Risk Modeling, Assessment, and Management
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Public interest in the field of risk analysis has expanded in leaps and bounds during the recent three decades. Furthermore, risk analysis has emerged as an effective and comprehensive procedure that supplements and complements the overall management of almost all aspects of our lives. Managers of health care, the environment, and physical infrastructure systems of systems (e.g., water resources, transportation, infrastructure interdependencies, homeland and cyber security, and electric power, to cite a few) all incorporate risk analysis in their decisionmaking processes. The omnipresent adaptations of risk analysis by many disciplines, along with its deployment by industry and government agencies in decisionmaking, have led to an unprecedented development of theory, methodology, and practical tools. As a fellow of seven diverse professional societies, I find technical articles on risk analysis published in all of their journals. These articles address concepts, tools, technologies, and methodologies that have been developed and practiced in such areas as planning, design, development, system integration, prototyping, and construction of physical infrastructure; in reliability, quality control, and maintenance; and in the estimation of costs and schedules and in project management.

The challenge that faces society today is that all of this knowledge has not been fully duplicated, shared, and transferred from one field of endeavor to another. This calls for a concerted effort to improve our understanding of the commonalities and differences among diverse fields for the mutual benefit of society as a whole. Such a transfer of knowledge has always been the key to advancing the natural, social, and behavioral sciences, as well as engineering. I believe that we can start meeting this challenge through our college and university classrooms and through continuing education programs in industry and government. It is essential to build bridges among the disciplines and to facilitate the process of learning from each other.

Risk, a measure of the probability and severity of adverse effects, is a concept that many find difficult to comprehend, and its quantification has challenged and confused laypersons and professionals alike. There are myriad fundamental reasons for this state of affairs. One is that risk is a complex composition and amalgamation of two components—one real (the potential damage, or unfavorable adverse effects and consequences), the other (the likelihood of projected adverse consequences), measured or estimated through an imagined mathematical human construct termed probability. Probability per se is intangible, yet its omnipresence in risk-based decisionmaking is indisputable. Furthermore, the measure of the probability that dominates the measure
of risk is itself uncertain, especially for rare and extreme events—for example, when there exists an element of surprise.

This book seeks to balance the quantitative and empirical dimensions of risk assessment and management with the more qualitative and normative aspects of decisionmaking under risk and uncertainty. In particular, select analytical methods and tools are presented without advanced mathematics or with no mathematics at all, to enable the less math-oriented reader to benefit from them. For example, hierarchical holographic modeling (HHM) is introduced and discussed in Chapter 3 for its value as a comprehensive and systemic tool for risk identification. While all mathematical details for hierarchical coordination (within the HHM philosophy) are mostly left out of the text, they are included in my earlier book, cited in Chapter 1, *Hierarchical Multiobjective Analysis of Large-Scale Systems* [Haimes et al., 1990]. Myriad case study applications of the HHM approach for risk identification are presented here, including studies conducted for the Presidential Commission for Critical Infrastructure Protection, the US Army, General Motors, the Federal Bureau of Investigation, Virginia Department of Transportation, VA Governor’s Office, Institute for Information Infrastructure Protection (I3P), US Department of Homeland Security, and the US Department of Defense, among others. The HHM philosophy is grounded on the premise that complex systems, such as air traffic control systems, should be studied and modeled in more than one way. Because such complexities cannot be adequately modeled or represented through a planar or single model or vision, overlapping of these visions is unavoidable. This can actually be helpful in providing a holistic appreciation of the interconnectedness among the various components, aspects, objectives, and decisionmakers associated with a system.

Furthermore, this holistic approach stems from the realization that the process of risk assessment and management is a blend of art and science; and although mathematical formulation and modeling of a problem are important for sound decisionmaking, they are not by themselves sufficient for that purpose. Clearly, institutional, organizational, managerial, political, and cultural considerations, among others, can be as dominant as scientific, technological, economic, or financial aspects, and must be accounted for in the decisionmaking process.

Consider, for example, the protection and management of a major water supply system. Deploying the HHM approach discussed in Chapter 3, it is possible to address the holistic nature of the system in terms of its hierarchical decisionmaking structure, which includes various time horizons, multiple decisionmakers, stakeholders, and users of the water supply system, and a host of hydrological, technological, legal, and other socio-economic conditions and factors that require consideration. The effective identification of the myriad sources of risk to which natural, cyber, or physical system are exposed is markedly improved by considering all real, perceived, or imaginary risks from their multiple decompositions, visions, and perspectives.

The adaptive multiplayer HHM (AMP-HHM) game, introduced in Chapter 3, is an important concept with the potential to serve as a repeatable, adaptive, and systemic process that can contribute to tracking terrorism scenarios [Haimes and Horowitz, 2004]. It builds on fundamental principles of systems engineering, systems modeling, and risk analysis. The AMP-HHM game captures multiple perspectives of a system through computer-based interactions. For example, a two-player game creates two opposing views of the opportunities for carrying out acts of terrorism: one developed by a Blue team defending against terrorism, and the other by a Red team planning to carry out a terrorist act.

This book draws on my experience in the practice of risk-based decisionmaking in government and industry, and it builds on results from numerous management-based projects. It is also based on homework and exams compiled during over 40 years of teaching graduate courses in risk analysis at Case Western Reserve University and at the University of Virginia. In addition, the text incorporates the results of close to four decades of research and consulting work with industry and government that has resulted in over 80 masters and 50 doctoral theses and numerous technical papers on risk analysis.

I have also gained experience and knowledge from organizing and chairing 12 Engineering Foundation conferences on risk-based decisionmaking since 1980.
The interaction with the participants in these intensely focused meetings has markedly influenced the structure of this book. I have benefited as well from the foresight and practical orientation of hundreds of participants in numerous short courses that I taught along with colleagues from 1968 to the present. For example, for 29 consecutive years, I offered a 1-week short course titled *Hierarchical-Multiobjective Approach in Water Resources Planning and Management*. I have been offering a graduate course on risk analysis at the University of Virginia since 1987.

In preparing the first (1998), second (2004), third (2009), and fourth (2016) editions of this book, I have been guided by the following premises and needs:

1. Increasingly, international as well as US federal and state legislators and regulatory agencies have been addressing the assessment and management of risk more explicitly, whether in environmental and health protection, human safety, manufacturing, or security.

2. There is a need for a text that presents both basic and advanced methodologies in risk analysis at a sufficiently detailed level so that the reader can confidently apply specific methods to appropriate problems. To achieve this fundamental goal, risk methodologies presented in this book are supplemented with example problems and, when possible, with case study applications.

3. The modeling and assessment of risk necessarily lead to noncommensurate and conflicting objectives. Invariably, the reduction or the management of risk requires the expenditure of funds and other resources. Thus, at its simplest modeling level, at least two objectives must be considered: (i) minimizing and managing risk (e.g., environmental risk, health risk, and risk of terrorism) and (ii) minimizing the cost associated with achieving these goals. Although the concept of a multiattribute utility may be grounded on a brilliant theory, it might not be practical when applied to real-world problems and human decisionmakers. Therefore, this book emphasizes multiobjective trade-off analysis, which avoids the pre-commensuration of risks, costs, and benefits through a single utopian utility function.

4. Risk has been commonly quantified through the mathematical expectation formula. Fundamentally, the mathematical expected value concept precommensurates low-frequency events of extreme or catastrophic consequences with high-frequency events of minor impact. Although the mathematical expectation provides a valuable measure of risk, it fails to recognize or accentuate extreme event consequences. To complement the expected value of risk, this book presents a supplementary measure termed the *conditional expected value of risk* and applies it throughout the text whenever possible.

5. One of the most difficult tasks that has been least addressed in most systems analysis literature is knowing how to model a system. Most systems engineering and operations research texts offer a wealth of theories and methodologies for problem solving—that is, optimizing a pre-assumed system’s model. Furthermore, most texts neglect the art and science of model building and the centrality of the state variables and other building blocks in model formulation. Given that risk cannot be managed unless it is properly assessed and that the best assessment process is realized through some form of model, the modeling process becomes an imperative step in the systemic assessment and management of risk. Consequently, this book devotes a concerted effort to the modeling task as a prelude to the ultimate assessment and management of risk.

6. Many tend to consider the field of risk analysis as a separate, independent, and well-defined discipline of its own. However, this book views the theory and methodology of risk analysis within the broader context of systems engineering (e.g., modeling and optimization), albeit with more emphasis on the stochasticity of the system and its components. This philosophical approach legitimizes the pedagogy of the separation and subsequent integration of systems modeling (risk assessment) and systems optimization and implementation (risk management). It also invites the risk
analyst to benefit fully from the utilization of the vast theories, methodologies, tools, and experience generated under the broader rubric of systems analysis and systems engineering. Indeed, imperative in any sound risk analysis is the use of such fundamental concepts as modeling, optimization, simulation, multiobjective trade-offs, regression, fault trees, fault tolerance, multiobjective decision trees, event trees, forecasting, scheduling, and numerous other tools for decisionmaking.

A book on such a broad subject as risk analysis has the potential for a significantly diverse readership. Thus, although there is a unifying theme for the theory and methodology developed for use in risk analysis, its applications can encompass every possible field and discipline. Furthermore, readers may have different levels of interest in the quantitative/empirical and the qualitative/normative aspects of risk. To at least partially meet this challenge, this book is organized in two parts.

Part I—Fundamentals of Risk Modeling, Assessment, and Management—which includes Chapters 1–7 and the Appendix to Part I, focuses on the more philosophical, conceptual, and decisionmaking aspects of risk analysis. It addresses fundamental concepts of modeling and optimization of systems under conditions of risk and uncertainty, articulates the intricate processes of risk assessment and management, and presents commonly known and newly developed risk analysis methodologies.

Chapter 1 provides an overview of risk analysis in the broader context of systems engineering. For example, relating Stephen Covey’s book, The Seven Habits of Highly Effective People [1989], to systems engineering principles and from there to risk analysis is one way in which the text attempts to bridge the quantitative and qualitative dimensions of risk analysis.

Chapter 2 introduces the reader to the fundamental building blocks of mathematical models—concepts that will be understood by all who have had two courses in college calculus. The chapter has been modified and updated with a major new section on the complex definition of risk, vulnerability, and resilience: a systems-based approach. Indeed, all readers in managerial and decisionmaking positions who have a basic knowledge of college calculus and some understanding of probability can benefit from Part I of this book. To further assist the reader, the Appendix provides a review of linear and nonlinear optimization, and Bayesian analysis.

Chapter 3 (as noted earlier) addresses the HHM philosophy for risk identification and introduces the reader to the contributions made to risk management by social and behavioral scientists.

Chapter 4, as its title indicates, offers a review of fundamentals in decision analysis and the construction of evidence-based probabilities for use in decisionmaking. At various levels of the decisionmaking process, managers often encounter situations where sparse statistical data do not lend themselves to the construction of probabilities. Through illustrative examples and case studies, this chapter will make it possible for such managers to augment evidence gained through their professional experience with evidence collected through other means.

Chapter 5 introduces the uninitiated reader to the analysis of multiple objectives. One of the characteristic features of risk-based decisionmaking is the imperative need to make trade-offs among all costs, benefits, and risks. Although multiobjective analysis is the focus of this chapter, utility theory is related to this and is also briefly discussed. While the centrality of multiobjective trade-off analysis in decisionmaking is dominant in this book, and more than one chapter would be needed to adequately addresses this subject, the reader is referred to a newly republished textbook (2008) by Dover Publishing company, titled Multiobjective Decision Making: Theory and Methodology, by Vira Chankong and Yacov Y. Haimes.

Chapter 6 discusses sensitivity analysis and, through an uncertainty taxonomy, the broader issues that characterize uncertainty in general; also, it develops the uncertainty sensitivity index method (USIM) and its extensions. Only the extensions of the USIM component of this chapter require advance knowledge of optimization.

Chapter 7 presents a modified and improved risk filtering ranking, and management (RFRM) method. The risk ranking and filtering (RRF) method, which was developed for NASA in the early 1990s and was introduced in Chapter 4 in the
first edition of this book, is only briefly discussed in this edition. The Appendix to Part I provides an overview of optimization techniques, including linear programming, Lagrange multipliers, and dynamic programming.

Part II—Advances in Risk Modeling, Assessment, and Management—which includes Chapters 8–19, shares with the readers the theory and ensuing methodology that define the state-of-the-art of risk analysis.

Chapter 8 covers the concept of conditional expected value of risk and discusses the partitioned multiobjective risk method (PMRM), which complements and supplements the expected (unconditional) value of risk. Several examples illustrate the erroneous analysis that is likely to result from using the conventional (unconditional) expected value as the sole measure of risk.

Chapter 9 extends the single-objective decision-tree analysis introduced in Chapter 4 to incorporate multiple objectives, and explains the multiple objective decision tree (MODET) method.

Chapter 10 extends the modeling, assessment, and management of risk from the static, time-invariant case to the dynamic case. Also, the multiobjective risk-impact analysis method (MRIAM) is described and is related to the MODET. Because the two methodologies are useful in decisionmaking at each step of the system life cycle, the theoretical and methodological relationship between MRIAM and MODET developed by Dicdican and Haimes [2005] is also presented in this chapter.

Chapter 11 incorporates the statistics of extremes with the conditional expected value of risk (developed through the PMRM), and thus it extends the theory and methodology upon which the PMRM is grounded.

Chapter 12 The old section on Bayesian analysis has been moved to the Appendix, and the remainder of the text has been replaced with systems-based guiding principles for risk modeling, planning, assessment, management, and communication.

Chapter 13 discusses the basics of fault-tree analysis, focusing on the central concept of minimal cut sets. It also introduces the distribution analyzer and risk evaluator (DARE) method using fault trees, and failure mode, effects, and criticality analysis (FMECA).

Chapter 14 explains the Multiobjective Statistical Method (MSM), where the symbiotic relationship between model simulation and multiobjective trade-off analysis is exploited. This chapter also focuses on modeling problems with one or more random variables, where the state variables play a central role in the modeling process.

Chapter 15 addresses principles and guidelines for project management and associated risk assessment and management issues, as well as the life cycle of software development.

Chapter 16 The old text on applying risk analysis to the space mission has been replaced with modeling complex systems of systems with phantom system models in recognition that the natural and the constructed environment are complex interdependent and interconnected systems of systems.

Chapter 17 The old text on risk modeling, assessment, and management of terrorism has been replaced with an updated text that builds on hierarchical holographic modeling (introduced in Chapter 3), with a focus on an adaptive two-player hierarchical holographic modeling game for counterterrorism intelligence analysis.

Chapter 18 is devoted in its entirety to modeling the interdependencies among infrastructures and sectors of the economy through the Leontief-based inoperability input–output model (IIM) and its derivatives: the dynamic IIM (DIIM), multiregional IIM (RIIM), and uncertainty IIM (UIIM). Detailed step-by-step derivations are presented of all the models introduced in this chapter. The chapter provides an extensive discussion on national, regional, state, and local supporting databases for the IIM and its derivatives.

Chapter 19 adds a sixth case study in this edition to further demonstrate the application of the risk-based methodologies introduced in this book. The theme of the sixth case study is on sequential Pareto-optimal decisions made within emergent complex systems of systems, with an application to the FAA NextGen.

The Appendix has been expanded to include Bayesian analysis for the prediction of chemical carcinogenicity (moved from old Chapter 12), and the Farmer’s Dilemma, introduced in Chapter 1, has been formulated and solved using a deterministic linear model in the Appendix.
This fourth edition comes with a companion website resulting from a longstanding collaboration with my colleagues and former students, Dr. Joost Santos and Dr. Zhenyu Guo. Although a large number of solved problems in risk-based decisionmaking are included in the text, the companion website contains over 200 exercises and problems that feature risk analysis theories, methodologies, and applications accompanies this Fourth Edition.

The objective of the companion website is to provide reinforced learning experiences for risk analysis scholars and practitioners through a diverse set of problems and hands-on exercises. For better tractability, these are organized similar to the chapters of this book and range from foundation topics (e.g., building blocks of modeling and structuring of risk scenarios) to relatively more complex concepts (e.g., multiobjective trade-off analysis and statistics of extremes). The problems encompass a broad spectrum of applications including disaster analysis, industrial safety, trans-
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The solved example problems add an important dimension to this book. They were developed as homework assignments or exams in the graduate course on risk analysis that I have taught for the last 20 years. Many of these problems were initiated and formulated by students. I am particularly indebted to the following students for their contributions: James Fellows, Hendrik Frohwein, Amy Chan Hilton, Bronwyn Jackson, Matthew M. Mehalik, Silla K. Mullei, David Romo Murillo, Michael A. Reynolds, Lauren A. Schiff, Yong Seon, Julie M. Stocker, Vijay Tuilsiani, Chenxi Wang, and Ganghuai Wang.

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Y. Y. H.

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Y. Y. H.
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I thank my wife Sonia once again for her constant encouragement and loving support. This fourth edition is again dedicated to her.

Y. Y. H.
Part I

Fundamentals of Risk Modeling, Assessment, and Management
1

The Art and Science of Systems and Risk Analysis

1.1 INTRODUCTION

Risk-based decisionmaking and risk-based approaches in decisionmaking are terms frequently used to indicate that some systemic process that deals with uncertainties is being used to formulate policy options and assess their various distributional impacts and ramifications. Today, an ever-increasing number of professionals and managers in industry, government, and academia are devoting a large portion of their time and resources to the task of improving their understanding and approach to risk-based decisionmaking. In this pursuit, they invariably rediscover (often with considerable frustration) the truism: The more you know about a complex subject, the more you realize how much still remains unknown. There are three fundamental reasons for the complexity of this subject. One is that decisionmaking under uncertainty literally encompasses every facet, dimension, and aspect of our lives. It affects us at the personal, corporate, and governmental levels, and it also affects us during the planning, development, design, operation, and management phases. Uncertainty colors the decisionmaking process regardless of whether it (i) involves one or more parties, (ii) is constrained by economic or environmental considerations, (iii) is driven by sociopolitical or geographical forces, (iv) is directed by scientific or technological know-how, or (v) is influenced by various power brokers and stakeholders. Uncertainty is inherent when the process attempts to answer the set of questions posed by William W. Lowrance: “Who should decide on the acceptability of what risk, for whom, in what terms, and why?” [Lowrance, 1976]. The second reason why risk-based decisionmaking is complex is that it is cross-disciplinary. The subject has been further complicated by the development of diverse approaches of varying reliability. Some methods, which on occasion produce fallacious results and conclusions, have become entrenched and would be hard to eradicate. The third reason is grounded on the need to make trade-offs among all relevant and important costs, benefits, and risks in a multiobjective framework, without assigning weights with which to commensurate risks, costs, and benefits.

In his book Powershift, Alvin Toffler [1991] states:

As we advance into the Terra Incognito of tomorrow, it is better to have a general and incomplete map,
subject to revision and correction, than to have no map at all.

Translating Toffler’s vision into the risk assessment process implies that a limited database is no excuse for not conducting sound risk assessment. On the contrary, with less knowledge of a system, the need for risk assessment and management becomes more imperative.

Consider, for example, the risks associated with natural hazards. Causes for major natural hazards are many and diverse, and the risks associated with these natural hazards affect human lives, the environment, the economy, and the country’s social well-being. Hurricane Katrina, which struck New Orleans in the United States on August 29, 2005, killing a thousand people and destroying properties, levees, and other physical infrastructures worth billions of dollars, is a classic example of a natural hazard with catastrophic effects [McQuaid and Schleifstein, 2006]. The medium within which many of these risks manifest themselves, however, is engineering-based physical infrastructure—dams, levees, water distribution systems, wastewater treatment plants, transportation systems (roads, bridges, freeways, and ports), communication systems, and hospitals, to cite a few. Thus, when addressing the risks associated with natural hazards, such as earthquakes and major floods, or willful hazards, that is, acts of terrorism, one must also account for the impact of these hazards on the integrity, reliability, and performance of engineering-based physical and human-based societal infrastructures. The next step is to assess the consequences—the impact on human and nonhuman populations and on the socioeconomic fabric of large and small communities.

Thus, risk assessment and management must be an integral part of the decisionmaking process, rather than a gratuitous add-on technical analysis. Figure 1.1 depicts this concept and indicates the ultimate need to balance all the uncertain benefits and costs.

For the purpose of this book, risk is defined as a measure of the probability and severity of adverse effects [Lowrance, 1976]. Lowrance also makes the distinction between risk and safety: Measuring risk is an empirical, quantitative, scientific activity (e.g., measuring the probability and severity of harm). Judging safety is judging the acceptability of risks—a normative, qualitative, political activity. Indeed, those private and public organizations that can successfully address the risks inherent in their business—whether in environmental protection, resource availability, natural forces, the reliability of man–machine systems, or future use of new technology—will dominate the technological and service-based market.

The premise that risk assessment and management must be an integral part of the overall decisionmaking process necessitates following a systemic, holistic approach to dealing with risk. Such a holistic approach builds on the principles and philosophy upon which systems analysis and systems engineering are grounded.

### 1.2 SYSTEMS ENGINEERING

#### 1.2.1 What Is a System?

The human body and each organ within it, electric power grids and all large-scale physical infrastructures, educational systems from preschool to higher education, and myriad other human, organizational, hardware, and software systems are large-scale, complex, multiscale interconnected and interdependent systems with life cycles that are characterized by risk and uncertainty along with emergent behavior. But exactly what is a system? Webster’s Third New
International Dictionary offers several insightful definitions:

A complex unity formed of many often diverse parts subject to a common plan or serving a common purpose; an aggregation or assemblage of objects joined in regular interaction or interdependence; a set of units combined by nature or art to form an integral, organic, or organizational whole.

Almost every living entity, all infrastructures, both the natural and constructed environment, and the entire households of tools and equipment are complex systems often composed of myriad subsystems that in their essence constitute systems of systems (SoS). Each is characterized by a hierarchy of interacting and networked components with multiple functions, operations, efficiencies, and costs; the component systems are selected and coordinated according to some existing trade-offs between multiple objectives and operational perspectives. Clearly, no single model can ever attempt to capture the essence of such systems—their multiple dimensions and perspectives.

1.2.2 What Is Systems Engineering?

Even after over half a century of systems engineering as a discipline, many engineers find themselves perplexed about the following question: What is systems engineering?

Systems engineering is distinguished by its practical philosophy that advocates holism in cognition and in decisionmaking. This philosophy is grounded on the arts, natural and behavioral sciences, and engineering and is supported by a complement of modeling methodologies, state-space theory, optimization and simulation techniques, data management procedures, and decisionmaking approaches. The ultimate purpose is to (i) build an understanding of the dynamic system’s nature, functional behavior, and interaction with its environment, (ii) improve the decisionmaking process (e.g., in planning, design, development, operation, management), and (iii) identify, quantify, and evaluate risks, and epistemic and aleatory uncertainties for a guided and actionable decisionmaking process.

One way of gaining greater understanding of systems engineering is to build on the well-publicized ideas of Stephen R. Covey in his best-selling book, The Seven Habits of Highly Effective People [Covey, 1989], and to relate these seven habits to various steps that constitute systems thinking or the systems approach to problem solving. Indeed, Covey’s journey for personal development as detailed in his book has much in common with the holistic systems concept that constitutes the foundation of the field of systems engineering. Even the transformation that Covey espouses, from thinking in terms of you to me to we, is similar to moving from the perception of interactions as reactive or linear to a holistic view of connected relationships. Viewed in parallel, the two philosophies—Covey’s and the systems approach—have a lot in common. The question is: How are they related, and what can they gain from each other?

Analyzing a system cannot be a selective process, subject to the single perspective of an analyst who is responsible for deciphering the maze of disparate and other knowledge. Rather, a holistic approach encompasses the multiple visions and perspectives inherent in any vast pool of data and information. Such a systemic process is imperative in order to successfully understand and address the complexity of an SoS [NRC, 2002].

1.2.3 Historical Perspectives of Systems Engineering

1.2.3.1 Classical philosophers who practiced holistic systems thinking

The systems concept has a long history. The art and science of systems engineering as a natural philosophy can be traced to Greek philosophers. Although the term system itself was not emphasized in earlier writings, the history of this concept includes many illustrious names, including Plato (428–348 b.c.) [Hutchins, 1952] and Aristotle (384–322 b.c.). The writings of Baron von Leibniz (1646–1716), a mathematician and philosopher, are directed by holism and systems thinking. He shares with Isaac Newton (1642–1727) the distinction of developing the theory of differential and integral calculus. By quantifying the causal relationships among the interplanetary SoS, Newton represents the epitome of a systems philosopher and modeler. In their seminal book, Isaac Newton,
The Principia, Cohen and Whitman [1999] write (p. 20):

Newton's discovery of interplanetary forces as a special instance of universal gravity enables us to specify two goals of the Principia. The first is to show the conditions under which Kepler's laws of planetary motion are exactly or accurately true; the second is to explore how these laws must be modified in the world of observed nature by perturbations in the motions of planets and their moons.

Johann Gottlieb Fichte (1762–1814) introduced the idea of synthesis—one of the fundamental concepts of systems thinking. For example, he argued that freedom can never be understood unless one loses it. Thus, the thesis is that a man is born free, the loss of freedom is the antithesis, and the ability to enjoy freedom and do good works with it is the synthesis. In other words, to develop an understanding of a system as a whole (synthesis), one must appreciate and understand the roles and perspectives of its subsystems (thesis and antithesis). Georg Hegel (1770–1831), a contemporary of Fichte, was one of the most influential thinkers of his time. Like Aristotle before him, Hegel tried to develop a system of philosophy in which all the contributions of his major predecessors would be integrated. His Encyclopedia of the Philosophical Sciences (1817), which contains his comprehensive thoughts in a condensed form, provides important foundations for the concept of holism and the overall systems approach [Hegel, 1952].

Around 1912, Max Wertheimer, Kurt Koffka, and Wolfgang Kohler founded the Gestalt psychology, which emphasizes the study of experience as a unified whole. The German word gestalt means pattern, form, or shape [World Book, Inc., 1980]:

Gestalt psychologists believe that pattern, or form, is the most important part of experience. The whole pattern gives meaning to each individual element of experience. In other words, the whole is more important than the sum of its parts. Gestalt psychology greatly influenced the study of human perception, and psychologists used Gestalt ideas in developing several principles—for example, the principle of closure (people tend to see incomplete patterns as complete or unified wholes).

1.2.3.2 Modern systems foundations

During his distinguished career, Albert Einstein attempted to develop a unified theory that embraces all forces of nature as a system. Feynman et al. [1963] describe a hierarchy or continuum of physical laws as distinct systems or disciplines that are cooperating and interdependent. Modern systems foundations are attributed to select scholars. Among them is Norbert Wiener, who in 1948 published his seminal book Cybernetics. Wiener's work was the outgrowth and development of computer technology, information theory, self-regulating machines, and feedback control. In the second edition of Cybernetics [1961], Wiener commented on the work of Leibniz:

At this point there enters an element which occurs repeatedly in the history of cybernetics—the influence of mathematical logic. If I were to choose a patron saint for cybernetics out of the history of science, I should have to choose Leibniz. The philosophy of Leibniz centers about two closely related concepts—that of a universal symbolism and that of a calculus of reasoning. From these are descended the mathematical notation and the symbolic logic of the present day.

Ludwig von Bertalanffy coined the term general systems theory around 1950; it is documented in his seminal book, General Systems Theory: Foundations, Development, Applications [Bertalanffy, 1968/1976]. The following quotes from pages 9 to 11 are of particular interest:

In the last two decades we have witnessed the emergence of the “system” as a key concept in scientific research. Systems, of course, have been studied for centuries, but something new has been added.... The tendency to study systems as an entity rather than as a conglomeration of parts is consistent with the tendency in contemporary science no longer to isolate phenomena in narrowly confined contexts, but rather to open interactions for examination and to examine larger and larger slices of nature. Under the banner of systems research (and its many synonyms) we have witnessed a convergence of many more specialized contemporary scientific developments. So far as can be ascertained, the idea of a “general systems theory” was first introduced by the present author prior to cybernetics, systems engineering and the emergence of related fields.
Although the term “systems” itself was not emphasized, the history of this concept includes many illustrious names.

Kenneth Boulding, an economist, published work in 1953 on *General Empirical Theory* [Boulding, 1953] and claimed that it was the same as the general systems theory advocated by Bertalanffy.

*The Society for General Systems Research* was organized in 1954 by the American Association for the Advancement of Science. The society’s mission was to develop theoretical systems applicable to more than one traditional department of knowledge.

The major functions of the society were to (i) investigate the isomorphy of concepts, laws, and models in various fields, as well as help in useful transfers from one field to another, (ii) encourage the development of adequate theoretical models in the fields that lack them, (iii) minimize the duplication of theoretical effect in different fields, and (iv) promote the unity of science by improving communication among specialists.

Several modeling philosophies and methods have been developed over the last three decades to address the intricacy of modeling complex large-scale systems and to offer various modeling schema. They are included in the following volumes: *New Directions in General Theory of Systems* [Mesarović, 1965], *General Systems Theory* [Macko, 1967], *Systems Theory and Biology* [Mesarović, 1968], *Advances in Control Systems* [Leondes, 1969], *Theory of Hierarchical Multilevel Systems* [Mesarović et al., 1970], *Methodology for Large-Scale Systems* [Sage, 1977], *Systems Theory: Philosophical and Methodological Problems* [Blauberg et al., 1977], *Hierarchical Analyses of Water Resources Systems: Modeling and Optimization of Large-Scale Systems* [Haimes, 1977], and *Multifaceted Modeling and Discrete Event Simulation* [Zigler, 1984].


Several modeling philosophies and methods have been developed over the years to address the complexity of modeling large-scale systems and to offer various modeling schema. In his book *Methodology for Large-Scale Systems*, Sage [1977] addressed the “need for value systems which are structurally repeatable and capable of articulation across interdisciplinary fields” with which to model the multiple dimensions of societal problems. Blauberg et al. [1977] pointed out that, for the understanding and analysis of a large-scale system, the fundamental principles of wholeness (representing the integrity of the system) and hierarchy (representing the internal structure of the system) must be supplemented by the principle of the multiplicity of description for any system. To capture the multiple dimensions and perspectives of a system, Haimes [1981] introduced hierarchical holographic modeling (HHM) (see Chapter 3) and asserted: “To clarify and document not only the multiple components, objectives, and constraints of a system but also its welter of societal aspects (functional, temporal, geographical, economic, political, legal, environmental, sectoral, institutional, etc.) is quite impossible with a single model analysis and interpretation.” Recognizing that a system “may be subject to a multiplicity of management, control and design objectives,” Zigler [1984] addressed such modeling complexity in his book *Multifaceted Modeling and Discrete Event*
Simulation. Zigler (p. 8) introduced the term multi-faceted “to denote an approach to modeling which recognizes the existence of multiplicities of objectives and models as a fact of life.” In his book *Synectics: The Development of Creative Capacity*, Gordon [1968] introduced an approach that uses metaphoric thinking as a means to solve complex problems. Hall [1989] developed a theoretical framework, which he termed Metasystems Methodology, to capture the multiple dimensions and perspectives of a system. Other early seminal works in this area include the book on societal systems and complexity by Warfield [1976] and the book *Systems Engineering* [Sage, 1992]. Sage identified several phases of the systems engineering life cycle; embedded in such analyses are the multiple perspectives—the structural definition, the functional definition, and the purposeful definition. Finally, the multiple volumes of the *Systems and Control Encyclopedia: Theory, Technology, Applications* [Singh, 1987] offer a plethora of theory and methodology on modeling large-scale and complex systems. Thus, multifaceted modeling, metasystems, HHM, and other contributions in the field of large-scale systems constitute the fundamental philosophy upon which systems engineering is built.

Reflecting on the origins of modern systems theory since the introduction of the Gestalt psychology in 1912, we cannot underestimate the intellectual power of the holistic philosophy that has sustained systems engineering. This multidisciplinary field transcends the arts, humanities, natural and physical sciences, engineering, medicine, and law, among others. The fact that systems engineering, systems analysis, and risk analysis have continued to grow and infiltrate other fields of study over the years can be attributed to the fundamental premise that a system can be understood only if all the intra- and interdependencies among its parts and its environment are also understood. For more than a century, mathematical models constituted the foundations upon which systems-based theory and methodologies were developed, including their use and deployment on the myriad large-scale projects in the natural and constructed environment. If we were to identify a single idea that has dominated systems thinking and modeling, it would be the state concept. Indeed, the centrality of state variables in this context is so dominant that no meaningful mathematical model of a real system can be built without identifying the critical states of that system and relating all other building blocks of the model to them (including decision, random, and exogenous variables, and inputs and outputs). In this respect, system modeling—the cornerstone of this book—has served, in many ways, as the medium with which to infuse and instill the holistic systems philosophy into the practice of risk analysis as well as of engineering and other fields.

1.2.4 Systems Engineering and Covey’s Seven Habits

The concepts that Covey introduces can be compared with the systems approach as applied to the entire life cycle of a system. Through this comparison, a joint model is developed that demonstrates how the ideas from the two approaches overlap and how an understanding of this view can benefit personal development as well as systems design and development [Haimes and Schneiter, 1996]. Covey’s philosophy is used in the following discussion as a vehicle with which to explain the holistic systems engineering philosophy.

1.2.4.1 Paradigm: The systems concept

From the outset, Covey stresses the understanding of paradigms—the lenses through which we see the universe. Furthermore, according to Covey, it is not what happens to us that affects our behavior; rather, it is our interpretation of what happens. Since our interpretation of the world we live in determines how we create new and innovative solutions to the problems we face, it is essential that we understand the elemental interrelationships in the world that surrounds us. Thus, both understanding the systemic nature of the universe and defining the system that we need to address are imperative requirements for our ability to solve problems.

In his book *The Fifth Discipline*, Peter Senge [1990] gives a good example of how to understand the systems concept. To illustrate the rudiments of the *new language* of systems thinking, he considers a very simple system—filling a glass of water:

From a linear viewpoint, we say, “I am filling a glass of water.” But in fact, as we fill the glass, we are