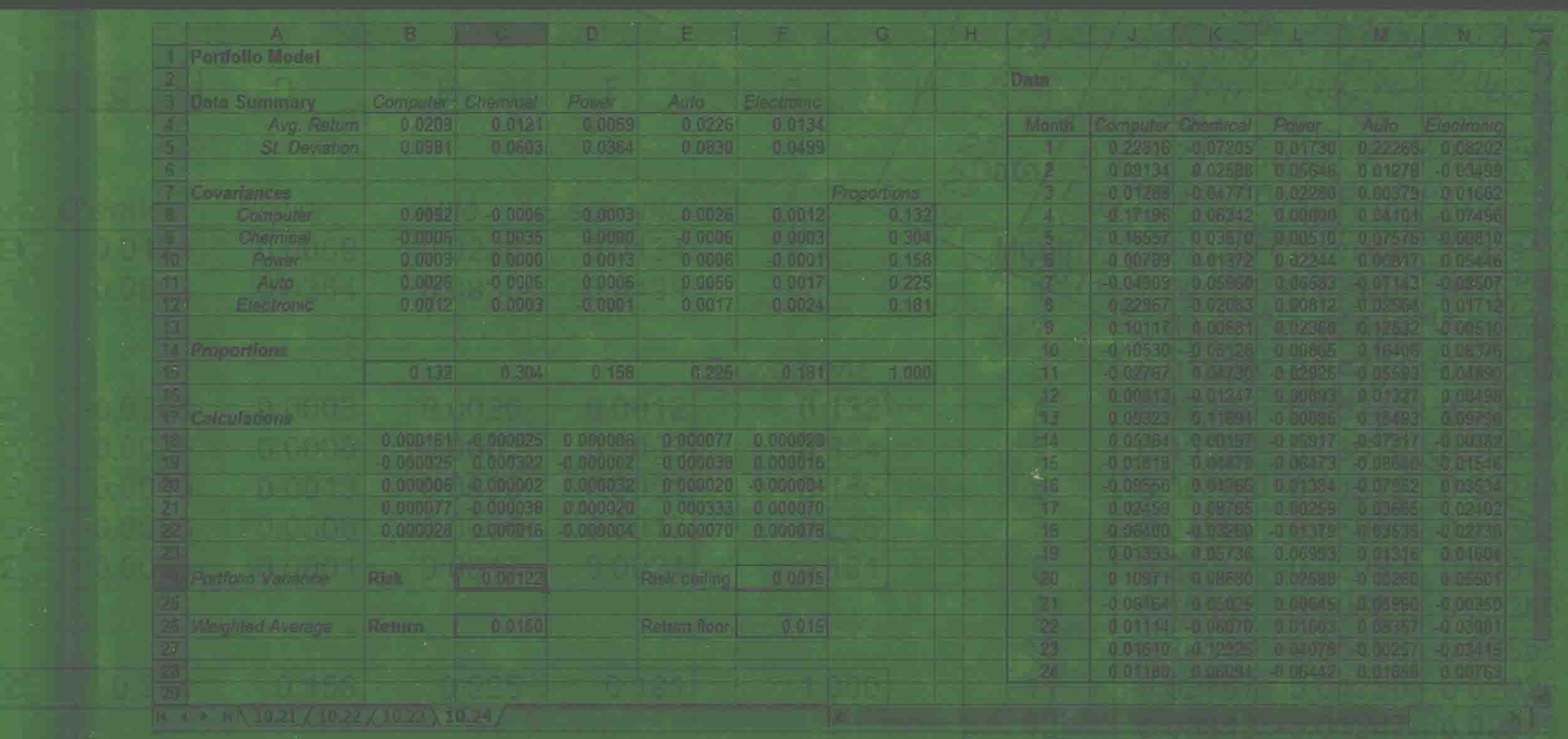
STEPHEN G. POWELL

KENNETH R. BAKER

MANAGEMENT SCIENCE

The ART of MODELING with SPREADSHEETS



THIRD EDITION

Compatible with Excel 2010

Featuring Risk Solver Platform

Third Edition

MANAGEMENT SCIENCE
The Art of Modeling with Spreadsheets

STEPHEN G. POWELL
Dartmouth College

KENNETH R. BAKER
Dartmouth College

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To Becky and Judy,
for all their encouragement and support

Preface

This is a book for business analysts about *modeling*. A *model* is a simplified representation of a situation or problem, and *modeling* is the process of building, refining, and analyzing that representation for greater insight and improved decision making. Some models are so common that they are thought of as routine instruments rather than models. A budget, a cash flow projection, or a business plan may have many uses, but each one is a model. In addition, many sophisticated models are embedded in software. Option pricing models, credit scoring models, or inventory models are key components of important decision-support systems. Beyond these types, we encounter many customized models, built by the millions of people who routinely use spreadsheet software to analyze business situations. This group includes consultants, venture capitalists, marketing analysts, and operations specialists. Almost anyone who uses spreadsheets in business has been involved with models and can benefit from formal training in the use of models.

Models also play a central role in management education. A short list of models that nearly every business student encounters would include cash flow models, stock price models, option pricing models, product life cycle models, market diffusion models, order quantity models, and project scheduling models. For the management student, a basic ability to model in spreadsheets can be a powerful tool for acquiring a deeper understanding of the various functional areas of business. But to fully understand the implications of these models, a student needs to appreciate what a model is and how to learn from it. Our book provides that knowledge.

For many years, modeling was performed primarily by highly trained specialists using mainframe computers. Consequently, even a simple model was costly and frequently required a long development time. The assumptions and results often seemed impenetrable to business managers because they were removed from the modeling process. This situation has changed radically with the advent of personal computers and electronic spreadsheets. Now, managers and analysts can build their own models and produce their own analyses. This new kind of modeling is known as *end-user modeling*. Now that virtually every analyst has access to a powerful computer, the out-of-pocket costs of modeling have become negligible. The major cost now is the analyst's *time*: time to define the problem, gather data, build and debug a model, and use the model to support the decision process. For this time to be well spent, the analyst must be efficient and effective in the modeling process. This book is designed to improve modeling *efficiency* by focusing on the most important tasks and tools and by suggesting how to avoid unproductive steps in the modeling effort. This book is also designed to improve modeling *effectiveness* by introducing the most relevant analytic methods and emphasizing procedures that lead to the deepest business insights.

WHY THIS BOOK?

One of our reasons for writing this book was the conviction that many analysts were not being appropriately educated as modelers. Business students tend to receive strong training in management science but little training in practical modeling. They often receive inadequate training, as well, in using spreadsheets for modeling. In most educational programs, the emphasis is on *models*, rather than on *modeling*. That is, the curriculum covers a number of classical models that have proven useful in management education or in business. Although studying the classics may be valuable for a number of reasons (and our book covers a number of the classics), studying models does not provide the full range of skills needed to build models for new situations.

We also have met many analysts who view modeling essentially as a matter of having strong spreadsheet skills. But spreadsheet skills are not sufficient. The spreadsheet is only one tool in the creative, open-ended problem-solving process we call modeling. Modeling is both a technical discipline and a *craft*. The craft aspects of the process have largely been overlooked in the education of business analysts. Our purpose is to provide both the technical knowledge and the craft skills needed to develop real expertise in business modeling. In this book, therefore, we cover the three skill areas that a business analyst needs to become an effective modeler:

- spreadsheet engineering
- management science
- modeling craft

NEW IN THE THIRD EDITION

We have revised this text twice in the six years that have elapsed since the First Edition appeared. In the Second Edition we broadened our coverage of both management science and Excel and shortened some chapters to make the book easier to use. In the Update Edition, we made the text compatible with Excel 2007. In this Third Edition, we update to Excel 2010 and convert to Risk Solver Platform for Education. Risk Solver Platform for Education replaces four separate software tools used in previous editions: the Sensitivity Toolkit, Premium Solver, Tree Plan, and Crystal Ball. Risk Solver Platform for Education is an integrated add-in to Excel that performs sensitivity analysis, optimization, decision-tree analysis, and simulation. To exploit its capabilities fully, we have also added a new Chapter 14 on Evolutionary Solver and substantially revised Chapter 16 (now Chapter 17) on Simulation Optimization.

TO THE READER

Modeling, like painting or singing, cannot be learned entirely from a book. However, a book can establish principles, provide examples, and offer additional practice. We suggest that the reader take an *active learning* attitude toward this book. This means working to internalize the skills taught here by tackling as many new problems as possible. It also means applying these skills to everyday situations in other classes or on the job. Modeling expertise (as opposed to modeling appreciation) can be acquired only by *doing* modeling. There is no substitute for experience.

The book is organized into five parts:

- Spreadsheet modeling in the context of problem solving (Chapters 1–4)
- Spreadsheet engineering (Chapters 5 and 6)
- Data analysis and statistics (Chapters 7–9)
- Optimization (Chapters 10–14)
- Decision analysis and simulation (Chapters 15–17)

Our table of contents provides details on the topic coverage in the various chapters, and in Chapter 1 we provide a diagram of the prerequisite logic among the chapters. Several chapters contain advanced material in sections marked with (*). Students can find spreadsheet files for all models presented in the text on the website at www.wiley.com/college/powell. For access to the Risk Solver Platform for Education software, contact your course instructor or Frontline Systems (email academic@solver.com or call 775-831-0300.)

TO THE TEACHER

It is far easier to teach technical skills in Excel or in management science than it is to teach modeling. Nonetheless, modeling skills *can* be taught successfully, and a variety of effective approaches are available. Feedback from users of our book and from reviewers of previous editions suggests that there are almost as many course designs as there are instructors for this subject. Our book does not represent an idealized version of our own course; rather, it is intended to be a versatile resource that can support a selection of topics in management science, spreadsheet engineering, and modeling craft.

At the book's website, www.wiley.com/college/powell, we provide some teaching tips and describe our views on the different ways that this material can be delivered successfully in a graduate or undergraduate course. All spreadsheet files for the models in the text, as well as PowerPoint slides, can be found on the site. In addition, we provide some sample syllabi to suggest the course designs that other instructors have delivered with the help of this book. For access to the Risk Solver Platform for Education software, contact Frontline Systems (email academic@solver.com or call 775-831-0300.)

SOFTWARE ACCOMPANYING THE THIRD EDITION

Users of the Third Edition have access to spreadsheet files for all the models presented in the text. Users also have access to Risk Solver Platform for Education, an integrated software platform for sensitivity analysis, optimization, decision trees, and simulation. Risk Solver Platform for Education replaces software in previous editions for the following purposes:

- Sensitivity Analysis (in place of the Sensitivity Toolkit in Chapters 6 and 10–17);
- Optimization (in place of Premium Solver for Education in Chapters 10–14);
- Decision Tree Analysis (in place of TreePlan in Chapter 15);
- Monte Carlo Simulation (in place of Crystal Ball 7 Student Edition in Chapters 16 and 17).

Purchasers of a **new** text (and its electronic format) have access to Risk Solver Platform for Education either through their course instructor or Frontline Systems (email academic@solver.com or call 775-831-0300).

ACKNOWLEDGMENTS

A book such as this evolves over many years of teaching and research. Our ideas have been influenced by our students and by other teachers, not all of whom we can acknowledge here. Our students at Dartmouth's Tuck School of Business have participated in many of our teaching experiments and improved our courses through their invaluable feedback. Without the collaborative spirit our students bring to their education, we could not have developed our ideas as we have.

As in the first edition, we wish to mention the many excellent teachers and writers whose ideas we have adapted. We acknowledge Don Plane, Cliff Ragsdale, and Wayne Winston for their pioneering work in teaching management science with spreadsheets, and the later influence of Tom Grossman, Peter Bell, Zeger Degraeve, and Erhan Erkut on our work.

The first edition benefited from careful reviews from the following reviewers: Jerry Allison (University of Central Oklahoma), Jonathan Caulkins (Carnegie-Mellon University), Jean-Louis Goffin (McGill University), Roger Grinde (University of New Hampshire), Tom Grossman (University of Calgary), Raymond Hill (Air Force Institute of Technology), Alan Johnson (United States Military

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Beth Golub of John Wiley & Sons encouraged us to write this book for years and supported us in writing a new kind of textbook. She also tapped an extensive network of contacts for feedback and helped us improve successive editions. With the Third Edition, the responsibility has passed from Beth to Lise Johnson and Sarah Vernon, who have continued the supportive editorial process we have come to appreciate.

SGP
KRB

About The Authors

Steve Powell is a Professor at the Tuck School of Business at Dartmouth College. His primary research interest lies in modeling production and service processes, but he has also been active in research in energy economics, marketing, and operations. At Tuck, he has developed a variety of courses in management science, including the core Decision Science course and electives in the Art of Modeling, Collaborative Problem Solving, Business Process Redesign, and Simulation. He originated the Teacher's Forum column in *Interfaces*, and has written a number of articles on teaching modeling to practitioners. He was the Academic Director of the annual INFORMS Teaching of Management Science Workshops. In 2001 he was awarded the INFORMS Prize for the Teaching of Operations Research/Management Science Practice. Along with Ken Baker, he has directed the Spreadsheet Engineering Research Project. In 2008 he co-authored *Modeling for Insight: A Master Class for Business Analysts* with Robert J. Batt.

Ken Baker is a faculty member at Dartmouth College. He is currently Nathaniel Leverone Professor of Management at the Tuck School of Business and Adjunct Professor at the Thayer School of Engineering. At Dartmouth, he has taught courses relating to Management Science, Decision Support Systems, Manufacturing Management, and Environmental Management. Along with Steve Powell, he has directed the Spreadsheet Engineering Research Project. He is the author of two other textbooks, *Optimization Modeling with Spreadsheets* and *Principles of Sequencing and Scheduling* (with Dan Trietsch), in addition to a variety of technical articles. He has served as Tuck School's Associate Dean and as the Co-Director of the Master's Program in Engineering Management. He is an INFORMS Fellow as well as a Fellow of the Manufacturing and Service Operations Management (MSOM) Society.

Brief Contents

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* Optional Sections

1 Introduction

1.1 MODELS AND MODELING

Modeling is the process of creating a simplified representation of reality and working with this representation in order to understand or control some aspect of the world. While this book is devoted to *mathematical* models, modeling itself is a ubiquitous human activity. In fact, it seems to be one of just a few fundamental ways in which we humans understand our environment.

As an example, a map is one of the most common models we encounter. Maps are models because they simplify reality by leaving out most geographic details in order to highlight the important features we need. A state road map, for example, shows major roads but not minor ones, gives rough locations of cities but not individual addresses, and so on. The map we choose must be appropriate for the need we have: a long trip across several states requires a regional map, while a trip across town requires a detailed street map. In the same way, a good model must be appropriate for the specific uses intended for it. A complex model of the economy is probably not appropriate for pricing an individual product. Similarly, a back-of-the-envelope calculation is likely to be inappropriate for acquiring a multibillion-dollar company.

Models take many different forms: mental, visual, physical, mathematical, and spreadsheet, to name a few. We use mental models constantly to understand the world and to predict the outcomes of our actions. Mental models are informal, but they do allow us to make a quick judgment about the desirability of a particular proposal. For example, mental models come into play in a hiring decision. One manager has a mental model that suggests that hiring older workers is not a good idea because they are slow to adopt new ways; another manager has a mental model that suggests hiring older workers is a good idea because they bring valuable experience to the job. We are often unaware of our own mental models, yet they can have a strong influence on the actions we take, especially when they are the primary basis for decision making.

While everyone uses mental models, some people routinely use other kinds of models in their professional lives. Visual models include maps, as we mentioned earlier. Organization charts are also visual models. They may represent reporting relationships, reveal the locus of authority, suggest major channels of communication, and identify responsibility for personnel decisions. Visual models are used in various sports, when a coach sketches the playing area and represents team members and opponents as *X*'s and *O*'s. Most players probably don't realize that they are using a model for the purposes of understanding and communication.

Physical models are used extensively in engineering to assist in the design of airplanes, ships, and buildings. They are also used in science, as, for example, in depicting the spatial arrangement of amino acids in the DNA helix or the makeup of a chemical compound. Architects use physical models to show how a proposed building fits within its surroundings.

Mathematical models take many forms and are used throughout science, engineering, and public policy. For instance, a groundwater model helps determine where flooding is most likely to occur, population models predict the spread of infectious disease, and exposure-assessment models forecast the impact of toxic spills. In other settings, traffic-flow models predict the buildup of highway congestion, fault-tree models help reveal the causes of an accident, and reliability models suggest when equipment may need replacement. Mathematical models can be extremely powerful, especially when they give clear insights into the forces driving a particular outcome.

1.1.1 Why Study Modeling?

What are the benefits of building and using formal models, as opposed to relying on mental models or just "gut feel?" The primary purpose of modeling is to generate *insight*, by which we mean an improved understanding of the situation or problem at hand. While mathematical models consist of numbers and symbols, the real benefit of using them is to make better *decisions*. Better decisions are most often the result of improved understanding, not just the numbers themselves.

Thus, we study modeling primarily because it improves our thinking skills. Modeling is a discipline that provides a structure for problem solving. The fundamental elements of a model—such as parameters, decisions, and outcomes—are useful concepts in all problem solving. Modeling provides examples of clear and logical analysis and helps raise the level of our thinking.

Modeling also helps improve our quantitative reasoning skills. Building a model demands care with units and with orders of magnitude, and it teaches the importance of numeracy. Many people are cautious about quantitative analysis because they do not trust their own quantitative skills. In the best cases, a well-structured modeling experience can help such people overcome their fears, build solid quantitative skills, and improve their performance in a business world that demands (and rewards) these skills.

Any model is a laboratory in which we can experiment and learn. An effective modeler needs to develop an open, inquiring frame of mind to go along with the necessary technical skills. Just as a scientist uses the laboratory to test ideas, hypotheses, and theories, a business analyst can use a model to test the implications of alternative courses of action and develop not only a recommended decision but, equally important, the rationale for why that decision is preferred. The easy-to-understand rationale behind the recommendation often comes from insights the analyst has discovered while testing a model.

1.1.2 Models in Business

Given the widespread use of mathematical models in science and engineering, it is not surprising to find that they are also widely used in the business world. We refer to people who routinely build and analyze formal models in their professional lives as **business analysts**. In our years of training managers and management students, we have found that strong modeling skills are particularly important for consultants, as well as for financial analysts, marketing researchers, entrepreneurs, and others who face challenging business decisions of real economic consequence. Practicing business analysts and students intending to become business analysts are the intended audience for this book.

Just as there are many types of models in science, engineering, public policy, and other domains outside of business, many different types of models are used in business. We distinguish here four model types that exemplify different levels of interaction with and participation by the people who use the models:

- One-time decision models
- Decision-support models
- Models embedded in computer systems
- Models used in business education

Many of the models business analysts create are used in **one-time decision problems**. A corporate valuation model, for example, might be used intensively during merger negotiations but never thereafter. In other situations, a one-time model might be created to evaluate the profit impact of a promotion campaign, or to help select a health insurance provider, or to structure the terms of a supply contract. One-time models are usually built by decision makers themselves, frequently under time pressure. Managerial judgment is often used as a substitute for empirical data in such models, owing to time constraints and data limitations. Most importantly, this type of model involves the user intensively, because the model is usually tailored to a particular decision-making need. One major benefit of studying modeling is to gain skills in building and using one-time models effectively.

Decision-support systems are computer systems that tie together models, data, analysis tools, and presentation tools into a single integrated package. These systems are intended for repeated use, either by executives themselves or by their analytic staff. Decision-support systems are used in research and development planning at pharmaceutical firms, pricing decisions at oil companies, and product-line profitability analysis at manufacturing firms, to cite just a few examples. Decision-support systems are usually built and maintained by information systems personnel, but they represent the routine use of what were once one-time decision models. After a one-time model becomes established, it can be adapted for broader and more frequent use in the organization. Thus, the models within decision-support systems may initially be developed by managers and business analysts, but later streamlined by information systems staff for a less intensive level of human interaction. An additional benefit of studying modeling is to recognize possible improvements in the design and operation of decision-support systems.

Embedded models are those contained within computer systems that perform routine, repeated tasks with little or no human involvement. Many inventory replenishment decisions are made by automated computer systems. Loan payments on auto leases or prices for stock options are also determined by automated systems. Routine real estate appraisals may also be largely automated. In these cases, the models themselves are somewhat hidden in the software. Many users of embedded models are not aware of the underlying models; they simply assume that the "system" knows how to make the right calculations. An ancillary benefit of studying modeling is to become more aware, and perhaps more questioning, of these embedded models.

1.1.3 Models in Business Education

Models are useful not only in the business world, but also in the academic world where business analysts are educated. The modern business curriculum is heavily dependent on models for delivering basic concepts as well as for providing numerical results. An introductory course in Finance might include an option-pricing model, a cash-management model, and the classic portfolio model. A basic Marketing course might include demand curves for pricing analysis, a diffusion model for new-product penetration, and clustering models for market segmentation. In Operations Management, we might encounter inventory models for stock control, allocation models for scheduling production, and newsvendor models for trading off shortage and surplus outcomes. Both micro- and macroeconomics are taught almost exclusively through models. Aggregate supply-and-demand curves are models, as are production functions.

Most of the models used in education are highly simplified, or *stylized*, in order to preserve clarity. Stylized models are frequently used to provide insight into qualitative phenomena, not necessarily to calculate precise numerical results. In this book, we frequently use models from business education as examples, so that we can combine learning about business with learning about models. In fact, the tools presented in this book can be used throughout the curriculum to better understand the various functional areas of business.