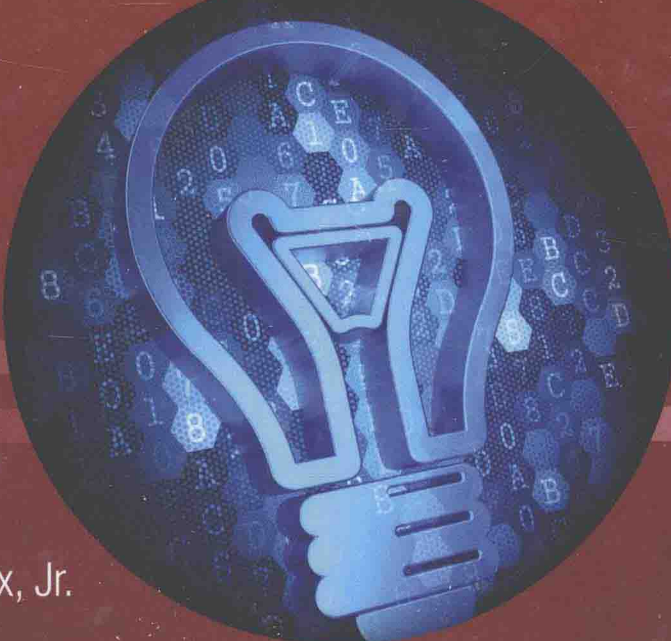
Wiley Essentials in Operations Research and Management Science

Breakthroughs in Decision Science and Risk Analysis



Edited by
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Foreword

The *Wiley Encyclopedia of Operations Research and Management Science* (*EORMS*), published in 2011, is the first multi-volume encyclopedia devoted to advancing state-of-the-art applications and principles of operations research and management science. *EORMS* is available online and in print and serves students, academics, and professionals as a comprehensive resource on the field.

The articles published in *EORMS* provide robust summaries of the many topics and concepts that comprise operations research and management science. However, many readers need additional access to greater details and more thorough discussions on a variety of topics. In turn, we have created the *Wiley Essentials in Operations Research and Management Science* book series. Books published in this series allow invited expert authors and editors to expand and extend the treatment of topics beyond *EORMS* and offer new contributions and syntheses.

I am delighted to introduce *Breakthroughs in Decision Science and Risk Analysis* as the inaugural book in this series. It exemplifies how individual books will meet the goals of the series, setting a high standard for later volumes. Dr. Louis Anthony (Tony) Cox, Jr., the editor of *Breakthroughs in Decision Science and Risk Analysis*, has assembled a collection of renowned authors who contribute exciting syntheses and advances to an area that is critically important in both applications and research. This book is unique and important because it focuses on recent advances and innovations in decision analysis with an emphasis on topics that are not traditionally found in the decision analysis literature. I am confident that this book will be extremely useful to the operations research and management science community as well as to readers from economics, engineering, business, psychology, finance, environmental sciences, public policy, forestry, political science, health and medicine, education, and other social and applied sciences. We hope that you will enjoy it, and we welcome comments and suggestions for our new *Wiley Essentials in Operations Research and Management Science* series.

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Preface

Decision and risk analysis can be exciting, clarifying, and fairly easy to apply to improve high-stakes policy and management decisions. The field has been undergoing a renaissance in the past decade, with remarkable breakthroughs in the psychology and brain science of risky decisions; mathematical foundations and techniques; integration with learning and pattern recognition methods from computational intelligence; and applications in new areas of financial, health, safety, environmental, business, engineering, and security risk management. These breakthroughs provide dramatic improvements in the potential value and realism of decision science. However, the field has also become increasingly technical and specialized, so that even the most useful advances are not widely known or applied by the general audience of risk managers and decision-makers who could benefit most from them. This book explains key recent breakthroughs in the theory, methods, and applications of decision and risk analysis. Its goal is to explain them in enough detail, but also with a simple and clear enough exposition, so that risk managers and decision-makers can understand and apply them.

There are several target audiences for this book. One is the operations research and management science (OR/MS) community. This overlaps with the audience for the *Wiley Encyclopedia of Operations Research and Management Science* (EORMS), including OR/MS professionals–academic and industry researchers, government organizations and contractors, and decision analysis (DA) consultants and practitioners. This book is also designed to appeal to managers, analysts, and decision and policy makers in the applications areas of financial, health and safety, environmental, business, engineering, and security risk management. By focusing on breakthroughs in decision and risk science that can significantly change and improve how we make (and learn from) important practical decisions, this book aims to inform a wide audience in these applied areas, as well as provide a fun and stimulating resource for students, researchers, and academics in DA and closely linked academic fields of psychology, economics, statistical decision theory, machine learning and computational intelligence, and OR/MS.

In contrast to other recent books on DA, this one spends relatively little space on "classical" topics such as the history of DA; the structure of decision problems in terms of acts, states, and consequences; and extensions of the traditional DA paradigm, such as fuzzy DA or multicriteria decision-making. Instead, the book is devoted to explaining and illustrating genuine *breakthroughs* in decision science—that is, developments that depart from, or break with, the standard DA paradigm in fundamental ways and yet have proved promising for leading to even more valuable insights and decision recommendations in practical applications. These breakthroughs include methods for deciding what to do when decision problems are incompletely known or described, useful probabilities cannot be specified, preferences and value tradeoffs are uncertain, future preferences may conflict with present ones, and "model uncertainty" about the cause-and-effect relation between choices and their probable consequences runs too deep to permit any single decision support model, or small set of models, to be highly credible. In addition to explaining the most important new ideas for coping with such realistic challenges, the chapters in this book will show how these techniques are being used to dramatically improve risk management decisions in a variety of important applications, from finance to medicine to terrorism. This emphasis on *new ideas that demonstrably work better than older ones*, rather than primarily on expositions of and advances in traditional decision and risk analysis, is the essential unique contribution of this work. In addition, a pedagogical emphasis on *simple, clear exposition* (accessible to readers at different technical levels, with a minimum of mathematical notation and technical jargon), and *important practical applications* should help to broaden the practical value of the chapters that follow in making important advances in decision and risk analysis useful to readers who want to learn about them and apply them to important real-world decisions.

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January 2015

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Contents

CHAPTER 1

Introduction: Five Breakthroughs in Decision and Risk Analysis

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This book is about breakthroughs in decision and risk analysis—new ideas, methods, and computational techniques that enable people and groups to choose more successfully when the consequences of different choices matter, yet are uncertain. The twentieth century produced several such breakthroughs. Development of subjective expected utility (SEU) theory combined with Bayesian statistical inference as a model of ideal, rational decision-making was among the most prominent of these. Chapter 2 introduces SEU theory as a point of departure for the rest of the book. It also discusses more recent developments—including prospect theory and behavioral decision theory—that seek to bridge the gap between the demanding requirements of SEU theory and the capabilities of real people to improve their decision-making. Chapters 5 and 8 address practical techniques for improving risky decisions when there are multiple objectives and when SEU cannot easily be applied, either because of

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uncertainty about relevant values, causal models, probabilities, and consequences; or because of the large number and complexity of available choices.

HISTORICAL DEVELOPMENT OF DECISION ANALYSIS AND RISK ANALYSIS

Perhaps the most audacious breakthrough in twentieth-century decision analysis was the very idea that a single normative theory of decision-making could be applied to all of the varied risky decisions encountered in life. It may not be obvious what the following problems, discussed in ensuing chapters, have in common:

- *Investment decisions:* How should investors allocate funds across investment opportunities in a financial portfolio? (Chapter 3)
- *Operations management decisions:* How should a hospital emergency room be configured to make the flow of patients as easy and efficient as possible? How should an insurance company staff its claims-handling operations? (Chapter 3)
- *Inventory management and retail decisions:* How much of an expensive, perishable product should a business buy if demand for the product is uncertain? (Chapter 4)
- *Trial evaluation and selection decisions:* How much trial, testing, and comparative evaluation should be done before selecting one of a small number of costly alternatives with uncertain consequences, for example, in choosing among alternative new public policies, consumer or financial products, health care insurance plans, research and development (R&D) projects, job applicants, supply contracts, locations in which to drill for oil, or alternative drugs or treatments in a clinical trial? (Chapter 4)
- *Adversarial risk management decisions:* How should we model the preferences and likely actions of others, in order to make effective decisions ourselves in situations where both their choices and ours affect the outcomes? (Chapters 2, 5, 9, and 10)
- *Regulatory decisions:* When experimentation is unethical or impractical, how can historical data be used to estimate and compare the probable consequences that would be caused by alternative choices,

such as revising versus maintaining currently permitted levels of air pollutants? (Chapter 6)

- *Learning how to decide in uncertain environments:* Suppose that not enough is known about a system or process to simulate its behavior. How can one use well-designed trial-and-error learning to quickly develop high-performance decision rules for deciding what to do in response to observations? (Chapters 4 and 7)
- *Medical decision-making:* How should one trade off the ordinary pleasures of life, such as consumption of sugar-sweetened drinks, against the health risks that they might create (e.g., risk of adult-onset diabetes)? More generally, how can and should individuals make decisions that affect their probable future health states in ways that may be difficult to clearly imagine, evaluate, or compare? (Chapter 8)

That the same basic ideas and techniques might be useful for decision-making in such very different domains is a profound insight that might once have excited incredulity among experts in these fields. It is now part of the canon of management science, widely taught in business schools and in many economics, statistics, and engineering programs.

Decision analysis views the "success" of a decision process in terms of the successes of the particular decisions that it leads to, given the information (usually incomplete and possibly incorrect or inconsistent) that is available when decisions must be made. The "success" of a single choice, in turn, can be assessed by several criteria. Does it minimize expected post-decision regret? Is it logically consistent with (or implied by) one's preferences for and beliefs about probable consequences? In hindsight, would one want to make the same choice again in the same situation, if given the same information? The giants of twentieth-century decision theory, including Frank Ramsey in the 1920s, John von Neumann in the 1940s, and Jimmy Savage in the 1950s, proved that, for perfectly rational people (*homo economicus*) satisfying certain mathematical axioms of coherence and consistency (i.e., complete and transitive preference orderings for outcomes and for probability distributions over outcomes), all of these criteria prescribe the same choices. All imply that a decision-maker should choose among risky prospects (including alternative acts, policies, or decision rules with uncertain consequences) as if she were maximizing subjective expected utility (SEU). Chapters 2 and 7 introduce SEU theory and some more recent alternatives. Decision-making processes and environments that encourage high-quality decisions as judged by one of these criteria will also promote the rest.

However, real people are not perfectly rational. As discussed in Chapter 2, *homo economicus* is a fiction. The prescriptions of decision theory are not necessarily easy to follow. Knowing that SEU theory, the long-reigning gold standard for rational decision-making, logically implies that one *should* act as if one had coherent (e.g., transitive) preferences, and clear subjective probabilities are cold comfort to people who find that they have neither. These principles and limitations of decision theory were well understood by 1957, when Duncan Luce and Howard Raiffa's masterful survey *Games and Decisions* explained and appraised much of what had been learned by decision theorists, and by game theorists for situations with multiple interacting decision-makers. Chapter 2 introduces both decision theory and game theory and discusses how they have been modified recently in light of insights from decision psychology and behavioral economics.

During the half-century after publication of *Games and Decisions*, a host of technical innovations followed in both decision analysis and game theory. Decision tree analysis (discussed in Chapters 8 and 10) was extended to include Monte Carlo simulation of uncertainties (see Chapter 3). Influence diagrams were introduced that could represent large decision problems far more compactly than decision trees, and sophisticated computer science algorithms were created to store and solve them efficiently. Methods of causal analysis and modeling were developed to help use data to create risk models that accurately predict the probable consequences of alternative actions (see Chapter 6). Markov decision processes for dynamic and adaptive decision-making were formulated, and algorithms were developed to adaptively and robustly optimize decision rules under uncertainty (see Chapter 7). SEU theory was generalized, e.g., to allow for robust optimization with ambiguity aversion when probabilities are not well known. Practical constructive approaches were created for structuring and eliciting probabilities and utilities, as discussed and illustrated in Chapters 5, 8, and 10.

These technical developments supported a firmly founded discipline of applied decision analysis, decision aids, and decision support consulting. The relatively new discipline of applied decision analysis, developed largely from the 1960s on, emphasized structuring of decision problems (especially, identifying and solving the right problem(s)); clearly separating beliefs about facts from values and preferences for outcomes; eliciting or constructing well-calibrated probabilities and coherent utilities; presenting decision recommendations, together with sensitivity and uncertainty analyses, in understandable ways that decision-makers find useful; assessing value of information and optimal timing of actions; and deliberate, careful learning from results, for both individuals and organizations. The 1976 publication of the landmark *Decisions with Multiple Objectives: Preferences and Value Tradeoffs* by Ralph Keeney and Howard Raiffa summarized much of the state of the art at the time, with emphasis on recently developed multiattribute value and utility theory and methods. These were designed to allow clearer thinking about decisions with multiple important consequence dimensions, such as costs, safety, profitability, and sustainability. Chapters 5, 8, and 10 review and illustrate developments in elicitation methods and multiattribute methods up to the present.

While decision analysis was being developed as a prescriptive discipline based on normative theory (primarily SEU theory), an increasingly realistic appreciation of systematic "heuristics and biases" and of predictable anomalies in both laboratory and real-world decision-making was being developed by psychologists such as Amos Tversky, Daniel Kahneman, Paul Slovic, and Baruch Fischhoff, and by many other talented and ingenious researchers in what became the new field of behavioral economics. Chapter 2 introduces these developments. Striking differences between decision-making by idealized, rational thinkers (*homo economicus*) and by real people were solidly documented and successfully replicated by different teams of investigators. For example, whether cancer patients and their physicians preferred one risky treatment procedure to another might be changed by presenting risk information as the probability of survival for at least 5 years instead of as the probability of death within 5 years—two logically equivalent descriptions (gain faming vs. loss framing) with quite different emotional impacts and effects on decisions. Many of these developments were reflected in the 1982 collection *Judgment under Uncertainty: Heuristics and Biases*, edited by Kahneman, Slovic, and Tversky. Chapter 10 summarizes key insights from the heuristic-and-biases literature in the context of eliciting expert judgments about probabilities of adversarial actions.

Twenty-five years later, the 2007 collection *Advances in Decision Analysis: From Foundations to Applications*, edited by Ward Edwards, Ralph Miles, and Detlof von Winterfeldt, took stock of the thriving and increasingly well-developed field of decision analysis, which now integrated both normative (prescriptive) theory and more descriptively realistic considerations, e.g., using Kahneman and Tversky's prospect theory. This collection looked back on decades of successful developments in decision analysis, including the field's history (as recalled by founding luminaries, including Ron Howard of Stanford and Howard Raiffa of the Harvard Business School), surveys of modern progress (including influence diagrams, Bayesian network models, and causal networks), and important practical applications, such as to engineering and health and safety risk analysis, military acquisitions, and nuclear supply chain and plutonium disposal decisions.

OVERCOMING CHALLENGES FOR APPLYING DECISION AND RISK ANALYSIS TO IMPORTANT, DIFFICULT, REAL-WORLD PROBLEMS

Despite over five decades of exciting intellectual and practical progress, and widespread acceptance and incorporation into business school curricula (and into some engineering, statistics, mathematics, and economics programs), decision analysis has limited impact on most important real-world decisions today. Possible reasons include the following:

- *Many real-world problems still resist easy and convincing decision-analytic formulations.* For example, a dynamic system with random events (i.e., patient arrivals, departures, and changes in condition in a hospital ward) with ongoing opportunities to intervene (e.g., by relocating or augmenting staff to meet the most pressing needs) cannot necessarily be represented by a manageably small decision tree, influence diagram, Markov decision process, or other tractable model—especially if the required transition rates or other model parameters are not known and data from which to estimate them are not already available. Chapters 3, 4, 6, and 7 present breakthroughs for extending decision and risk analysis principles to such realistically complex settings. These include increasingly well-developed *simulation–optimization* methods for relatively well-characterized systems (Chapter 3) and *adaptive learning*, statistical methods for estimating causal relations from data (Chapter 6), model ensemble, and robust optimization