

Stephen G.
POWELL

Kenneth R.
BAKER

MANAGEMENT SCIENCE

The ART of MODELING
with SPREADSHEETS

SECOND
EDITION



CD ROM INCLUDED

SECOND EDITION

MANAGEMENT SCIENCE

The Art of Modeling with Spreadsheets

STEPHEN G. POWELL

Dartmouth College

KENNETH R. BAKER

Dartmouth College



PUBLISHER *Susan Elbe*
EXECUTIVE EDITOR *Beth Lang Golub*
PRODUCTION EDITOR *Nicole Repasky*
ASSISTANT EDITOR *Jennifer Devine*
SENIOR MARKETING MANAGER *Jillian Rice*
SENIOR DESIGNER *Kevin Murphy*
SENIOR MEDIA EDITOR *Allie K. Morris*
SENIOR EDITORIAL ASSISTANT *Maria Guarascio*
PRODUCTION MANAGEMENT SERVICES *Hermitage Publishing Services*
COVER DESIGN *David Levy*

This book was set in Times Ten by Thomson Press and printed and bound by Courier/Westford. The cover was printed by Phoenix Color.

This book is printed on acid free paper. ∞

Copyright © 2007 John Wiley & Sons, Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc. 222 Rosewood Drive, Danvers, MA 01923, website www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030-5774, (201)748-6011, fax (201)748-6008, website <http://www.wiley.com/go/permissions>.

To order books or for customer service please, call 1-800-CALL WILEY (225-5945).

Library of Congress Cataloging-in-Publication Data

Powell, Stephen G.

Management science : the art of modeling with spreadsheets / Stephen G. Powell,
Kenneth R. Baker — 2nd ed.

p. cm.

ISBN-978-0-470-03840-6

1. Business—Computer simulation. 2. Electronic spreadsheets. I. Baker, Kenneth R., 1943– II. Title. HF5548.2.P654 2007 650.01'13—dc22

2006021650

Printed in the United States of America

10 9 8 7 6 5 4 3 2



THE WILEY BICENTENNIAL—KNOWLEDGE FOR GENERATIONS

Each generation has its unique needs and aspirations. When Charles Wiley first opened his small printing shop in lower Manhattan in 1807, it was a generation of boundless potential searching for an identity. And we were there, helping to define a new American literary tradition. Over half a century later, in the midst of the Second Industrial Revolution, it was a generation focused on building the future. Once again, we were there, supplying the critical scientific, technical, and engineering knowledge that helped frame the world. Throughout the 20th Century, and into the new millennium, nations began to reach out beyond their own borders and a new international community was born. Wiley was there, expanding its operations around the world to enable a global exchange of ideas, opinions, and know-how.

For 200 years, Wiley has been an integral part of each generation's journey, enabling the flow of information and understanding necessary to meet their needs and fulfill their aspirations. Today, bold new technologies are changing the way we live and learn. Wiley will be there, providing you the must-have knowledge you need to imagine new worlds, new possibilities, and new opportunities.

Generations come and go, but you can always count on Wiley to provide you the knowledge you need, when and where you need it!

WILLIAM J. PESCE
PRESIDENT AND CHIEF EXECUTIVE OFFICER

PETER BOOTH WILEY
CHAIRMAN OF THE BOARD

*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 covering 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 SECOND EDITION

In the time that has elapsed since the first edition of this book was published, we have had the opportunity to discuss it with numerous readers and teachers. The second edition offers us an opportunity to make the book easier to use and to broaden its appeal. The key changes in the second edition include:

- Additional coverage of management science
To provide instructors with more options, we have added depth to our coverage of forecasting, decision analysis, and optimization. In addition, each chapter contains some advanced material in a designated section.
- Broader coverage of Excel
To create an integrated treatment of spreadsheet topics, we have added a chapter that covers the skills every reader should have, as well as a chapter that covers some of the skills used by experts.
- Shorter chapters
To make the book more flexible as a textbook, we have devoted three separate chapters to data analysis, regression, and forecasting; four chapters to optimization topics; and two chapters to simulation.
- Additional exercises and cases
We have added exercises to the chapters and extended the set of cases. We have also added elementary exercises to provide practice for less experienced students.

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 10–13)
- Decision analysis and simulation (Chapters 14–16)

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.

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 the first edition 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 all models in the text as well as PowerPoint slides created by Alan Olinsky at Bryant University can be found on the site as well. In addition, we provide some sample syllabi to suggest the course designs that other instructors have delivered with the help of this book.

SOFTWARE ACCOMPANYING THE TEXT

Users of this text have access to the following software applications found on the CD accompanying the text:

- *Premium Solver for Education*
- *Crystal Ball 7 Student Edition*
- *TreePlan*
- *Spreadsheet Professional*
- *Sensitivity Toolkit*

Users of this book can download the spreadsheets referred to in the text from the Student Companion Site at www.wiley.com/college/powell.

Premium Solver is used for linear and nonlinear optimization, which is the topic of Chapters 10–13, and is revisited briefly in Chapter 16.

Crystal Ball is used for Monte Carlo simulation, which is the topic of Chapter 15. Its OptQuest package is used for optimization in simulation models, which is covered in Chapter 16, and its CB Predictor package is used for Forecasting, as illustrated in Chapter 9.

TreePlan is used for decision analysis, the subject of Chapter 14.

Spreadsheet Professional is an add-in for Excel that automates error checking. It is introduced in Chapter 5.

The *Sensitivity Toolkit* is an Excel add-in that provides the capability to perform four types of sensitivity analysis:

- Data Sensitivity
- Tornado Chart
- Solver Sensitivity
- Crystal Ball Sensitivity

These tools are covered in Chapters 6, 10, and 15.

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 inimitable 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 Academy), Prafulla Joglekar (LaSalle University), Tarja Joro (University of Alberta), Ron Klimberg (Saint Joseph's University), Larry Leblanc (Vanderbilt University), Jerry May (University of Pittsburgh), Jim Morris (University of Wisconsin), Jim Mote (RPI), Chuck Noon (University of Tennessee), Tava Olsen (Washington University), Fred Raafat (San Diego State University), Gary Reeves (University of South Carolina), Moshe Rosenwein (Columbia University), David Schilling (Ohio State University), Linus Schrage (University of Chicago), Donald Simmons (Ithaca College), George Steiner (McMaster University), Stephen Thorpe (Drexel University).

Additional feedback and help on the second edition came from: R. Kim Craft (Southern Utah University), Joan Donohue (University of South Carolina), Steve Ford (University of the South), Phillip Fry (Boise State University), Li Guodong (Maryville University), LeRoy Honeycutt (Gardner-Webb University), Rich Kilgore (St. Louis University), Frank Krzystofiak (University at Buffalo SUNY), Shailesh Kulkarni (University of North Texas), Dale Lehman (Alaska Pacific University), Vedran Lelas (Plymouth State University), David Walter Little (High Point University), Leo Lopes (University of Arizona), Alvin J. Martinez (University of Puerto Rico, Rio Piedras), Jacquelynne McLellan (Frostburg State University), Ajay Mishra (Binghamton University SUNY), Shimon Y. Nof (Purdue University), Manuel Nunez (University of Connecticut), Alan Olinsky (Bryant University), Tava Olsen (Washington University), Susan Palocsay (James Madison University), Ganga P. Ramdas (Lincoln University), B. Madhu Rao (Bowling Green State University), Jim Robison (Sonoma State University), Christopher M. Rump (Bowling Green State University), Thomas Sandman (California State University, Sacramento), Sergei Savin (Columbia University), Daniel Shimshak (University of Massachusetts Boston), Minghe Sun (University of Texas at San Antonio), David Tufte (Southern Utah University).

Beth Golub of John Wiley & Sons encouraged us to write this book for years and has been a supportive influence since we began. We appreciate the extensive network she has continually tapped for feedback and her initial willingness to support us in writing a new kind of textbook.

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, Business Process Redesign, and Applications of Simulation. He originated the Teacher's Forum column in *Interfaces*, and has written a number of articles on teaching modeling to practitioners. He is 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.

Ken Baker is a faculty member at Dartmouth College. He is currently Nathaniel Leverone Professor of Management at the Tuck School of Business and also Adjunct Professor at the Thayer School of Engineering. At Dartmouth, he has taught courses relating to Management Science, Manufacturing Management, and Environmental Management. He is the author of two other textbooks, *Elements of Sequencing and Scheduling* and *Optimization Modeling with Spreadsheets*, in addition to a variety of technical articles. He has served as Tuck School's Associate Dean and directed the Tuck School's management development programs in the manufacturing area. He is an INFORMS Fellow as well as a Fellow of the Manufacturing and Service Operations Management (MSOM) Society.

Brief Contents

CHAPTER 1	INTRODUCTION	1
CHAPTER 2	MODELING IN A PROBLEM-SOLVING FRAMEWORK	17
CHAPTER 3	BASIC EXCEL SKILLS	52
CHAPTER 4	ADVANCED EXCEL SKILLS	73
CHAPTER 5	SPREADSHEET ENGINEERING	95
CHAPTER 6	ANALYSIS USING SPREADSHEETS	123
CHAPTER 7	DATA ANALYSIS FOR MODELING	140
CHAPTER 8	REGRESSION ANALYSIS	162
CHAPTER 9	SHORT-TERM FORECASTING	189
CHAPTER 10	NONLINEAR OPTIMIZATION	214
CHAPTER 11	LINEAR PROGRAMMING	246
CHAPTER 12	NETWORK MODELS	285
CHAPTER 13	INTEGER PROGRAMMING	317
CHAPTER 14	DECISION ANALYSIS	342
CHAPTER 15	MONTE CARLO SIMULATION	370
CHAPTER 16	OPTIMIZATION IN SIMULATION	436
	MODELING CASES	478
	APPENDIX: BASIC PROBABILITY CONCEPTS	494

Table of Contents

CHAPTER 1 INTRODUCTION 1

- 1.1 Models and Modeling 1
 - 1.1.1 Why Study Modeling? 2
 - 1.1.2 Models in Business 2
 - 1.1.3 Models in Business Education 3
 - 1.1.4 Benefits of Business Models 4
- 1.2 The Role of Spreadsheets 4
 - 1.2.1 Risks of Spreadsheet Use 5
 - 1.2.2 Challenges for Spreadsheet Users 7
 - 1.2.3 Background Knowledge for Spreadsheet Modeling 8
- 1.3 The Real World and the Model World 9
- 1.4 Lessons from Expert and Novice Modelers 11
 - 1.4.1 Expert Modelers 11
 - 1.4.2 Novice Modelers 12
- 1.5 Organization of the Book 14
- 1.6 Summary 16

CHAPTER 2 MODELING IN A PROBLEM-SOLVING FRAMEWORK 17

- 2.1 Introduction 17
- 2.2 The Problem-Solving Process 18
 - 2.2.1 Some Key Terms 19
 - 2.2.2 The Six-Stage Problem-Solving Process 20
 - 2.2.3 Mental Models and Formal Models 26
- 2.3 Influence Charts 27
 - 2.3.1 A First Example 28
 - 2.3.2 An Income Statement as an Influence Chart 29
 - 2.3.3 Principles for Building Influence Charts 30
 - 2.3.4 Two Additional Examples 31
- 2.4 Craft Skills for Modeling 34
 - 2.4.1 Simplify the Problem 36
 - 2.4.2 Break the Problem into Modules 37
 - 2.4.3 Build a Prototype and Refine It 38
 - 2.4.4 Sketch Graphs of Key Relationships 42
 - 2.4.5 Identify Parameters and Perform Sensitivity Analysis 43
 - 2.4.6 Separate the Creation of Ideas from Their Evaluation 45
 - 2.4.7 Work Backward from the Desired Answer 46
 - 2.4.8 Focus on Model Structure, not on Data Collection 47
- 2.5 Summary 49

CHAPTER 3 BASIC EXCEL SKILLS 52

- 3.1 Introduction 52
- 3.2 Excel Prerequisites 52
- 3.3 The Excel Window 53
- 3.4 Configuring Excel 55
- 3.5 Manipulating Windows and Sheets 56
- 3.6 Navigation 57
- 3.7 Selecting Cells 58
- 3.8 Entering Text and Data 59
- 3.9 Editing Cells 59
- 3.10 Formatting 60
- 3.11 Basic Formulas 61
- 3.12 Basic Functions 62
- 3.13 Charting 65
- 3.14 Printing 69
- 3.15 Help Options 70
- 3.16 Summary 71

CHAPTER 4 ADVANCED EXCEL SKILLS 73

- 4.1 Introduction 73
- 4.2 Keyboard Shortcuts 73
- 4.3 Controls 74
- 4.4 Cell Comments 77
- 4.5 Naming Cells and Ranges 78
- 4.6 Advanced Formulas and Functions 81
 - 4.6.1 R1C1 Reference Style 81
 - 4.6.2 Mixed Addresses 82
 - 4.6.3 Nesting Calculations 83
 - 4.6.4 Parameterization 83
 - 4.6.5 Advanced Functions 84
- 4.7 Recording Macros And Using VBA 88
 - 4.7.1 Recording a Macro 89
 - 4.7.2 Editing a Macro 90
 - 4.7.3 Creating a User-Defined Function 93
- 4.8 Summary 94

CHAPTER 5 SPREADSHEET ENGINEERING 95

- 5.1 Introduction 95
- 5.2 Designing a Spreadsheet 96
 - 5.2.1 Sketch the Spreadsheet 97
 - 5.2.2 Organize the Spreadsheet into Modules 98
 - 5.2.3 Start Small 99
 - 5.2.4 Isolate Input Parameters 100
 - 5.2.5 Design for Use 100
 - 5.2.6 Keep It Simple 101
 - 5.2.7 Design for Communication 101
 - 5.2.8 Document Important Data and Formulas 102

5.3	Designing a Workbook	103
5.3.1	Use Separate Worksheets to Group Similar Kinds of Information	104
5.3.2	Design Workbooks for Ease of Navigation and Use	105
5.3.3	Design a Workbook as a Decision-Support System	106
5.4	Building a Workbook	108
5.4.1	Follow a Plan	109
5.4.2	Build One Worksheet or Module at a Time	109
5.4.3	Predict the Outcome of Each Formula	109
5.4.4	Copy and Paste Formulas Carefully	109
5.4.5	Use Relative and Absolute Addressing to Simplify Copying	110
5.4.6	Use the Function Wizard to Ensure Correct Syntax	110
5.4.7	Use Range Names to Make Formulas Easy to Read	110
5.4.8	Choose Input Data to Make Errors Stand Out	111
5.5	Testing a Workbook	111
5.5.1	Check That Numerical Results Look Plausible	112
5.5.2	Check That Formulas Are Correct	112
5.5.3	Test That Model Performance Is Plausible	116
5.6*	Auditing Software: Spreadsheet Professional	117
5.6.1	Building Tools	117
5.6.2	Testing Tools	118
5.6.3	Documenting Tools	120
5.6.4	Usage Tools	121
5.7	Summary	121

CHAPTER 6 ANALYSIS USING SPREADSHEETS 123

6.1	Introduction	123
6.2	Base-case Analysis	124
6.3	What-If Analysis	124
6.3.1	Benchmarking	126
6.3.2	Scenarios	127
6.3.3	Data Sensitivity	129
6.3.4	Tornado Charts	131
6.4	Breakeven Analysis	133
6.5	Optimization Analysis	135
6.6	Simulation and Risk Analysis	136
6.7	Summary	137

CHAPTER 7 DATA ANALYSIS FOR MODELING 140

7.1	Introduction	140
7.2	Finding Facts from Databases	141
7.2.1	Searching and Editing	143
7.2.2	Sorting	143
7.2.3	Filtering	145
7.2.4	Tabulating	148
7.3	Analyzing Sample Data	151
7.4	Estimating Parameters: Point Estimates	153

7.5*	Estimating Parameters: Interval Estimates	154
7.5.1	Interval Estimates for the Mean	155
7.5.2	Interval Estimates for a Proportion	158
7.5.3	Sample-size Determination	158
7.6	Summary	159

CHAPTER 8 REGRESSION ANALYSIS 162

8.1	Introduction	162
8.2	A Decision-Making Example	163
8.2.1	Base-case Analysis	163
8.2.2	Sensitivity Analysis	164
8.2.3	Base-case Summary	166
8.3	Exploring Data: Scatter Plots and Correlation	166
8.4	Simple Linear Regression	168
8.5	Goodness-of-Fit	169
8.6	Simple Regression in the BPI Example	173
8.7	Simple Nonlinear Regression	176
8.8	Multiple Linear Regression	177
8.9	Multiple Regression in the BPI Example	179
8.10	Regression Assumptions	181
8.11*	Using the Excel Tools Trendline and LINEST	182
8.11.1	Trendline	182
8.11.2	LINEST	184
8.12	Summary	185

CHAPTER 9 SHORT-TERM FORECASTING 189

9.1	Introduction	189
9.2	Forecasting with Time Series Models	189
9.2.1	The Moving Average Model	190
9.2.2	Measures of Forecast Accuracy	193
9.3	The Exponential Smoothing Model	194
9.4	Exponential Smoothing with a Trend	198
9.5	Exponential Smoothing with Trend and Cyclical Factors	202
9.6*	Using CB Predictor	205
9.6.1	Single Moving Average	205
9.6.2	Single Exponential Smoothing	207
9.7	Summary	209

CHAPTER 10 NONLINEAR OPTIMIZATION 214

10.1	Introduction	214
10.2	An Optimization Example	215
10.2.1	Optimizing Q1	215
10.2.2	Optimization Over All Four Quarters	217
10.2.3	Incorporating the Budget Constraint	218
10.3	Building Models for Solver	219
10.3.1	Formulation	220
10.3.2	Layout	222
10.3.3	Interpreting Results	223
10.4	Model Classification and the Nonlinear Solver	223
10.5	Nonlinear Programming Examples	225
10.5.1	Facility Location	225
10.5.2	Revenue Maximization	227
10.5.3	Curve Fitting	229
10.5.4	Economic Order Quantity	232
10.6	Sensitivity Analysis for Nonlinear Programs	234
10.7*	The Portfolio Optimization Model	238
10.8	Summary	241

CHAPTER 11 LINEAR PROGRAMMING 246

- 11.1 Introduction 246
 - 11.1.1 Linearity 246
 - 11.1.2 Simplex Algorithm 247
- 11.2 Allocation Models 248
 - 11.2.1 Formulation 249
 - 11.2.2 Spreadsheet Model 249
 - 11.2.3 Optimization 251
- 11.3 Covering Models 252
 - 11.3.1 Formulation 253
 - 11.3.2 Spreadsheet Model 254
 - 11.3.3 Optimization 254
- 11.4 Blending Models 255
 - 11.4.1 Blending Constraints 256
 - 11.4.2 Formulation 257
 - 11.4.3 Spreadsheet Model 258
 - 11.4.4 Optimization 259
- 11.5 Sensitivity Analysis for Linear Programs 260
 - 11.5.1 Sensitivity to Objective Function Coefficients 261
 - 11.5.2 Sensitivity to Constraint Constants 262
- 11.6 Patterns in Linear Programming Solutions 265
 - 11.6.1 Identifying Patterns 265
 - 11.6.2 Further Examples 267
 - 11.6.3 Review 272
- 11.7* Data Envelopment Analysis 273
- 11.8 Summary 277
- Appendix 11.1 282

CHAPTER 12 NETWORK MODELS 285

- 12.1 Introduction 285
- 12.2 The Transportation Model 285
 - 12.2.1 Flow Diagram 286
 - 12.2.2 Formulation 286
 - 12.2.3 Spreadsheet Model 287
 - 12.2.4 Optimization 288
 - 12.2.5 Modifications to the Model 289
 - 12.2.6 Sensitivity Analysis 290
- 12.3 Assignment Model 294
 - 12.3.1 Formulation 294
 - 12.3.2 Spreadsheet Model 295
 - 12.3.3 Optimization 296
 - 12.3.4 Sensitivity Analysis 296
- 12.4 The Transshipment Model 297
 - 12.4.1 Formulation 297
 - 12.4.2 Spreadsheet Model 299
 - 12.4.3 Optimization 299
 - 12.4.4 Sensitivity Analysis 300
- 12.5 A Standard Form for Network Models 300
- 12.6 Network Models with Yields 303
 - 12.6.1 Yields as Reductions in Flow 303
 - 12.6.2 Yields as Expansions in Flow 304
 - 12.6.3 Patterns in General Network Models 307
- 12.7* Network Models for Process Technologies 308
 - 12.7.1 Formulation 309
 - 12.7.2 Spreadsheet Model 310
 - 12.7.3 Optimization 311
- 12.8 Summary 312

CHAPTER 13 INTEGER PROGRAMMING 317

- 13.1 Introduction 317
- 13.2 Integer Variables and the Integer Solver 318
- 13.3 Binary Variables and Binary Choice Models 320
 - 13.3.1 The Capital Budgeting Problem 320
 - 13.3.2 The Set Covering Problem 322
- 13.4 Binary Variables and Logical Relationships 324
 - 13.4.1 Relationships among Projects 324
 - 13.4.2 Linking Constraints and Fixed Costs 326
 - 13.4.3 Threshold Levels and Quantity Discounts 329
- 13.5* The Facility Location Model 331
 - 13.5.1 The Capacitated Problem 331
 - 13.5.2 The Uncapacitated Problem 334
 - 13.5.3 The Assortment Model 335
- 13.6 Summary 337

CHAPTER 14 DECISION ANALYSIS 342

- 14.1 Introduction 342
- 14.2 Payoff Tables and Decision Criteria 343
 - 14.2.1 Benchmark Criteria 343
 - 14.2.2 Incorporating Probabilities 345
- 14.3 Using Trees to Model Decisions 346
 - 14.3.1 Decision Trees 347
 - 14.3.2 Decision Trees for a Series of Decisions 350
 - 14.3.3 Principles for Building and Analyzing Decision Trees 353
 - 14.3.4 The Cost of Uncertainty 354
- 14.4 Using TreePlan Software 355
 - 14.4.1 Solving a Simple Example with TreePlan 356
 - 14.4.2 Sensitivity Analysis with TreePlan 359
 - 14.4.3 Minimizing Expected Costs with TreePlan 360
- 14.5* Maximizing Expected Utility with TreePlan 360
- 14.6 Summary 365

CHAPTER 15 MONTE CARLO SIMULATION 370

- 15.1 Introduction 370
- 15.2 A Simple Illustration 371
- 15.3 The Simulation Process 374
 - 15.3.1 Base-case Model 374
 - 15.3.2 Sensitivity Analysis 376
 - 15.3.3 Selecting Probability Distributions—Creating Assumption Cells 376
 - 15.3.4 Selecting Outputs—Creating Forecast Cells 379
 - 15.3.5 Setting Simulation Parameters 380
 - 15.3.6 Analyzing Simulation Outputs 380
- 15.4 Corporate Valuation Using Simulation 383
 - 15.4.1 Base-case Model 383
 - 15.4.2 Sensitivity Analysis 386
 - 15.4.3 Selecting Probability Distributions 387
 - 15.4.4 Simulation Analysis 388
 - 15.4.5 Simulation Sensitivity 389
- 15.5 Option Pricing Using Simulation 391
 - 15.5.1 The Logic of Options 392
 - 15.5.2 Modeling Stock Prices 392

15.5.3	Pricing an Option	396
15.5.4	Sensitivity to Volatility	397
15.5.5	Simulation Accuracy	398
15.6	Selecting Uncertain Parameters	398
15.7	Selecting Probability Distributions	401
15.7.1	Empirical Data and Judgmental Data	401
15.7.2	Six Essential Distributions	402
15.7.3	Fitting Distributions to Data	406
15.8	Ensuring Precision in Outputs	407
15.8.1	Illustrations of Simulation Error	408
15.8.2	Precision Versus Accuracy	409
15.8.3	An Experimental Method	410
15.8.4	Simulation Error in a Decision Context	411
15.9	Interpreting Simulation Outcomes	411
15.9.1	Forecast Charts	412
15.9.2	Statistics and Percentiles	413
15.10*	When Not to Simulate	415
15.11	Summary	417
Appendix 15.1	Choosing Crystal Ball Settings	423
Appendix 15.2	Additional features of Crystal Ball	426

* Optional Sections

16.1	Introduction	436
16.2	Optimization with One or Two Decision Variables	436
16.2.1	Base-case Model	437
16.2.2	Grid Search	439
16.2.3	Replicating the Model	440
16.2.4	Using CB Sensitivity	443
16.3	Complex Optimization Problems	444
16.3.1	OptQuest Concepts	445
16.3.2	A Production Planning Problem	446
16.3.3	A Portfolio Optimization Problem	451
16.3.4	A Cash-Management Problem	458
16.4*	Embedded Optimization: Using Solver within Crystal Ball	465
16.4.1	A Capacity Planning Example	467
16.4.2	Creating a Macro to Embed Solver	470
16.5	Summary	472

MODELING CASES **478**

APPENDIX BASIC PROBABILITY CONCEPTS **494**

INDEX **505**

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