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 on achieving the results, not the system for the system's sake . . . Systems give you a floor, not a ceiling.
>
> —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 describes 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 was founded to develop and disseminate the interdisciplinary principles and practices that enable the realization of successful systems. INCOSE organizes several meetings each year, including the annual INCOSE international symposium.

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- *The American Society for Engineering Management (ASEM)* [2] was founded in 1979 to assist its members in developing and improving their skills as practicing managers of engineering and technology and to promote the profession of engineering management. ASEM has an annual conference.
- *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. The ORS 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

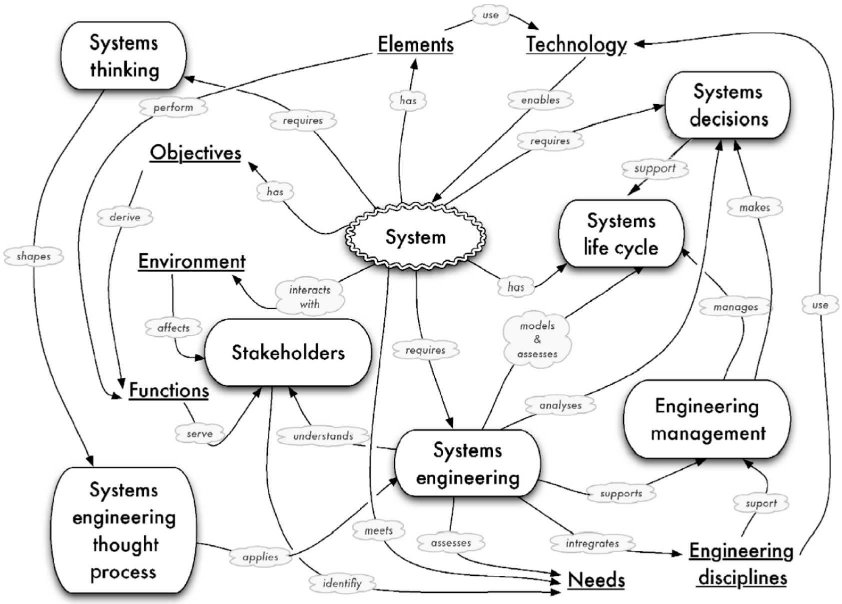

Figure 1.1 Concept map for Chapter 1.

key concepts we explore. This book addresses the concepts of systems, system life cycles, system engineering thought process, 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 Figure 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 (a) identified and assessed by systems engineers and (b) 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, the definitions of which have a long chronology in the management sciences literature [6]. A stakeholder, in the context of systems engineering, is a person or organization that has a vested interest in a system or its outputs. When such a system is an organization, this definition aligns with Freeman's: "any group of individuals who can affect or is affected by the achievement of the organization's objectives" [7]. It is this vested interest that establishes stakeholder 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 their success. Consequently, it is prudent and wise to identify and prioritize stakeholders in some organized fashion and to integrate their needs, wants, and desires in any possible candidate solution. In the systems decision process (SDP) that we introduce in 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 which are minimum requirements that any potential solution must meet. Alternatives failing to meet such requirements are eliminated from further consideration.

It is important to recognize that all stakeholder input is conditionally valid based upon their individual perspectives and vested interests. In other words, from their experience with and relationship to the problem or opportunity being addressed, and within the environment of openness they have chosen to engage the systems engineering team, the information they provide is accurate. The same can be said of the client's information. What acts to fill any gaps in this information is independent research on the part of the team. Research never stops once it has begun, and it begins prior to the first meeting with any client. This triumvirate of input, so critical to accurately defining a problem, is illustrated in Figure 1.2.

Managing stakeholder expectations has become so intrinsic to project success that a number of other formalizations have been developed to understand the inter-relationship between key individuals and organizations and the challenges that could arise as a project unfolds. Mitchell et al. [6] posit that stakeholders can be identified by their possessing or being attributed to possess one, two, or all three of the following attributes, which we generalize here to systems.

1. The stakeholder's *power* to influence the system.
2. The *legitimacy* of the stakeholder's relationship to the system.
3. The *urgency* of the stakeholder's claim on the system.

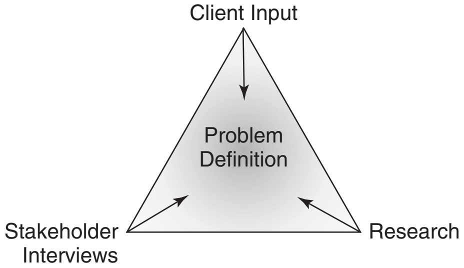

Figure 1.2 Three required ingredients for proper problem definition.

These attributes interact in a manner that defines *stakeholder salience*, the degree to which managers give priority to competing stakeholder claims. Salience then results in a classification of stakeholders by eight types shown in Figure 1.3. Throughout the systems decision process (SDP), there is a strong emphasis on identifying, engaging with, cultivating a trust relationship with, and crafting high value system solutions for a stakeholder called the *decision authority*. Mitchell's characterization clearly illustrates why this is so. The *decision maker* is a salience type 7 in Figure 1.3. The decision maker possesses an *urgency* to find a solution to the dilemma facing the system, the *power* to select and implement a value-based solution, and a recognized *legitimacy* by all stakeholders to make this selection.

Beyond understanding how stakeholders relate to one another and the system, these attributes are relevant to systems decision problems because Matty [8] has connected them to elements of value, a characteristic that comprises one-half of the tradeoff space advocated by the approach presented in this book (see Chapter 9). Stakeholder legitimacy strongly influences value identification; power strongly influences value positioning; and urgency strongly influences value execution.

Two other recent approaches have garnered broad interest in professional practice: the Stakeholder Circle™ and the Organizational Zoo [9].

The Stakeholder Circle™ is a commercially available software tool (www.stakeholder-management.com) which originated in a doctoral thesis [10, 23] motivated by several decades of project management experience in which "poor stakeholder engagement due to not seeing where some stakeholders were coming from led to project delivery failure." The software provides a visualization tool that measures and illustrates various stakeholders' power, influence, and positioning. It leverages a useful metaphor of stakeholders in a concentric circle surrounding the project itself. A five-step methodology is used to manage the stakeholder pool over the complete life cycle of a project: Identify the stakeholders and their needs, prioritize the stakeholders, visualize their relationship to the project, develop an engagement strategy, and monitor changes over time.

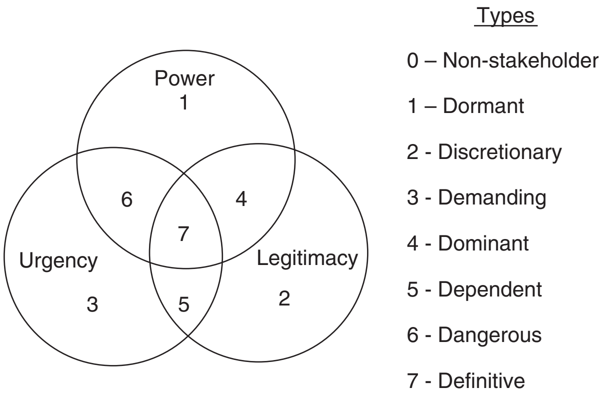

Figure 1.3 Stakeholder salience types [8].

The “Organizational Zoo” concept uses the metaphor of an animal kingdom and its familiar inhabitants to persuade stakeholders to see “how various situations and environments can facilitate or inhibit a knowledge-sharing culture.” By associating key individuals with stereotypical behaviors expressed by lions, eagles, ants, mice, rattlesnakes, hyenas, unicorns, and other creatures, stakeholders gain an understanding of how and why they are likely to react to project-related situations. This approach is more stakeholder-centric in its application than the Stakeholder Circle™, though both methods possess similarities to the use of rich pictures in soft system methodology [11].

Notice that this notion of a stakeholder makes no distinction based on the motivation of stakeholder vested interest. We should allow the possibility that for any system of reasonable presence in its surrounding environment, there exists a subset of adversarial 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 so on, are obvious examples of adversarial groups that might typify this malevolent category of stakeholders. Cleland [12] and Winch [13] introduce and elaborate upon several useful techniques for mitigating the risk to project success posed by hostile stakeholders.

More complex and challenging to identify are the less obvious stakeholders, namely, 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 Figure 1.7 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 six types. In some systems decisions it may be useful to include additional types of stakeholders. For example, it may be helpful to divide the User group into two subgroups—operators and maintainers—to more clearly identify their role in interacting with the system and to better classify their individual perspectives.

Decision Authority. The stakeholder(s) with ultimate decision gate authority to approve and implement a system solution.

Client. The person or organization that solicited systems decision support for a project; the source of project compensation; and/or the stakeholder that principally defines system requirements.

Owner. The person or organization responsible for proper and purposeful system operation.

User. The person or organization accountable for proper and purposeful system operation.

Consumer. The person(s) or organization(s) that realize direct or indirect benefits from the products or services of the system.

Interconnected. The persons or organizations that will be virtually or physically connected to the system and have potential benefits, costs, and/or risks caused by the connection.

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 nonrecreational vehicle rental in his region. When asked, the Client stated that while 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 a document 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 of the project and relevance of the impact of the decisions made increases in the pool of passive stakeholders.

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 engineering 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. For most systems decision challenges and all system design problems, when coupled with the uncertainties associated with cost, performance, and schedule, life cycle models become important tools to help these same engineers and managers understand, predict, and plan for how a system will evolve into the future.

A system's performance level, its supportability, and all associated costs are important considerations in any systems decision process. The process we introduce in Section 1.9 is fundamentally life cycle centered. 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 decision of whether or not to advance the system to the next stage is called a *decision gate*.

The performance of a system will degrade if it is not maintained properly. Maintaining a system consumes valuable resources. At some point, system owners are faced with critical decisions as to whether to continue to maintain the current system, modify the system to create new functionality with new objectives in mind, or retire the current system and replace it with a new system design. These decisions should be made taking into consideration 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 [14] 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 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 Figure 1.4, 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 [15].

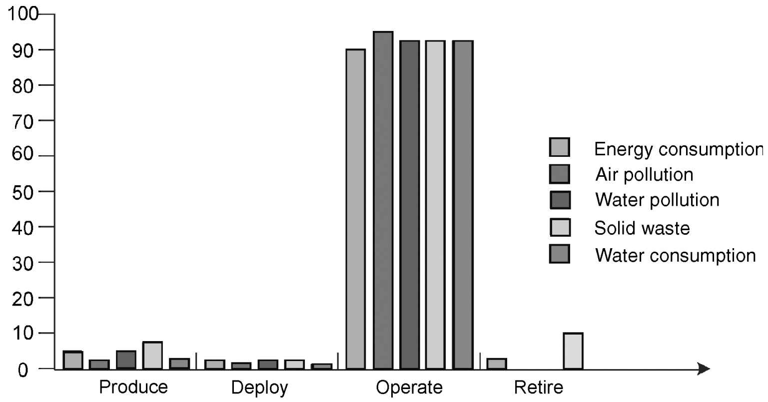

Figure 1.4 Life cycle assessment of environmental costs of a washing machine [14].

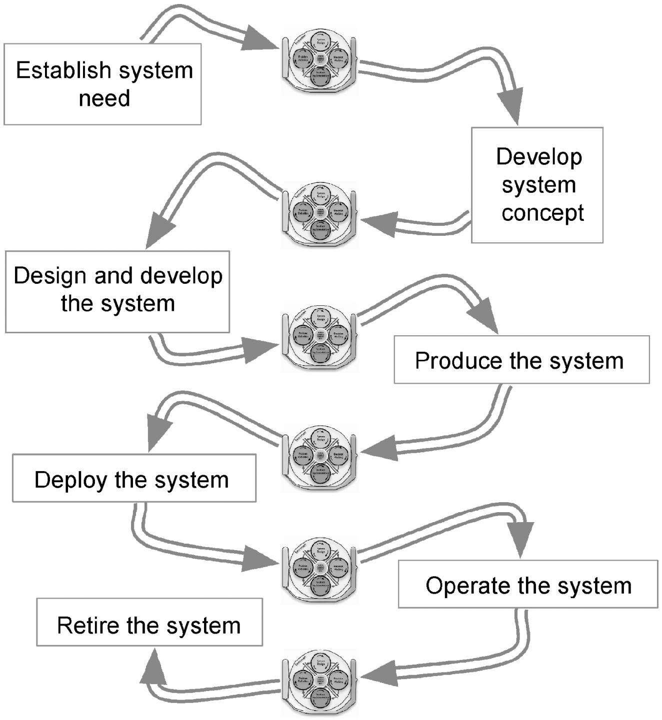

Figure 1.5 Systems decision process used throughout a system life cycle.

We use the system life cycle shown in Figure 1.5 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. The stages of this life cycle are aligned with how a system matures during its lifetime. We assume in our approach that there also exist 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.

Throughout all of these considerations, uncertainties are present to varying degrees. While some cost components can be fixed through contractual agreements, others are dependent upon environmental factors well beyond the control and well outside of the knowledge base of systems engineering teams. Illness, labor strikes, late detected code errors, raw material shortages, weather-related losses, legal challenges, and so on, are all phenomena of the type that impose cost increases despite the best intentions and planning of the team. Important modeling parameters such as

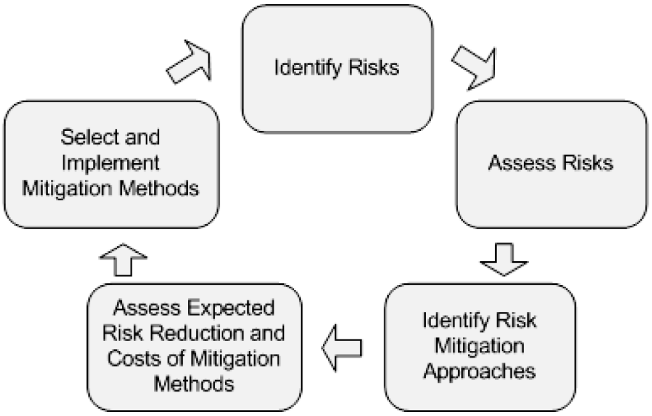

Figure 1.6 Simplified risk management cycle for systems decisions.

cost coefficients used in cost estimating relationships and component performance estimates are based on past data which, as all investment professionals will proclaim, are no guarantee of future performance. Performing the proper due diligence to identify, assess, and manage the potential downside impact of events driven by uncertainty such as these is the role of risk management.

As will be discussed in Chapter 3 in more detail, risk management involves a constant cycle of activities whose purpose is to leverage the most accurate information concerning uncertain events that could threaten system success to construct effective plans that eliminate, mitigate, relocate, or accept (and adapt to) the occurrence of these events [22]. Figure 1.6 shows a simplified risk management cycle whose elements are in common to all risk planning efforts.

Risk is a fundamental concept in systems decision making. Various forms of risk present themselves throughout the life cycle of a system: 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 mitigation planning, starts early and continues throughout a system's 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 not only between these markets but also among 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 precision 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 analysis effort. How can we ensure that critical interactions and relationships are represented in any model we build and that those that play only a minor role are discounted but not forgotten? For these 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 [16]. 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 on delivering value is what underscores every activity of modern systems engineering [17].

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Systems thinking combined with engineering principles focused on creating value for stakeholders is a modern world view embedded in systems engineering capable 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 [11].

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 and quantifying 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 makes 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 [18]. 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 systems 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. Thus, while it is critical to identify the boundaries that set the system under study apart from its environment, the system is immediately placed back into its environment for all subsequent considerations. The diversity of environmental factors shown in the SDP of Figure 1.7 clearly illustrates the need for systems engineering teams to

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	Leadership in 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 multilevel 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 incorporates components arising from environmental factors (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

be multidisciplinary. Each of these factors represent potential systems, stakeholders, and vested interests that will affect any systems decision and must be considered in the design and implementation of any feasible system solutions.

1.7 SYSTEMS ENGINEERING

The definition used by the INCOSE, the world's leading systems engineering professional society, aligns with the philosophy of 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.” [19]

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

- Understanding stakeholders (including clients, users, consumers) to identify system functions and objectives to meet their needs.
- Measuring how well system elements will perform functions to meet stakeholder 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), management, finance, manufacturing, services, logistics, marketing, sales, and so on.
- Remaining involved in many tasks throughout the system life cycle (defining client and user needs and required functionality; documenting requirements; design; identifying, assessing, and managing risks; and system validation).
- Participating in system cost analysis and resource management to ensure cost estimate credibility and system affordability.
- Performing system modeling and analysis to ensure 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?

Systems engineers are leaders of multidisciplinary technical teams. Azad Madni, an INCOSE Fellow, describes the expectations of systems engineers in the following way [18]: 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

The American Society for Engineering Management (ASEM) developed a definition of engineering management that aligns with the philosophy of this book:

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

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 1.7 shows the four dimensions of this

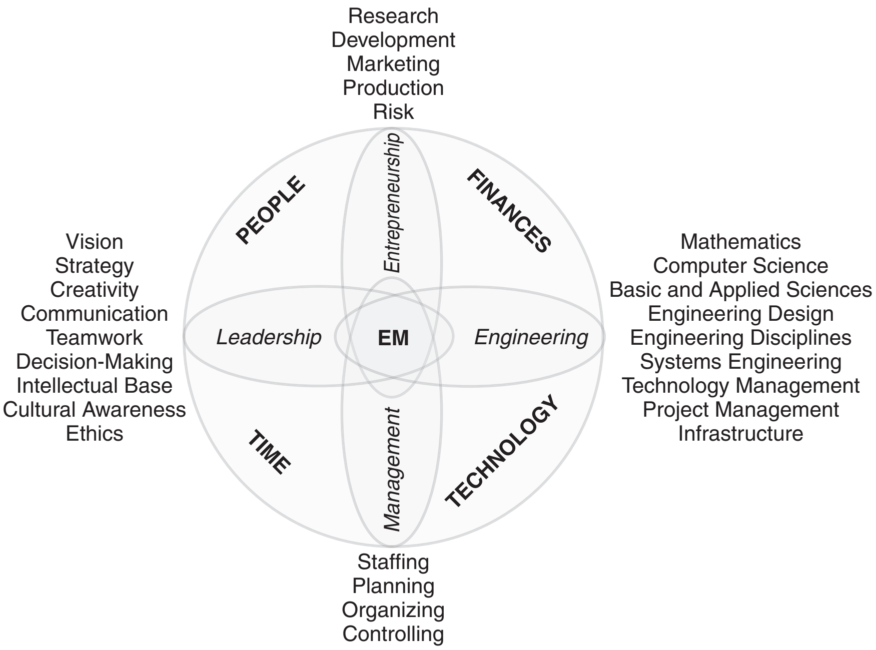

Figure 1.7 Engineering management.

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

Figure 1.7 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 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 as stand-alone or networked devices and applications. 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 resource, 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.

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 Figure 1.8.

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[1] Modified from original management diagram developed by our West Point colleague, Dr. John Farr.

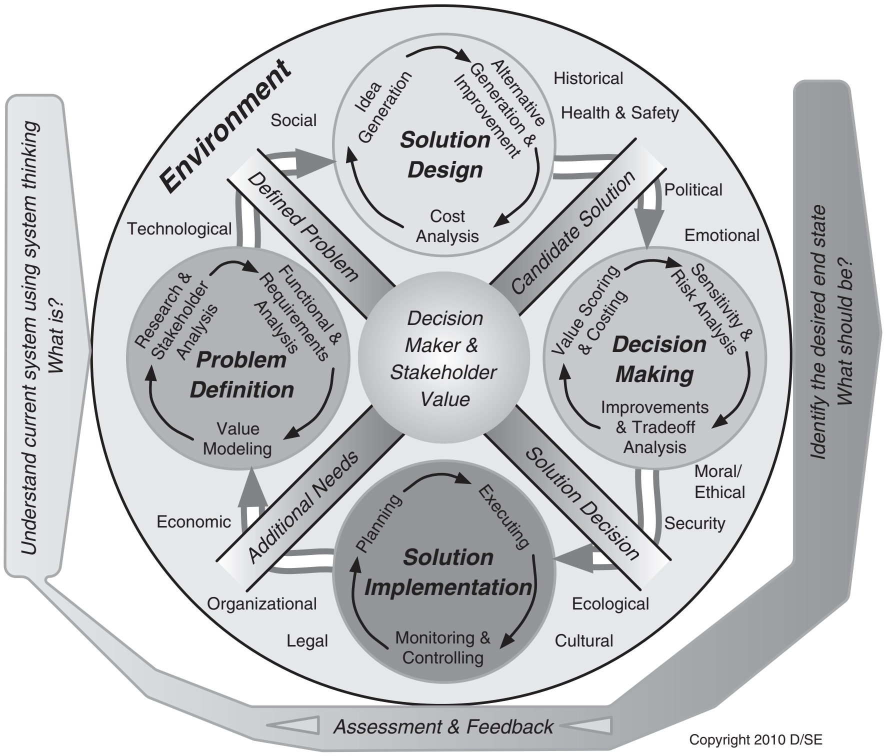

Figure 1.8 Systems decision process.

> The systems decision process (SDP) is a collaborative, iterative, and value-based decision process that can be applied in any system life cycle stage.

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 is a collaborative process that focuses 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 it highlights a requirement for multidisciplinary systems engineering teams.
- It emphasizes value creation (value modeling, idea generation and alternative improvement, and value-focused thinking) in addition to evaluation (scoring and sensitivity analysis) of alternatives.

The mathematical foundation of the SDP is found in multiobjective decision analysis [20]. This approach affords an ability to qualitatively and quantitatively define value by identifying requirements (solution screening criteria) and evaluation criteria that are essential to guide the development and evaluation of system solutions in all life cycle stages. Chapter 10 describes and illustrates the role of both qualitative and quantitative value models in the SDP. Chapter 11 describes and illustrates the process of using requirements to screen alternatives in order to develop feasible candidate solutions. Chapter 12 describes and illustrates the use of the quantitative value model to evaluate, analyze, and improve the candidate system solutions. Chapter 13 describes the use of planning, executing, and monitoring and control to ensure that value is delivered to the stakeholders.

The definition of a “systems decision” is very encompassing because a system can be defined in many ways. The SDP is a broadly applicable process that can be used to support a variety of enterprise and organizational decisions involving strategy, policy analysis, resource allocation, facility design and location, personnel hiring, event planning, college selection, and many others. The concepts and techniques arising from a systems thinking approach define systems, and the SDP provides the collaborative, dynamic, value-focused decision process that subsequently informs decision makers.

The SDP is a process, an organized way of thinking and taking action that maximizes the likelihood of success when supporting a systems decision. It captures the iterative, cyclical flow of activities that should be performed prior to passing through each of the critical decision gates shown. In practice and in educational settings, highlighting the modeling and analysis flow that typically accompanies the activities prescribed by the SDP greatly facilitates work breakdown and task assignments for team members. Figure 1.9 illustrates this product perspective of the decision support effort. While all of the elements shown are addressed in the chapters that follow, a few comments at this point will be helpful.

The diagram flows from top to bottom, aligning with the first three phases of the SDP: Problem Definition, Solution Design, and Decision Making. It culminates with a comprehensive trade space that supports the system solution decision gate immediately preceding the Solution Implementation phase. All of the analysis products developed in this flow carry over to the Solution Implementation phase once the solution decision has been made.

The top block contains the three primary products of the Problem Definition phase that must be developed before proceeding on: proper identification

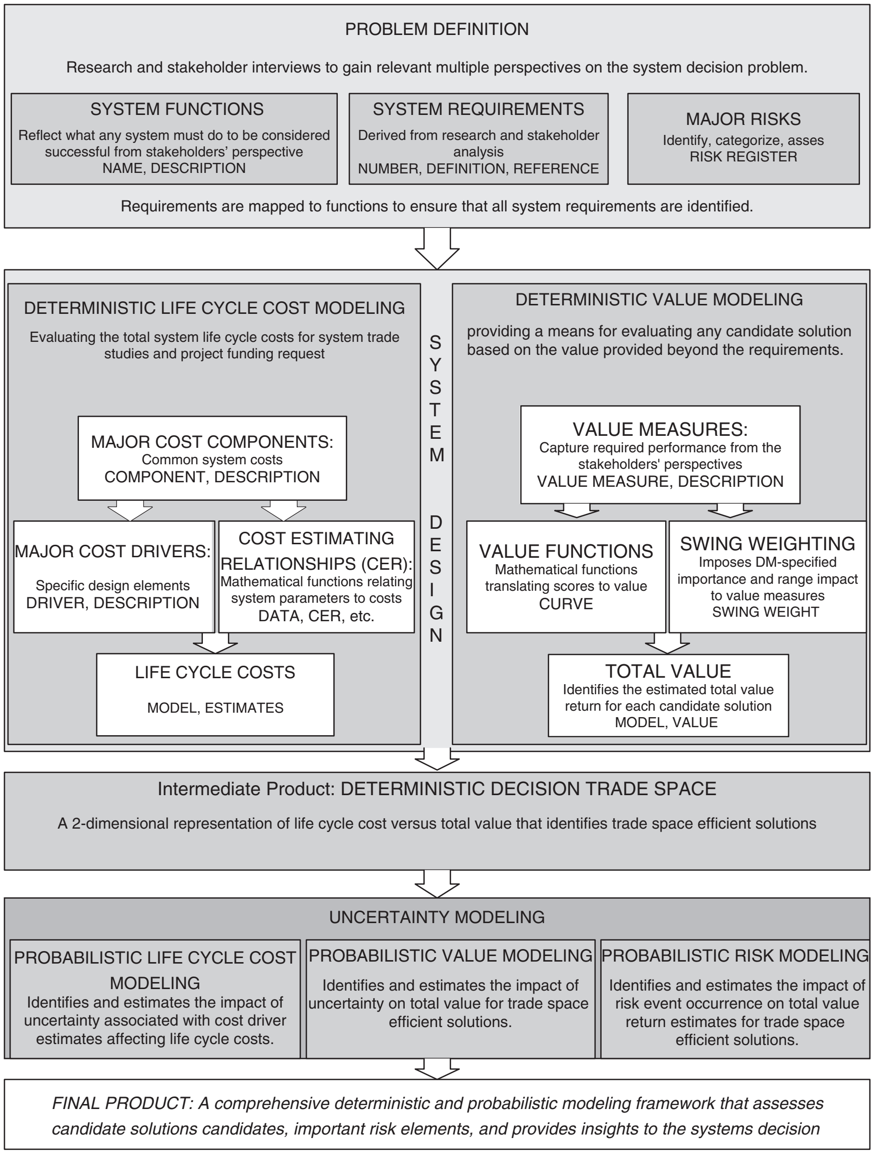

Figure 1.9 Modeling and analysis flow for typical SDP application.

and listing of systems functions, identifying and cataloging requirements, and identifying, categorizing, and assessing major risks. These represent what the system is expected to do, what every alternative must contain to be considered a feasible candidate solution, and the due diligence with respect to risk that every systems decision project must receive.

The second block shows a parallel, yet separate, effort to model and analyze life cycle costs and estimated value returns for candidate solutions under an assumption that uncertainties associated with any parameters or information input will be addressed after these efforts have been successfully concluded. Both of these deterministic analyses require candidate solutions against which they will be used. Hence, they are shown as intrinsic to solution design. Cost is separated from the value model construction because it defines the tradeoff dimension against which total value return is compared in the deterministic trade space shown.

Finally, any uncertainty or probabilistic considerations associated with the models and with their input, output, or modeling parameters are directly addressed. For most SDP applications, this is accomplished using Monte Carlo simulation (see Sections 5.5 and 12.6.1). Risk modeling, whether subjective or objective in nature, is usually a probabilistic venture. For this reason it is not shown as concurrent with the deterministic modeling efforts. For completeness however, we note that once the overall risk management process has begun early in a systems decision project, it is sustained throughout the systems decision process in each stage of the system life cycle.

The modeling and analysis flow ingrained in the SDP results in powerful decision support models. Teams developing these models need to keep in mind both who the models are being developed for and purpose they are intended to serve. The latter prevent models from becoming unwieldy by containing unneeded levels of sophistication and detail, or by exceeding their design scope. Adhering to the modeling purpose focuses team effort and prevents function creep from occurring as a result of late requirements imposed by stakeholders once the model is operating satisfactorily. The diagram in Figure 1.10 shows one such approach to identifying the modeling purpose [21].

The partitioned rectangle on top illustrates a spectrum of model use being distributed between 100% frequent and routine use on the left and 100% human interaction on the right. Arrayed along the axis below it are four modeling archetypes whose positioning approximates their characterization in the spectrum. Thus, a model whose purpose is purely exploratory in nature and whose results are intended to promote discussion among stakeholders would a position to the right extreme.

An example of an exploratory modeling purpose within the SDP framework would be a model constructed to examine the feasibility of futuristic, fully automated ground force engagement systems for the military. The interest in such a hypothetical case would not be in designing a system to accommodate stakeholder requirements, but rather to expose and discuss the implications with respect to the

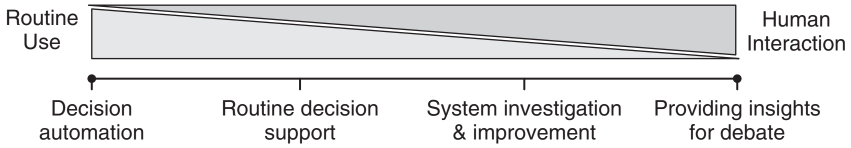

Figure 1.10 Spectrum of modeling purposes [21].

various environmental factors shown in Figure 1.8. Conversely, a decision support model built to aid a one-time systems decision might fall somewhere between the decision automation and routine decision support archetypes shown. While the cost, value, and risk models developed for a one-time decision require stakeholder interaction during their construction, they typically would not require intensive human interaction after their purpose has been served. Building sophisticated user interfaces to these models would not be a wise investment of the team's effort.

1.10 OVERVIEW

The organization of this book follows a logical and sequentially building pattern. Part I defines and describes system concepts. Chapter 2 introduces systems thinking as a discipline for thinking about complex, dynamic, and interacting systems, and it 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 that are essential for systems engineering trade studies and ensuring system affordability.

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. Do any of the four professional societies mentioned in this chapter have programs and resources specifically designed for students? If so, provide a brief summary of the services or products they provide that you might find valuable now.

1.2. Answer the following questions regarding a concept map.

- **(a)** How would you define a concept map? Is there a standard positioning of nouns and verbs on a concept map?
- **(b)** Is a concept map different from Checkland's [11] LUMAS model? Explain. Draw the LUMAS model that is associated with its definition.
- **(c)** Where on the spectrum of Figure 1.10 would you position a concept map as a model? Why?

1.3. Draw a concept map that illustrates the relationship between the objects within each of the following sets:

- **(a)** Space, planet, astronaut, satellite, space shuttle, NASA, missions, food, fuel, control center.
- **(b)** River, fish, water, insects, rocks, oxygen, riverbanks, trees, pollutants, EPA, boats.
- **(c)** Teachers, students, books, software applications, models, computers, graphics.
- **(d)** Facebook™, friends, hackers, pictures, personal information, lost classmates, jobs, services, movies.

1.4. Write a single sentence about each of the eight relationships of systems identified in the concept map in Figure 1.1.

1.5. Consider the automobile as a system.

- **(a)** Select a specific automobile introduced this year, and identify the major components of its system.
- **(b)** What new functions does this automobile do that set it apart from previous versions offered by the manufacturer?
- **(c)** Describe the life cycle this automobile.
- **(d)** Describe the major environmental factors that should have been considered when designing this new automobile. Do you think they were? Explain.
- **(e)** Using the environmental factors shown in the SDP, identify the major stakeholders whom you think have a vested interest this new automobile as a system.
- **(f)** For each of the stakeholders that you identified in part (e), conduct a sufficient amount of research to confirm the vested interest you suspected they held. List the source.

1.6. For each of the systems decision problems below, identify any possible stakeholders who could be classified into the six stakeholder taxonomy categories. Provide a brief justification for each choice.

- **(a)** The day manager of Todd French's up-scale dining restaurant called “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 software application that automatically sends a computer disabling virus back to the "From" address on any spam email passing through the firewall.
- **(e)** The musician Boi Rappa has reached such success with his last five DVD releases that he is planning on creating a new line of casual clothing for suburban teenagers. He hires you to help design a successful system to accomlish this.

1.7. Which future stages of a system life cycle are most important to be considered during the system concept stage? Explain.

1.8. Define "systems thinking." Does it have any utility outside of systems engineering? Explain.

1.9. What is systems engineering? List four of the major activities that systems engineers engage in.

1.10. What is engineering management and what do engineering managers do? List four of their major activities.

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

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

1.13. Are there any environmental factors missing from those listed in the SDP? Why would you include these, if at all?

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