake the effort?), market risk (is there a viable and profitable market for the products and/or services the system is designed to deliver?), system program risk (can technical, schedule, and program risks be identified, mitigated, or resolved in a manner that satisfies system owners?), decision risk (is there a sufficient amount of accurate information to make critical decisions?), and implementation risk (can the system be put into action to deliver value?). Risk management, including risk forecasting and miligation planning, starts early and continues throughout a system's life cycle.

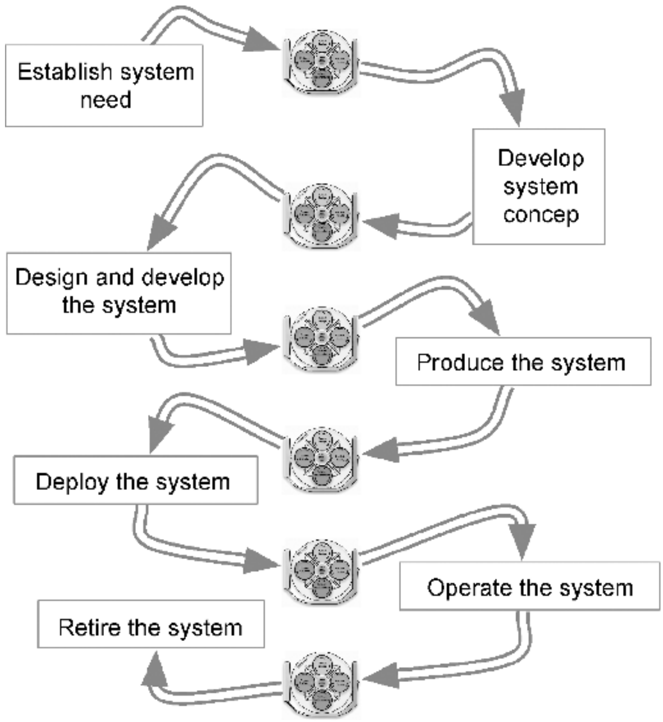

Figure 1.3 Systems decision process used throughout a system life cycle.

1.5 SYSTEMS THINKING

Systems have become increasingly more complex, dynamic, interconnected, and automated. Both the number and diversity of stakeholders have increased, as global systems have become more prevalent. For example, software companies take advantage of time zone differences to apply continuous effort to new software systems by positioning development teams in the United States, Europe, India, and Japan. Financial systems previously operating as independent ventures now involve banks, businesses, customers, markets, financial institutions, exchange services, and national and international auditing agencies. Changes occurring in one system impact in a very short time those they are connected to . A change in the Tokyo market, for example, propagates quickly to the U.S. market because of strong relationships existing between not only these markets but the monetary exchange rates, trade balance levels, manufacturing production levels and inventory levels as well. In order to respond quickly to these market changes, buy and sell rules are automated so as to keep disrupting events from escalating out of control over time.

Military systems have dramatically increased in complexity as well. Currently, complex, interconnected systems use real-time satellite data to geo-locate themselves and find, identify, and classify potential targets using a worldwide network of sensor systems. These, in turn, are connected to a host of weapons platforms having the capacity to place precisions guided munitions on targets. With systems such as these a host of systems decisions arise. Is there a lower limit to human participation in a targeting process such as these? Are these limits defined by technological, cultural, moral, legal, or financial factors? Likewise, should there be an upper limit on the percentage of automated decision making? What measures of effectiveness (MOE) are appropriate for the integrated system behavior present only when all systems are operational?

In general then, for complex systems, how many systems interactions do we need to consider when we are faced with analyzing a single system? Answers to this question shape both the system boundaries and scope of our effort. How can we insure that critical interactions and relationships are represented in any model we build, and those that play only a minor role are discounted but not forgotten? For this and other important considerations to not be overlooked, we need a robust and consistent systems decision process driven by systems thinking that we can repeatedly apply in any life cycle stage of any system we are examining.

As is addressed in detail in Chapter 2, systems thinking is a holistic philosophy capable of uncovering critical system structure such as boundaries, inputs, outputs, spatial orientation, process structure, and complex interactions of systems with their environment (8). This way of thinking considers the system as a whole, examining the behavior arising from the total system without assuming that it is necessary to decompose the system into its elements in order to improve or modify its performance. Understanding system structure enables system engineers to design, produce, deploy, and operate systems focused on delivering high value capabilities to customers. The focus is on delivering value that underscores every activity of modern systems engineering (9).

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Systems thinking combined with engineering principles focused on creating value to stakeholders is a modern worldview embedded in systems engineering as an effective way of addressing many of the challenges posed by the growing complexity of systems. Systems engineers necessarily must consider both hard and soft systems analysis techniques (10).

In applying the SDP that we introduce in Section 1.9 and use throughout this book, a significant amount of time is consumed in the early steps of the process, carefully identifying the core issues from stakeholders' perspectives, determining critical functions that the system must perform as a whole in order to be considered successful, and clearly identifying how these functions will deliver value to stakeholders. Many of the techniques used to accomplish these tasks are considered "soft" in the sense that they are largely subjective and qualitative, as opposed to "hard" techniques that are objective and quantitative. Techniques used in later steps of the SDP involving system modeling and analysis, which are introduced in Chapter 4, lean more toward the quantitative type. Together, they form an effective combination of approaches that make systems engineering indispensable.

1.6 SYSTEMS ENGINEERING THOUGHT PROCESS

The philosophy of systems thinking is essentially what differentiates modern systems engineering from other engineering disciplines such as civil, mechanical, electrical, aerospace, and environmental. Table 1.1 presents some of the more significant differences (11). While not exhaustive in its listings, the comparison clearly illustrates that there is something different about systems engineering that is fundamental to the discipline.

The engineering thought process underpinning these other engineering fields assumes that decomposing a structure into its smallest constituent parts, understanding these parts, and reassembling these parts will enable one to understand the structure. Not so with a systems engineering thought process. Many of these engineering fields are facing problems that are increasingly more interconnected and globally oriented. Consequently, interdisciplinary teams are being formed using professionals from a host of disciplines so that the team represents as many perspectives as possible.

> The systems engineering thought process is a holistic, logically structured sequence of cognitive activities that support system design, systems analysis, and systems decision making to maximize the value delivered by a system to its stakeholders for the resources.

Systems decision problems occur in the context of their environment. The diversity of environmental factors shown in the SDP of Fig. 1.5 clearly illustrates the need for systems engineering teams to be multidisciplinary. Each of these factors represent potential systems, stakeholders, and vested interests that will affect any systems decision and must be considered in any feasible system solutions.

1.7 SYSTEMS ENGINEERING

The definition used by the INCOSE, the world's preeminent systems engineering professional society, aligns with the approach advocated in this book.

> Systems engineering is "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem." (12)

This definition highlights several key functions of systems engineering as a professional practice:

TABLE 1.1 Comparison of Engineering Disciplines

Comparison Criteria	Systems Engineering	Traditional Engineering Discipline
Problem characteristics	Complex, multidisciplinary, incrementally defined	Primarily requiring expertise in no more than a couple of disciplines; problem relatively well defined at the onset
Emphasis	Formulating and framing the right problem to solve; focus on methodology and process; finding parsimonious solutions; associative thinking	Finding the right technique to solve; focus on outcome or result; finding parsimonious explanations; vertical thinking
Basis	Aesthetics, envisioning, systems science, systems theory	Physical sciences and attendant laws
Key challenges	Architecting unprecedented systems; legacy migration; new/legacy system evolution; achieving multi-level interoperability between new and legacy software-intensive systems	Finding the most elegant or optimal solution; formulating hypothesis and using deductive reasoning methods to confirm or refute them; finding effective approximations to simplify problem solution or computational load
Complicating factors	SE has a cognitive component and oftentimes components arising from the environment (see SDP)	Nonlinear phenomena in various physical sciences
Key metric examples	Cost and ease of legacy migration; system complexity; system parsimony; ability to accommodate evolving requirements; ability to meet stakeholder expectations of value	Solution accuracy, product quality, and reliability; solution robustness

- Understanding stakeholders (including customers, users, consumers) to identify system functions and objectives to meet their needs.
- Measuring how well system elements will perform functions to meet consumer needs.
- Integrating multiple disciplines into the systems engineering team and in consideration of systems alternatives: engineering (aerospace, bioengineering, chemical, civil, electrical, environmental, industrial, mechanical, and others), man-

agement, finance, manufacturing, services, logistics, marketing, sales, and so on.

- Remaining involved in many tasks throughout the system life cycle (defining consumer and user needs and required functionality, documenting requirements, design, and system validation).
- Performing modeling and analysis to insure that a sufficient and comprehensive system representation is being considered at each decision gate of the system life cycle.
- Supporting engineering managers' decision making as they manage the system throughout the system life cycle.

These functions, among others, serve to clarify an important point: systems engineering and engineering management are inextricably linked. They work in a complementary fashion to design, develop, deploy, operate, maintain, and eventually retire successful systems that deliver value to stakeholders. So, what is expected of a systems engineer?

Azad Madni, an INCOSE Fellow, describes the expectations of systems engineers in the following way (11): Systems engineers are required to be broad thinkers, capable of generating creative options and synthesizing solutions. They are lateral thinkers at heart, which underscores the natural multidisciplinary structure of systems engineering teams. They must be capable of formulating the right problem to solve and to challenge *every* assumption prior to accepting any. Systems engineers must have the necessary skills and knowledge to imbed aesthetics into systems (solutions), to create required abstractions and associations, to synthesize solutions using metaphors, analogies, and heuristics, and to know where and where not to infuse cognitive engineering in the system life cycle.

1.8 ENGINEERING MANAGEMENT

In the complex, global, competitive world of technology-driven products and services, there is a need for engineers who understand the essential principles of both engineering and management. Figure 1.4 shows the four dimensions of this engineering management discipline: entrepreneurship, engineering, management, and leadership.[1] Entrepreneurship is the term used to describe how engineering managers creatively use research and experimentation to develop new technologies to provide products and services that create value for customers. Engineering is used to describe the multidisciplinary teams of individuals from engineering disciplines that apply science and technology to develop these products and services for customers. Management includes the techniques used to plan, staff, organize, and control activities that effectively and efficiently use resources to deliver value to customers. Leadership includes the ability to develop a vision, motivate people, make decisions,

[1] Modified from original management diagram developed by Dr. John Farr, Stevens Institute of Technology.

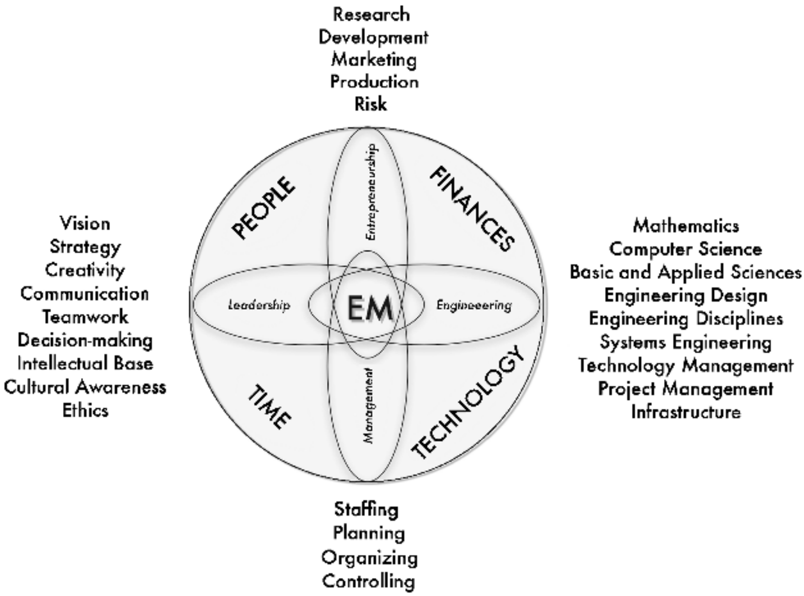

Figure 1.4 Engineering management.

and implement solutions while considering all the appropriate environmental factors and stakeholder concerns.

Figure 1.4 also identifies the four critical resources that engineering managers must effectively and efficiently manage: finances, technology, time, and people. All four of these resources are linked together in their effects, but a brief comment on each separately is appropriate here. Sufficient financing is a key to any engineering management project; it takes money to make money. Technology provides a means of providing products and services to support an engineering management project, whether they are bought in a store, provided by the government, or delivered over the Internet. Time is the third key resource inextricably linked to money. Projects that are managed in such a way that they adhere to schedule have a greater opportunity to maintain the organizational support needed to successfully complete the project and satisfy stakeholder needs. People, the fourth resources, are the most critical resource that an engineering manager must control. Recruiting, motivating, developing, using, and retaining key human resources directly determines the success of any engineering management project.

We use the American Society for Engineering Management (ASEM) definition of engineering management:

> Engineering management is "the art and science of planning, organizing, allocating resources, and directing and controlling activities which have a technological component." (2)

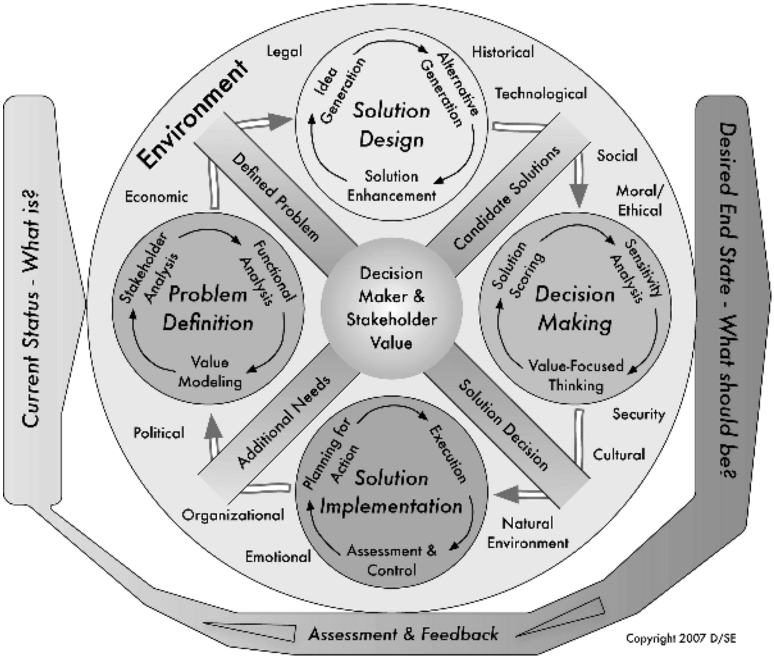

Figure 1.5 Systems decision process.

1.9 SYSTEMS DECISION PROCESS

As a system operates and matures, it competes for resources necessary to maintain its ability to deliver value to stakeholders. Systems decisions involving the allocation of these resources are inevitably made during all phases of a system life cycle up to and including the point where system owners decide to retire the system from operation. As long as a system is operating successfully, other system owners will look to leverage its capabilities to increase the performance of their systems as well. There are many examples of this leveraging taking place, particularly in transportation, software systems, and telecommunications.

As a consequence, systems decisions have become more and more complicated as the number of dependencies on a system's elements or functions grows. Systems engineers need a logically consistent and proven process for helping a system owner (including all stakeholders) make major systems decisions, usually to continue to the next life cycle stage. The process we advocate is shown in Fig. 1.5.

The systems decision process (SDP) can be applied in any stage in the system life cycle.

Part III of this book develops a detailed understanding of the SDP. However, among its many advantages, five inherent characteristics are worth highlighting at this point:

- The SDP encapsulates the dynamic flow of system engineering activities and the evolution of the system state, starting with the current status (what is) and ending with a system that successfully delivers value to system stakeholders (what should be).
- It has a core focus on the needs and objectives of stakeholders and decision makers concerned with the value being delivered by the system.
- It has four major phases organized into a logical progression (problem definition, solution design, decision making, and solution implementation) that embrace systems thinking and apply proven systems engineering approaches, yet are highly iterative.
- It explicitly considers the environment (its factors and interacting systems) that systems operate in as critical to systems decision making, and thus highlights a requirement for multidisciplinary systems engineering teams.
- It emphasizes value creation (value modeling, solution enhancements, and value focused thinking) in addition to evaluation (scoring and sensitivity analysis) of alternatives.

1.10 OVERVIEW

Part I defines and describes system concepts. Chapter 2 introduces systems thinking as a discipline for thinking about complex, dynamic, and interacting systems, and describes methods for representing systems that improve the clarity of our thinking about systems. Chapter 3 introduces the concept of a system life cycle and describes the system life cycle we use in this book. It also introduces the concept of risk, how risk affects systems decision making, and a technique for assessing the levels of various risk factors early in the system life cycle. Chapter 4 introduces system modeling and analysis techniques used to validate system functions and assess system performance. Chapter 5 introduces life cycle cost and other economic analysis considerations.

Part II introduces the role of systems engineering in engineering management. Chapter 6 describes the fundamentals of systems engineering. Chapter 7 delineates the role of systems engineering in each phase of the system life cycle. Chapter 8 introduces the system effectiveness considerations and provides models of system suitability that enable a system to perform the function that it was designed for in the user environment.

Part III proposes, describes, and illustrates a systems decision process that can be used in all phases of the system life cycle. A rocket design problem and an academic information technology problem are used to explain the concepts and serve as illustrative examples. Chapter 9 introduces our recommended systems decision process and the illustrative problem. Chapter 10 describes and illustrates the problem definition phase, Chapter 11 the solution design phase, Chapter 12 the decision-making phase, and Chapter 13 the solution implementation phase. Finally, Chapter 14 summarizes the book and discusses future challenges of systems engineering.

1.11 EXERCISES

1.1. What are the four professional organizations identified in this chapter? Visit their web sites and find out the purposes of each of the societies.

1.2. What is a concept map? Why is it useful as the introduction to a chapter?

1.3. Write a sentence about each of the eight relationships of systems identified in the concept map in Fig. 1.1.

1.4. Consider the automobile as a system.

(a) Identify the elements in an automobile system.

(b) Identify the major stakeholders for the development of a new automobile.

(c) Describe the automobile life cycle.

1.5. For each of the systems decision problems below, identify possible stakeholders who would be classified into the five stakeholder taxonomy categories. Provide a brief justification for each choice.

(a) The day manager of Todd French's up-scale dining restaurant Prunes hires you to help 'modernize' the restaurant's table reservation system.

(b) The Commissioner of the State of New York's Highway Department asks you to assist in selecting a new distributed computer simulation program for use in its Albany office.

(c) Danita Nolan, a London-based independent management consultant, asks you to help her with an organizational restructuring project involving the headquarters of DeWine Diamond Distributors.

(d) Fedek DeNut, one of the principals of a new high technology company called GammaRaze, has hired you to help them design an internet firewall application that automatically sends a computer disabling virus back to the 'From' address on any spam email passing through the firewall.

1.6. Which future stages of the system life cycle should be considered in the system concept stage? Explain.

1.7. What is systems thinking and who should be doing it? Explain.

1.8. What is systems engineering and what do systems engineers do? List four tasks.

1.9. What is engineering management and what do engineering managers do? List four tasks.

1.10. What is the relationship between systems engineers and engineering managers?

1.11. Describe the four phases of the SDP. Describe the relationships that exist between the SDP and a system life cycle.

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