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Andrew P. Sage, Series Editor

Fourth Edition

RISK MODELING, ASSESSMENT, AND MANAGEMENT

Yacov Y. Haimes

with website

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Fourth Edition

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Risk Modeling, Assessment, and Management

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A complete list of the titles in this series appears at the end of this volume.

Preface to the Fourth Edition

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 socioeconomic 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 (MODT) 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 MODT. Because the two methodologies are useful in decisionmaking at each step of the system life cycle, the theoretical and methodological relationship between MRIAM and MODT 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.

The Companion Website

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 tradeoff analysis and statistics of extremes). The problems encompass a broad spectrum of applications including disaster analysis, industrial safety, transportation security, production efficiency, and portfolio selection, among others.

The exercises and problems in the companion website are attributable to numerous students who participated in my Risk Analysis course during the last 30 years. The production of the content on the website would have not been possible without the help of the following student encoders: Dexter Galozo, Jonathan Goodnight, Miguel Guerra, Sung Nam Hwang, Jeesang Jung, Oliver Platt-Mills, Chris Story, Scott Tucker, Gen Ye, Zhenyu Guo, Joshua Bogdanor, Eva Andrijcic, and Bryan Lewis. The administrative as well as the technical support from Erika Evans and Rosemary Shaw are greatly appreciated. Last but not least, I would like to once again acknowledge Grace Zisk for her meticulous editing of the first three editions and Anne Sussman for help in editing this fourth edition.

Yacov Y. Haimes

June, 4, 2015
Charlottesville, Virginia

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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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The frequent daily walks and stimulating colloquies with my colleague Barry Horowitz have germinated many of the ideas discussed in this edition.

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