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Introduction to MANAGEMENT SCIENCE

A Modeling and Case Studies Approach with Spreadsheets

6e

Frederick S. Hillier

Mark S. Hillier

Mc Graw Hill Education

Introduction to Management Science

A Modeling and Case Studies Approach with Spreadsheets

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Introduction to Management Science

A Modeling and Case Studies Approach with Spreadsheets

Sixth Edition

Frederick S. Hillier
Stanford University

Mark S. Hillier
University of Washington

Cases developed by
Karl Schmedders
University of Zurich

Molly Stephens
Quinn, Emanuel, Urquhart & Sullivan, LLP

Mc Graw Hill Education

INTRODUCTION TO MANAGEMENT SCIENCE

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To the memory of

Christine Phillips Hillier
a beloved wife and daughter-in-law

Gerald J. Lieberman
an admired mentor and one of the true giants
of our field

About the Authors

Frederick S. Hillier is professor emeritus of operations research at Stanford University. Dr. Hillier is especially known for his classic, award-winning text, *Introduction to Operations Research,* co-authored with the late Gerald J. Lieberman, which has been translated into well over a dozen languages and is currently in its 10th edition. The 6th edition won honorable mention for the 1995 Lanchester Prize (best English-language publication of any kind in the field), and Dr. Hillier also was awarded the 2004 INFORMS Expository Writing Award for the 8th edition. His other books include *The Evaluation of Risky Interrelated Investments, Queueing Tables and Graphs, Introduction to Stochastic Models in Operations Research,* and *Introduction to Mathematical Programming.* He received his BS in industrial engineering and doctorate specializing in operations research and management science from Stanford University. The winner of many awards in high school and college for writing, mathematics, debate, and music, he ranked first in his undergraduate engineering class and was awarded three national fellowships (National Science Foundation, Tau Beta Pi, and Danforth) for graduate study. After receiving his PhD degree, he joined the faculty of Stanford University, where he earned tenure at the age of 28 and the rank of full professor at 32. Dr. Hillier's research has extended into a variety of areas, including integer programming, queueing theory and its application, statistical quality control, and production and operations management. He also has won a major prize for research in capital budgeting. Twice elected a national officer of professional societies, he has served in many important professional and editorial capacities. For example, he served The Institute of Management Sciences as vice president for meetings, chairman of the publications committee, associate editor of *Management Science,* and co-general chairman of an international conference in Japan. He also is a Fellow of the Institute for Operations Research and the Management Sciences (INFORMS). He served for 20 years (until 2013) as the founding series editor for a prominent book series, the International Series in Operations Research and Management Science, for Springer Science + Business Media. He has had visiting appointments at Cornell University, the Graduate School of Industrial Administration of Carnegie-Mellon University, the Technical University of Denmark, the University of Canterbury (New Zealand), and the Judge Institute of Management Studies at the University of Cambridge (England).

Mark S. Hillier, son of Fred Hillier, is associate professor of quantitative methods at the Michael G. Foster School of Business at the University of Washington. Dr. Hillier received his BS in engineering (plus a concentration in computer science) from Swarthmore College. He then received his MS with distinction in operations research and PhD in industrial engineering and engineering management from Stanford University. As an undergraduate, he won the McCabe Award for ranking first in his engineering class, won election to Phi Beta Kappa based on his work in mathematics, set school records on the men's swim team, and was awarded two national fellowships (National Science Foundation and Tau Beta Pi) for graduate study. During that time, he also developed a comprehensive software tutorial package, *OR Courseware,* for the Hillier–Lieberman textbook, *Introduction to Operations Research.* As a graduate student, he taught a PhD-level seminar in operations management at Stanford and won a national prize for work based on his PhD dissertation. At the University of Washington, he currently teaches courses in management science and spreadsheet modeling. He has won over twenty MBA teaching awards for the core course in management science and his elective course in spreadsheet modeling, as well as a universitywide teaching award for his work in teaching undergraduate classes in operations management. He was chosen by MBA students in both 2007 and 2013 as the winner of the prestigious PACCAR award for Teacher of the Year (reputed to provide the largest monetary award for MBA teaching in the nation). He won the Ron Crocket Award for Innovation in Education in 2014. He also has been awarded an appointment to the Evert McCabe Endowed Faculty Fellowship. His research interests include issues in component commonality, inventory, manufacturing, and the design of production systems. A paper by Dr. Hillier on component commonality won an award for best paper of 2000–2001 in *IIE Transactions.* He also has been serving as principal investigator on a grant from the Bill and Melinda Gates Foundation to lead student research projects that apply spreadsheet modeling to various issues in global health being studied by the foundation.

About the Case Writers

Karl Schmedders is professor of quantitative business administration at the University of Zurich in Switzerland and a visiting professor of executive education at the Kellogg School of Management of Northwestern University. His research interests include management science, business analytics, and computational economics and finance. He received his PhD in operations research from Stanford University, where he taught both undergraduate and graduate classes in management science, including a case studies course. He received several teaching awards at Stanford, including the universitywide Walter J. Gores Teaching Award. After a post-doc at the Hoover Institution, a think tank on the Stanford campus, he became assistant professor of managerial economics and decision sciences at the Kellogg School. He was promoted to associate professor in 2001 and received tenure in 2005. In 2008 he joined the University of Zurich, where he currently teaches courses in management science, business analytics, and computational economics and finance. He has published research articles in international academic journals such as *Management Science, Operations Research, Econometrica, The Review of Economic Studies,* and *The Journal of Finance,* among others. He is the area editor of the field "Computational Economics" for the INFORMS journal *Operations Research.* At Kellogg he received several teaching awards, including the L. G. Lavengood Professor of the Year Award. Most recently he won the best professor award of the Kellogg School's European EMBA program (2011, 2012, 2013, 2014, 2015) and its EMBA program in Hong Kong (2017).

Molly Stephens is a partner in the Los Angeles office of Quinn, Emanuel, Urquhart & Sullivan, LLP. She graduated from Stanford with a BS in industrial engineering and an MS in operations research. Ms. Stephens taught public speaking in Stanford's School of Engineering and served as a teaching assistant for a case studies course in management science. As a teaching assistant, she analyzed management science problems encountered in the real world and transformed these into classroom case studies. Her research was rewarded when she won an undergraduate research grant from Stanford to continue her work and was invited to speak at INFORMS to present her conclusions regarding successful classroom case studies. Following graduation, Ms. Stephens worked at Andersen Consulting as a systems integrator, experiencing real cases from the inside, before resuming her graduate studies to earn a JD degree with honors from the University of Texas School of Law at Austin. She is a partner in the largest law firm in the United States devoted solely to business litigation, where her practice focuses on complex financial and securities litigation. She also is ranked as a leading securities litigator by Chambers USA (2013 and 2014), which acknowledged "praise for her powerful and impressive securities litigation practice" and noted that she is "phenomenally bright, a critical thinker and great listener."

Preface

We have long been concerned that traditional management science textbooks have not taken the best approach in introducing business students to this exciting field. Our goal when initially developing this book during the late 1990s was to break out of the old mold and present new and innovative ways of teaching management science more effectively. We have been gratified by the favorable response to our efforts. Many reviewers and other users of the first five editions of the book have expressed appreciation for its various distinctive features, as well as for its clear presentation at just the right level for their business students.

Our goal for this sixth edition has been to build on the strengths of the first five editions. Co-author Mark Hillier has won over twenty schoolwide teaching awards for his spreadsheet modeling and management science courses at the University of Washington while using the first five editions, and this experience has led to many improvements in the current edition. We also incorporated many user comments and suggestions. Throughout this process, we took painstaking care to enhance the quality of the preceding edition while maintaining the distinctive orientation of the book.

This distinctive orientation is one that closely follows the recommendations in the 1996 report of the operating subcommittee of the INFORMS Business School Education Task Force, including the following extract.

> There is clear evidence that there must be a major change in the character of the (introductory management science) course in this environment. There is little patience with courses centered on algorithms. Instead, the demand is for courses that focus on business situations, include prominent non-mathematical issues, use spreadsheets, and involve model formulation and assessment more than model structuring. Such a course requires new teaching materials.

This book is designed to provide the teaching materials for such a course.

In line with the recommendations of this task force, which continue to be widely accepted today, we believe that a modern introductory management science textbook should have three key elements. As summarized in the subtitle of this book, these elements are a *modeling* and *case studies* approach with *spreadsheets.*

SPREADSHEETS

The modern approach to the teaching of management science clearly is to use *spreadsheets* as a primary medium of instruction. Both business students and managers now live with spreadsheets, so they provide a comfortable and enjoyable learning environment. Modern spreadsheet software, including Microsoft Excel used in this book, now can be used to do real management science. For student-scale models (which include many practical real-world models), spreadsheets are a much better way of implementing management science models than traditional algebraic solvers. This means that the algebraic curtain that continues to be prevalent in traditional management science courses and textbooks now can be lifted.

However, with the current enthusiasm for spreadsheets, there is a danger of going overboard. Spreadsheets are not the only useful tool for performing management science analyses. Occasional modest use of algebraic and graphical analyses still have their place and we would be doing a disservice to the students by not developing their skills in these areas when appropriate. Furthermore, the book should not be mainly a spreadsheet cookbook that focuses largely on spreadsheet mechanics. Spreadsheets are a means to an end, not an end in themselves.

A MODELING APPROACH

This brings us to the second key feature of the book, a *modeling approach.* Model formulation lies at the heart of management science methodology. Therefore, we heavily emphasize the art of model formulation, the role of a model, and the analysis of model results. We primarily (but not exclusively) use a spreadsheet format rather than algebra for formulating and presenting a model.

Some instructors have many years of experience in teaching modeling in terms of formulating algebraic models (or what the INFORMS Task Force called "model structuring"). Some of these instructors feel that students should do their modeling in this way and then transfer the model to a spreadsheet simply to use the Excel Solver to solve the model. We disagree with this approach. Our experience (and the experience reported by many others) is that most business students find it more natural and comfortable to do their modeling directly in a spreadsheet. Furthermore, by using the best spreadsheet modeling techniques (as presented in this edition), formulating a spreadsheet model tends to be considerably more efficient and transparent than formulating an algebraic model. Another benefit is that the spreadsheet model includes all the relationships that can be expressed in an algebraic form and we often will summarize the model in this format as well.

Another break from past tradition in this book (and several contemporary textbooks) is to virtually ignore the algorithms that are used to solve the models. We feel that there is no good reason why typical business students should learn the details of algorithms executed by computers. Within the time constraints of a one-term management science course, there are far more important lessons to be learned. Therefore, the focus in this book is on what we believe are these far more important lessons. High on this list is the art of modeling managerial problems on a spreadsheet.

We believe that training business students in spreadsheet modeling will provide them with two key benefits when they later become managers. First, this will give them a powerful tool for analyzing small managerial problems without requiring outside help. Second, this will enable them to recognize when a management science team could be very helpful for analyzing more complicated managerial problems.

Formulating a spreadsheet model of a real problem typically involves much more than designing the spreadsheet and entering the data. Therefore, we work through the process step by step: understand the unstructured problem, verbally develop some structure for the problem, gather the data, express the relationships in quantitative terms, and then lay out the spreadsheet model. The structured approach highlights the typical components of the model (the data, the decisions to be made, the constraints, and the measure of performance) and the different types of spreadsheet cells used for each. Consequently, the emphasis is on the modeling rather than spreadsheet mechanics.

A CASE STUDIES APPROACH

However, all this still would be quite sterile if we simply presented a long series of brief examples with their spreadsheet formulations. This leads to the third key feature of this book—a *case studies* approach. In addition to examples, nearly every chapter includes one or two case studies patterned after actual applications to convey the whole process of applying management science. In a few instances, the entire chapter revolves around a case study. By drawing the student into the story, we have designed each case study to bring that chapter's technique to life in a context that vividly illustrates the relevance of the technique for aiding managerial decision making. This storytelling, case-centered approach should make the material more enjoyable and stimulating while also conveying the practical considerations that are key factors in applying management science.

We have been pleased to have several reviewers of the first five editions express particular appreciation for our case study approach. Even though this storytelling approach has received little use in other management science textbooks, we feel that it is a real key to preparing students for the practical application of management science in all its aspects. Some of the reviewers have highlighted the effectiveness of the dialogue/scenario enactment approach used in some of the case studies. Although unconventional, this approach provides a way of demonstrating the process of managerial decision making with the help of management science. It also enables previewing some key concepts in the language of management.

Every chapter also contains full-fledged cases following the problems at the end of the chapter. These cases usually continue to employ a stimulating storytelling approach, so they can be assigned as interesting and challenging projects. Most of these cases were developed

jointly by two talented case writers, Karl Schmedders (a faculty member at the University of Zurich in Switzerland) and Molly Stephens (formerly a management science consultant with Andersen Consulting). The authors also have added some cases, including several shorter ones. In addition, the University of Western Ontario Ivey School of Business (the second-largest producer of teaching cases in the world) has specially selected cases from their case collection that match the chapters in this textbook. These cases are available on the Ivey website, **cases.ivey.uwo.ca/cases,** in the segment of the CaseMate area designated for this book. This website address is provided at the end of each chapter as well.

We are, of course, not the first to incorporate any of these key features into a management science textbook. However, we believe that the book currently is unique in the way that it fully incorporates all three key features together.

OTHER SPECIAL FEATURES

We also should mention some additional special features of the book that are continued from the fifth edition.

- Diverse examples, problems, and cases convey the pervasive relevance of management science.
- A strong managerial perspective.
- Learning objectives at the beginning of each chapter.
- Numerous margin notes that clarify and highlight key points.
- Excel tips interspersed among the margin notes.
- Review questions at the end of each section.
- A glossary at the end of each chapter.
- Partial answers to selected problems in the back of the book.
- Extensive supplementary text materials (nine supplements to book chapters and seven additional chapters) are available in the Instructor Resources of McGraw-Hill's online homework management platform, Connect, (described later) and on the website, **www.mhhe.com/Hillier6e.**

A NEW SOFTWARE PACKAGE

This edition continues to integrate Excel and its Solver (a product originally created by Frontline Systems) throughout the book. However, we are excited to also add to this edition an impressive more recent product of Frontline Systems called **Analytic Solver ® for Education** (hereafter referred to as Analytic Solver). Analytic Solver can be used with Microsoft Excel for Windows (as an add-in), or 'in the cloud" at **AnalyticSolver.com** using any device (PC, Mac, tablet) with a web browser. It offers comprehensive features for prescriptive analytics (optimization, simulation, decision analysis) and predictive analytics (forecasting, data mining, text mining). Its optimization features are upward compatible from the standard Solver in Excel. Analytic Solver includes:

- A more interactive user interface, with the model parameters always visible alongside the main spreadsheet, rather than only in the Solver dialog box.
- Parameter analysis reports that provide an easy way to see the effect of varying data in a model in a systematic way.
- A model analysis tool that reveals the characteristics of a model (e.g., whether it is linear or nonlinear, smooth or nonsmooth).
- Tools to build and solve decision trees within a spreadsheet.
- A full range of time series forecasting and data mining models.
- The ability to build and run sophisticated Monte Carlo simulation models.
- An interactive simulation mode that allows simulation results to be shown instantly whenever a change is made to a simulation model.
- The Solver in Analytic Solver can be used in combination with computer simulation to perform simulation optimization.

- **If interested in having students get individual licenses for class use, instructors should send an email to support@solver.com to get their course code and receive student pricing and access information as well as their own access information.** Note that this software is no longer free with the purchase of this text, but low-cost student licenses are available.

A CONTINUING FOCUS ON EXCEL AND ITS SOLVER

As with all the preceding editions, this edition continues to focus on spreadsheet modeling in an Excel format. Although it lacks some of the functionalities of Analytic Solver, the Excel Solver continues to provide a completely satisfactory way of solving most of the spreadsheet models encountered in this book. This edition continues to feature this use of the Excel Solver whenever either it or the Analytic Solver could be used.

Many instructors prefer this focus because it avoids introducing other complications that might confuse their students. We agree.

However, the key advantage of introducing Analytic Solver in this edition is that it provides an all-in-one complement to the Excel Solver. There are some important topics in the book (including decision analysis and computer simulation) where the Excel Solver lacks the functionalities needed to deal fully with these kinds of problems. Multiple Excel add-ins—Solver Table, TreePlan, SensIt, RiskSim, Crystal Ball, and OptQuest (a module of Crystal Ball)—were introduced in previous editions to provide the needed functionalities. Analytic Solver alone now replaces all of these add-ins.

To further enhance a continuing focus on Excel and its Solver, **www.mhhe.com/Hillier6e** includes all the Excel files that provide the live spreadsheets for all the various examples and case studies throughout the book. In addition to further investigating the examples and case studies, these spreadsheets can be used by either the student or instructor as templates to formulate and solve similar problems. This website also includes dozens of Excel templates for solving various models in the book as well as a Queueing Simulator for performing computer simulations of queueing systems (used in Chapter 12).

NEW FEATURES IN THIS EDITION

We have made some important enhancements to the current edition.

- **A New Section Describes the Relationship Between Analytics and Management Science.** Recent years have seen an exciting *analytics revolution* as the business world has come to recognize the key role that *analytics* can play in managerial decision making. A new Section 1.3 fully describes the close relationship between analytics and management science.
- **A New Section on the Role of Robust Optimization in What-If Analysis.** The goal of *robust optimization* is to find a solution for a model that is virtually guaranteed to remain feasible and near optimal for all plausible combinations of the actual values for the parameters of the model. A new Section 5.7 describes this key tool for performing what-if analysis for linear programming models.
- **A New Section on Chance Constraints.** Constraints in a model usually are fully required to be satisfied, but occasionally constraints arise that actually have a little flexibility. C*hance constraints* provide a way of dealing with such constraints that actually can be violated a little bit without serious complications. A new Section 5.8 describes the role of chance constraints and how to implement them.
- **A Thorough Updating Throughout the Book.** Given that the writing of the first edition occurred approximately 20 years ago, it is inevitable that some of that writing now is somewhat outdated. Even though the descriptions of management science techniques may still be accurate, the numbers and other details describing their application in certain problems, cases, and examples may now seem quite obsolete. Wage standards have changed. Prices have changed. Technologies have changed. Dates have changed. Although we did some updating with each new edition, we made a special effort this time to thoroughly update numbers and other details as needed to reflect conditions in 2017.
- **Additional Links to Articles that Describe Dramatic Real Applications.** The fifth edition included 28 application vignettes that described in a few paragraphs how an actual application of management science had a powerful effect on a company or organization by using

techniques like those being studied in that portion of the book. The current edition adds five more vignettes based on recent applications (while deleting seven outdated ones) and also updates the information in nine of the other vignettes. We continue the practice of adding a link to the journal articles that fully describe these applications (except that the vignette for Chapter 1 doesn't require a link), through a special arrangement with the Institute for Operations Research and the Management Sciences (INFORMS®). Thus, the instructor now can motivate his or her lectures by having the students delve into real applications that dramatically demonstrate the relevance of the material being covered in the lectures. The end-of-chapter problems also include an assignment after reading each of these articles.

We continue to be excited about this partnership with INFORMS, our field's preeminent professional society, to provide a link to each of these articles describing spectacular applications of management science. INFORMS is a learned professional society for students, academics, and practitioners in analytics, operations research, and management science. Information about INFORMS journals, meetings, job bank, scholarships, awards, and teaching materials is available at **www.informs.org.**

- **A Word-by-Word Review to Further Increase Clarity in Each Chapter.** A hallmark of each edition has been a particularly heavy use of certain techniques to maximize the clarity of the material: use cases to bring the material to life, divide sections into smaller subsections, use short paragraphs, use bullet points, set off special conclusions, use italics or boldface to highlight key points, add margin notes, never assume too much about understanding preceding material, etc. However, we have doubled down with this approach in the current edition by using a word-by-word review of each chapter to further increase clarity while also taking into special account the input provided by reviewers and others.

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Connect is a teaching and learning platform that is proven to deliver better results for students and instructors. Connect empowers students by continually adapting to deliver precisely what they need, when they need it, and how they need it, so your class time is more engaging and effective.

New to the 6th edition, Connect includes multiple-choice questions for each chapter to be used as practice or homework for students, SmartBook(R), instructor resources (including the test bank), and student resources. For access, visit **connect.mheducation.com** or contact your McGraw-Hill sales representative.

SMARTBOOK(R)

Proven to help students improve grades and study more efficiently, SmartBook contains the same content within the print book, but actively tailors that content to the needs of the individual. SmartBook's adaptive technology provides precise, personalized instruction on what the student should do next, guiding the student to master and remember key concepts, targeting gaps in knowledge and offering customized feedback, and driving the student toward comprehension and retention of the subject matter. Available on desktops and tablets, SmartBook puts learning at the student's fingertips—anywhere, anytime.

INSTRUCTOR RESOURCES

The Instructor Resource Library within Connect is password-protected and a convenient place for instructors to access course supplements that include nine supplements to chapters in the print book and seven supplementary chapters. Resources for professors include the complete solutions to all problems and cases, PowerPoint slides which include both lecture materials for nearly every chapter and nearly all the figures (including all the spreadsheets) in the book, and an expanded Test Bank. The test bank contains almost 1,000 multiple-choice and true-false questions, all tagged according to learning objective, topic, level of difficulty, Bloom's taxonomy and AACSB category for filtering and reporting, and in delivered in the following ways:

- As a Connect assignment for online testing and automatic grading; can be used for actual exams or assigned as quizzes or practice;

- In TestGen, a desktop test generator and editing application for instructors to provide printed tests that can incorporate both McGraw-Hill's and instructors' questions;

- As Word files, with both question-only and answer files.

STUDENT RESOURCES

As described above, SmartBook provides a powerful tool to students for personalized instruction. For the additional convenience of students, we also are providing the website, **www.mhhe.com/Hillier6e,** to provide the full range of resources of interest to students. In addition to providing access to supplementary text material (both supplements to book chapters and additional chapters), this website provides solutions to the "solved problems" (additional examples) that are included at the end of each chapter. For each spreadsheet example in the book, a live spreadsheet that shows the formulation and solution for the example also is provided in the website for easy reference and for use as a template. (At the end of each chapter, the page entitled "Learning Aids for This Chapter" lists the Excel files and other resources that are relevant for that chapter.) Information about accessing the book's software is provided. In addition, the website includes a tutorial with sample test questions (different from those in the instructor's test bank) for self-testing quizzes on the various chapters. It also provides access to the INFORMS articles cited in the application vignettes as well as updates about the book, including errata.

AN INVITATION

We invite your comments, suggestions, and errata. You can contact either one of us at the e-mail addresses given below. While giving these addresses, let us also assure instructors that *we will continue our policy of not providing solutions to problems and cases in the book to anyone* (including your students) who contacts us. We hope that you enjoy the book.

Frederick S. Hillier
Stanford University (fhillier@stanford.edu)

Mark S. Hillier
University of Washington (mhillier@uw.edu)

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We also are grateful for the valuable input provided by many of our students as well as various other students and instructors who contacted us via e-mail.

This book has continued to be a team effort involving far more than the two coauthors. As a third coauthor for the first edition, the late Gerald J. Lieberman provided important initial impetus for this project. We also are indebted to our case writers, Karl Schmedders and Molly Stephens, for their invaluable contributions. Ann Hillier again devoted numerous hours to sitting with a Macintosh, doing word processing and constructing figures and tables. They all were vital members of the team.

McGraw-Hill/Irwin's editorial and production staff provided the other key members of the team, including Noelle Bathurst, Portfolio Manager; Allison McCabe, and Tobi Philips, Product Developers, Harper Christopher, Marketing Manager, and Daryl Horrocks, Program Manager. This book is a much better product because of their guidance and hard work. It has been a real pleasure working with such a thoroughly professional staff.

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Chapter **One**

Introduction

Learning Objectives

After completing this chapter, you should be able to

1. Define the term *management science*.
2. Describe the nature of management science.
3. Explain what a mathematical model is.
4. Use a mathematical model to perform break-even analysis.
5. Use a spreadsheet model to perform break-even analysis.
6. Describe the relationship between analytics and management science.
7. Identify the levels of annual savings that management science sometimes can provide to organizations.
8. Identify some special features of this book.

Welcome to the field of *management science!* We think that it is a particularly exciting and interesting field. Exciting because management science is having a dramatic impact on the profitability of numerous business firms around the world. Interesting because the methods used to do this are so ingenious. We are looking forward to giving you a guided tour to introduce you to the special features of the field.

Some people approach management science with a certain amount of anxiety and skepticism. The main source of the anxiety is the reputation of the field as being highly mathematical. This reputation then generates skepticism that such a theoretical approach can have much relevance for dealing with practical managerial problems. Most traditional courses (and textbooks) about management science have only reinforced these perceptions by emphasizing the mathematics of the field rather than its practical application.

Rest easy. This is not a traditional management science textbook. We realize that most readers of this book are aspiring to become managers, not mathematicians. Therefore, the emphasis throughout is on conveying what a future manager needs to know about management science. Yes, this means including a little mathematics here and there, because it is a major language of the field. The mathematics you do see will be at the level of high school algebra plus (in the later chapters) basic concepts of elementary probability theory. We think you will be pleasantly surprised by the new appreciation you gain for how useful and intuitive mathematics at this level can be. However, managers do not need to know any of the heavy mathematical theory that underlies the various techniques of management science. Therefore, the use of mathematics plays only a strictly secondary role in the book.

One reason we can deemphasize mathematics is that powerful *spreadsheet software* is available for applying management science. Spreadsheets provide a comfortable and familiar environment for formulating and analyzing managerial problems. The spreadsheet takes care of applying the necessary mathematics automatically in the background with only a minimum of guidance by the user. This has revolutionized the use of management science. In the past, technically trained management scientists were needed to carry out significant management science studies for management. Now spreadsheets are bringing many of the tools and concepts of management science within the reach of managers for conducting their own analyses. Although busy managers will continue to call upon management science teams to conduct major studies for them, they are increasingly becoming direct users themselves through the

medium of spreadsheet software. Therefore, since this book is aimed at future managers (and management consultants), we will emphasize the use of spreadsheets for applying management science.

What does an enlightened future manager need to learn from a management science course?

1. Gain an appreciation for the relevance and power of management science. (Therefore, we include many *application vignettes* throughout the book that give examples of *actual applications* of management science and the *impact* they had on the organizations involved.)
2. Learn to recognize when management science can (and cannot) be fruitfully applied. (Therefore, we will emphasize the *kinds of problems* to which the various management science techniques can be applied.)
3. Learn how to apply the major techniques of management science to analyze a variety of managerial problems. (Therefore, we will focus largely on how spreadsheets enable many such applications with no more background in management science than provided by this book.)
4. Develop an understanding of how to interpret the results of a management science study. (Therefore, we will present many *case studies* that illustrate management science studies and how their results depend on the assumptions and data that were used.)

The objectives just described are the key teaching goals of this book.

We begin this process in the next four sections by introducing the nature of management science and the impact that it is having on many organizations. (This process will continue throughout the remaining chapters as well.) Section 1.5 then points out some of the special features of this book that you can look forward to seeing in the subsequent chapters.

1.1 THE NATURE OF MANAGEMENT SCIENCE

What is the name *management science* (sometimes abbreviated MS) supposed to convey? It does involve *management* and *science* or, more precisely, *the science of management,* but this still is too vague. Here is a more suggestive definition.

> Management science is a *discipline* that attempts to *aid managerial decision making* by applying a *scientific approach* to managerial problems that involve *quantitative factors.*

Now let us see how elaborating upon each of the italicized terms in this definition conveys much more about the nature of management science.

Management Science Is a Discipline

As a discipline, management science is a whole body of knowledge and techniques that are based on a scientific foundation. For example, it is analogous in some ways to the medical field. A medical doctor has been trained in a whole body of knowledge and techniques that are based on the scientific foundations of the medical field. After receiving this training and entering practice, the doctor must diagnose a patient's illness and then choose the appropriate medical procedures to apply to the illness. The patient then makes the final decision on which medical procedures to accept. For less serious cases, the patient may choose not to consult a doctor and instead use his own basic knowledge of medical principles to treat himself. Similarly, a management scientist must receive substantial training (albeit considerably less than for a medical doctor). This training also is in a whole body of knowledge and techniques that are based on the scientific foundations of the discipline. After entering practice, the management scientist must diagnose a managerial problem and then choose the appropriate management science techniques to apply in analyzing the problem. The cognizant manager then makes the final decision as to which conclusions from this analysis to accept. For less extensive managerial problems where management science can be helpful, the manager may choose not to consult a management scientist and instead use his or her own basic knowledge of management science principles to analyze the problem.

Although it has considerably longer roots, the rapid development of the discipline began in the 1940s and 1950s. The initial impetus came early in World War II, when large numbers of scientists were called upon to apply a scientific approach to the management of the war effort

for the allies. When the war ended, the success of this approach in the war effort spurred interest in applying it outside the military as well. By the early 1950s, substantial applications of management science were being seen in a variety of organizations in business, industry, and government.

Another landmark event in the history of management science was the discovery in 1947 by George Dantzig of the *simplex method* for solving linear programming problems. (Linear programming is the subject of several early chapters.) Considerable progress in developing the other techniques of management science also occurred throughout the middle of the 20th century. However, the very limited computational power available at that time (whether when doing the computations by hand or with the relatively primitive electronic computers of the day) prevented applying these techniques except to small problems. Fortunately, another factor that gave great impetus to the growth of the discipline ever since that time was the onslaught of the computer revolution. Even massive problems usually can be solved now with today's powerful computers.

operations research
Management science began its rapid development during World War II with the name *operations research.*

The traditional name given to the discipline (and the one that still is widely used today outside of business schools) is **operations research.** This name was applied because the teams of scientists in World War II were doing *research* on how to manage military *operations.* The abbreviation OR also is widely used. This abbreviation often is combined with the one for management science (MS), thereby referring to the discipline as OR/MS. According to estimates from the U.S. Bureau of Labor Statistics in 2015, there were approximately 96,000 individuals at that time working as operations research analysts in the United States (some with just a B.S. degree) with an average annual salary of about $84,000. The Bureau also forecasted that this number of individuals working as operations research analysts would grow by 30 percent over the subsequent decade.

Another discipline that is closely related to management science is **analytics** (sometimes called *business analytics* when dealing with business problems). Like management science, analytics attempts to aid managerial decision making but with particular emphasis on three types of analysis: (1) *descriptive analytics*—the use of data (sometimes massive amounts of data) to analyze trends, (2) *predictive analytics*—the use of data to predict what will happen in the future (perhaps by using the forecasting techniques described in Chapter 10), and (3) *prescriptive analytics*—the use of data to prescribe the best course of action (frequently by using the optimization techniques described throughout this book). Broadly speaking, the techniques of the management science discipline provide the firepower for prescriptive analytics and, to a lesser extent, for predictive analytics, but not so much for descriptive analytics. (Section 1.3 will further describe the relationship between analytics and management science.)

One major international professional society for the management science discipline (as well as for business analytics) is the *Institute for Operations Research and the Management Sciences* (INFORMS). Headquartered in the United States, with well over 12,000 members, this society holds major conferences in the United States each year (including an annual Conference for Business Analytics and Operations Research) plus occasional conferences elsewhere. It also publishes several prominent journals, including *Management Science, Operations Research, Analytics,* and *Interfaces.* (Articles describing actual applications of management science are featured in *Interfaces,* so you will see many references and links to this journal throughout the book.) In addition, a few dozen countries around the world have their own national operations research societies. (More about this in Section 1.4.)

Thus, operations research/management science (OR/MS) is a truly international discipline. (We hereafter will normally just use the name *management science* or the abbreviation MS.)

Management Science Aids Managerial Decision Making

The key word here is that management science *aids* managerial decision making. Management scientists don't make managerial decisions. Managers do. A management science study only provides an analysis and recommendations, based on the quantitative factors involved in the problem, as input to the cognizant managers. Managers must also take into account various intangible considerations that are outside the realm of management science and then use their best judgment to make the decision. Sometimes managers find that qualitative factors are as important as quantitative factors in making a decision.

A small informal management science study might be conducted by just a single individual, who may be the cognizant manager. However, management science *teams* normally are used for larger studies. (We often will use the term *team* to cover both cases throughout the book.) Such a team often includes some members who are not management scientists but who provide other types of expertise needed for the study. Although a management science team often is entirely *in-house* (employees of the company), part or all of the team may instead be *consultants* who have been hired for just the one study. Consulting firms that partially or entirely specialize in management science currently are a growing industry.

Management Science Uses a Scientific Approach

Management science is based strongly on some scientific fields, including mathematics, statistics, and computer science. It also draws on the social sciences, especially economics. Since the field is concerned with the practical management of organizations, a management scientist should have solid training in business administration, including its various functional areas, as well.

To a considerable extent, a management science team will attempt to use the *scientific method* in conducting its study. This means that the team will emphasize conducting a *systematic investigation* that includes careful data gathering, developing and testing hypotheses about the problem (typically in the form of a mathematical model), and then applying sound logic in the subsequent analysis.

When conducting this systematic investigation, the management science team typically will follow the (overlapping) steps outlined and described below.

Step 1: Define the problem and gather data. In this step, the team consults with management to clearly identify the problem of concern and ascertain the appropriate objectives for the study. The team then typically spends a surprisingly large amount of time gathering relevant data about the problem with the assistance of other key individuals in the organization. A common frustration is that some key data are either very rough or completely unavailable. This may necessitate installing a new computer-based management information system.

Another increasingly common problem is that there may be *too much* data available to be easily analyzed. Dramatic advances in computerized data capture, processing power, data transmission, and storage capabilities are enabling organizations to integrate their various databases into massive *data warehouses.* This has led to the development of *data-mining software* for extracting hidden predictive information, correlations, and patterns from large databases.

Fortunately, the rapid development of the *information technology (IT)* field in recent years is leading to a dramatic improvement in the quantity and quality of data that may be available to the management science (MS) team. Corporate IT now is often able to provide the computational resources and databases, as well as any helpful data mining, that are needed by the MS team. Thus, the MS team often will collaborate closely with the IT group.

Step 2: Formulate a model (typically a mathematical model) to represent the problem. Models, or approximate representations, are an integral part of everyday life. Common examples include model airplanes, portraits, globes, and so on. Similarly, models play an important role in science and business, as illustrated by models of the atom, models of genetic structure, mathematical equations describing physical laws of motion or chemical reactions, graphs, organization charts, and industrial accounting systems. Such models are invaluable for abstracting the essence of the subject of inquiry, showing interrelationships, and facilitating analysis.

Mathematical models are also approximate representations, but they are expressed in terms of mathematical symbols and expressions. Such laws of physics as $F = ma$ and $E = mc^2$ are familiar examples. Similarly, the mathematical model of a business problem is the system of equations and related mathematical expressions that describes the essence of the problem.

With the emergence of powerful spreadsheet technology, **spreadsheet models** now are widely used to analyze managerial problems. A spreadsheet model lays out the relevant data, measures of performance, interrelationships, and so forth, on a spreadsheet in

an organized way that facilitates fruitful analysis of the problem. It also frequently incorporates an underlying mathematical model to assist in the analysis, but the mathematics is kept in the background so the user can concentrate on the analysis.

The *modeling process* is a creative one. When dealing with real managerial problems (as opposed to some cut-and-dried textbook problems), there normally is no single "correct" model but rather a number of alternative ways to approach the problem. The modeling process also is typically an evolutionary process that begins with a simple "verbal model" to define the essence of the problem and then gradually evolves into increasingly more complete mathematical models (perhaps in a spreadsheet format).

We further describe and illustrate such mathematical models in the next section.

Step 3: Develop a computer-based procedure for deriving solutions to the problem from the model. The beauty of a well-designed mathematical model is that it enables the use of mathematical procedures to find good solutions to the problem. These procedures usually are run on a computer because the calculations are too extensive to be done by hand. In some cases, the management science team will need to develop the procedure. In others, a standard software package already will be available for solving the model. When the mathematical model is incorporated into a spreadsheet, the spreadsheet software normally includes a Solver that usually will solve the model.

Step 4: Test the model and refine it as needed. Now that the model can be solved, the team needs to thoroughly check and test the model to make sure that it provides a sufficiently accurate representation of the real problem. A number of questions should be addressed, perhaps with the help of others who are particularly familiar with the problem. Have all the relevant factors and interrelationships in the problem been accurately incorporated into the model? Does the model seem to provide reasonable solutions? When it is applied to a past situation, does the solution improve upon what was actually done? When assumptions about costs and revenues are changed, do the solutions change in a plausible manner?

Step 5: Apply the model to analyze the problem and develop recommendations for management. The management science team now is ready to solve the model, perhaps under a variety of assumptions, in order to analyze the problem. The resulting recommendations then are presented to the managers who must make the decisions about how to deal with the problem.

If the model is to be applied repeatedly to help guide decisions on an ongoing basis, the team might also develop a **decision support system**. This is an interactive computer-based system that aids managerial decision making. The system draws current data from *databases* or *management information systems* and then solves the various versions of the model specified by the manager.

Step 6: Help to implement the team's recommendations that are adopted by management. Once management makes its decisions, the management science team normally is asked to help oversee the implementation of the new procedures. This includes providing some information to the operating management and personnel involved on the rationale for the changes that are being made. The team also makes sure that the new operating system is consistent with its recommendations as they have been modified and approved by management. If successful, the new system may be used for years to come. With this in mind, the team monitors the initial experience with the system and seeks to identify any modifications that should be made in the future.

Management Science Considers Quantitative Factors

Many managerial problems revolve around such quantitative factors as production quantities, revenues, costs, the amounts available of needed resources, and so on. By incorporating these quantitative factors into a *mathematical model* and then applying mathematical procedures to solve the model, management science provides a uniquely powerful way of analyzing such managerial problems. Although management science is concerned with the practical management of organizations, including taking into account relevant qualitative factors, its special contribution lies in this unique ability to deal with the quantitative factors.

The Special Products Company example discussed next will illustrate how management science considers quantitative factors.

Review *Questions*

1. When did the rapid development of the management science discipline begin?
2. What is the traditional name given to this discipline that still is widely used outside of business schools?
3. What does a management science study provide to managers to aid their decision making?
4. Upon which scientific fields and social sciences is management science especially based?
5. What is a *decision support system?*
6. What are some common quantitative factors around which many managerial problems revolve?

1.2 AN ILLUSTRATION OF THE MANAGEMENT SCIENCE APPROACH: BREAK-EVEN ANALYSIS

The **Special Products Company** produces expensive and unusual gifts to be sold in stores that cater to affluent customers who already have everything. The latest new-product proposal to management from the company's Research Department is a first-of-its-kind iWatch. This iWatch would combine the features of a top-of-the-line atomic wristwatch and a next-generation smartphone, including the ability to respond to voice commands or questions with voice responses. It also would connect to the Internet wirelessly to provide weather, sports scores, stock quotes, and more. An extensive research-and-development project would be needed to develop the iWatch. The proposal is to provide a generous budget of $10 million for this project in order to provide as many desirable features as possible within this budget. It is clear that the production costs for the iWatch would be very large because of the extreme miniaturization that would be required, so the selling price would need to be far beyond the reach of middle-class customers. Therefore, the marketing of the iWatch would be aimed at wealthy customers who want the most advanced products regardless of cost.

Management needs to decide whether to develop and market this new product and, if so, how many of these watches to produce. Before making these decisions, a sales forecast will be obtained to estimate how many watches can be sold. Since most of these sales would occur quickly during the relatively brief time before the "next big thing" arrives to take over the market, there would be only one production run for the iWatch and the number produced would be set equal to the sales forecast. Following the production run, the iWatch would be marketed as aggressively as needed to sell this entire inventory if possible. Management now needs a management science study to be conducted to determine how large this sales potential needs to be to make the iWatch profitable after considering all the prospective revenues and costs, so let's next look at the estimates of these financial figures.

A cost that remains the same regardless of the production volume is referred to as a *fixed cost,* whereas a cost that varies with the production volume is called a *variable cost.*

If the company goes ahead with this product, the research-and-development cost of $10 million is referred to as a *fixed cost* because it remains the same regardless of how many watches are produced and sold. (However, note that this cost would *not* be incurred if management decides not to introduce the product since the research-and-development project then would not be undertaken.)

In addition to this fixed cost, there is a production cost that varies with the number of watches produced. This *variable cost* is $1,000 per watch produced, which adds up to $1,000 *times* the number of watches produced. (The cost for each additional unit produced, $1,000, is referred to as the *marginal cost.*) Each watch sold would generate a unit revenue of $2,000 for the company.

Spreadsheet Modeling of the Problem

You will see throughout this book that spreadsheets provide a very convenient way of using a management science approach for modeling and analyzing a wide variety of managerial problems. This certainly is true for the Special Products Company problem as well, as we now will demonstrate.

Figure 1.1 shows a spreadsheet formulation of this problem after obtaining a preliminary sales forecast that indicates 30,000 watches can be sold. The data have been entered into cells C4 to C7. Cell C9 is used to record a trial value for the decision as to how many watches to produce. As one of the many possibilities that eventually might be tried, Figure 1.1 shows the specific trial value of 20,000.

FIGURE 1.1
A spreadsheet formulation of the Special Products Company problem.

	A	B	C	D	E	F
1	**Special Products Co. Break-Even Analysis**					
2						
3			**Data**			**Results**
4		Unit Revenue	$2,000		Total Revenue	$40,000,000
5		Fixed Cost	$10,000,000		Total Fixed Cost	$10,000,000
6		Marginal Cost	$1,000		Total Variable Cost	$20,000,000
7		Sales Forecast	30,000		Profit (Loss)	$10,000,000
8						
9		Production Quantity	20,000			

Range Name	Cell
FixedCost	C5
MarginalCost	C6
ProductionQuantity	C9
Profit	F7
SalesForecast	C7
TotalFixedCost	F5
TotalRevenue	F4
TotalVariableCost	F6
UnitRevenue	C4

	E	F
3		**Results**
4	Total Revenue	=UnitRevenue * MIN(SalesForecast, ProductionQuantity)
5	Total Fixed Cost	=IF(ProductionQuantity > 0, FixedCost, 0)
6	Total Variable Cost	=MarginalCost * ProductionQuantity
7	Profit (Loss)	=TotalRevenue – (TotalFixedCost + TotalVariableCost)

Excel Tip: To update formulas throughout the spreadsheet to incorporate a newly defined range name, choose Apply Names from the Define Name menu on the Formulas tab.

Cells F4 to F7 give the resulting total revenue, total costs, and profit (loss) by using the Excel equations shown under the spreadsheet in Figure 1.1. The Excel equations could have been written using cell references (e.g., F6 = C6*C9). However, the spreadsheet model is made clearer by giving "range names" to key cells or blocks of cells. (A **range name** is a descriptive name given to a cell or range of cells that immediately identifies what is there. Appendix A provides details about how to incorporate range names into a spreadsheet model.) To define a name for a selected cell (or range of cells), click on the name box (on the left of the formula bar above the spreadsheet) and type a name. These cell names then can be used in other formulas to create an equation that is easy to decipher (e.g., TotalVariableCost = MarginalCost*ProductionQuantity rather than the more cryptic F6 = C6*C9). Note that spaces are not allowed in range names. When a range name has more than one word, we have used capital letters to distinguish the start of each new word (e.g., ProductionQuantity).

Excel Tip: A list of all the defined names and their corresponding cell references can be pasted into a spreadsheet by choosing Paste Names from the Use in Formula menu on the Formulas tab, and then clicking on Paste List.

The lower left-hand corner of Figure 1.1 lists the names of the quantities in the spreadsheet in alphabetical order and then gives cell references where the quantities are found. Although this isn't particularly necessary for such a small spreadsheet, you should find it helpful for the larger spreadsheets found later in the book.

A spreadsheet is a convenient tool for performing what-if analysis.

This same spreadsheet, along with all of the other spreadsheets in the book, are available to you at **www.mhhe.com/Hillier6e.** As you can see for yourself by bringing up and playing with the spreadsheet, it provides a straightforward way of performing *what-if analysis* on the problem. What-if analysis involves addressing such questions as, What happens if the sales forecast should have been considerably lower? What happens if some of the cost and revenue estimates are wrong? Simply enter a variety of new values for these quantities in the spreadsheet and see what happens to the profit shown in cell F7.

The Excel function MIN (*a, b*) gives the minimum of the numbers in the cells whose addresses are *a* and *b*.

The lower right-hand corner of Figure 1.1 introduces two useful Excel functions, the MIN(*a, b*) function and the IF(*a, b, c*) function. The equation for cell F4 uses the MIN(*a, b*) function, which gives the minimum of *a* and *b*. In this case, the estimated number of watches that will be sold is the minimum of the sales forecast and the production quantity, so

F4 = UnitRevenue*MIN(SalesForecast, ProductionQuantity)

enters the unit revenue (from cell C4) times the minimum of the sales forecast (from C7) and the production quantity (from C9) into cell F4.

Also note that the equation for cell F5 uses the IF(*a, b, c*) function, which does the following: If statement *a* is true, it uses *b;* otherwise, it uses *c.* Therefore,

The Excel function IF (*a, b, c*) tests if *a* is true. If so, it uses *b;* otherwise it uses *c.*

$$\text{F5} = \text{IF(ProductionQuantity} > 0, \text{FixedCost}, 0)$$

says to enter the fixed cost (C5) into cell F5 if the production quantity (C9) is greater than zero, but otherwise enter 0 (the fixed cost is avoided if production is not initiated).

The spreadsheet in Figure 1.1, along with its equations for the results in column F, constitutes a *spreadsheet model* for the Special Products Company problem. You will see many examples of such spreadsheet models throughout the book.

This particular spreadsheet model is based on an underlying *mathematical model* that uses algebra to spell out the equations in cells F4:F7 and then to derive some additional useful information. Let us take a look at this mathematical model next.

Expressing the Problem Mathematically

The issue facing management is to make the following decision.

Decision to be made: Number of watches to produce (if any).

Since this number is not yet known, we introduce an algebraic variable Q to represent this quantity. Thus,

$$Q = \text{Number of watches to produce,}$$

where Q is referred to as a **decision variable**. Naturally, the value chosen for Q should not exceed the sales forecast for the number of watches that can be sold. Choosing a value of 0 for Q would correspond to deciding not to introduce the product, in which case none of the costs or revenues described in the preceding paragraph would be incurred.

The objective is to choose the value of Q that maximizes the company's profit from this new product. The management science approach is to formulate a mathematical model to represent this problem by developing an equation that expresses the profit in terms of the decision variable Q. To get there, it is necessary first to develop equations in terms of Q for the total cost and revenue generated by the watches.

If $Q = 0$, no cost is incurred. However, if $Q > 0$, there is both a fixed cost and a variable cost.

$$\text{Fixed cost} = \$10 \text{ million (if } Q > 0)$$
$$\text{Variable cost} = \$1{,}000Q$$

Therefore, the total cost would be

$$\text{Total cost} = \begin{cases} 0 & \text{if } Q = 0 \\ \$10 \text{ million} + \$1{,}000Q & \text{if } Q > 0 \end{cases}$$

Since each watch sold would generate a revenue of \$2,000 for the company, the total revenue from selling Q watches would be

$$\text{Total revenue} = \$2{,}000Q$$

Consequently, the profit from producing and selling Q watches would be

$$\begin{aligned} \text{Profit} &= \text{Total revenue} - \text{Total cost} \\ &= \begin{cases} 0 & \text{if } Q = 0 \\ \$2{,}000Q - (\$10 \text{ million} + \$1{,}000Q) & \text{if } Q > 0 \end{cases} \end{aligned}$$

Thus, since $\$2{,}000Q - \$1{,}000Q = \$1{,}000Q$

$$\text{Profit} = -\$10 \text{ million} + \$1{,}000Q \qquad \text{if } Q > 0$$

Analysis of the Problem

This last equation shows that the attractiveness of the proposed new product depends greatly on the value of Q, that is, on the number of watches that can be produced and sold. A small

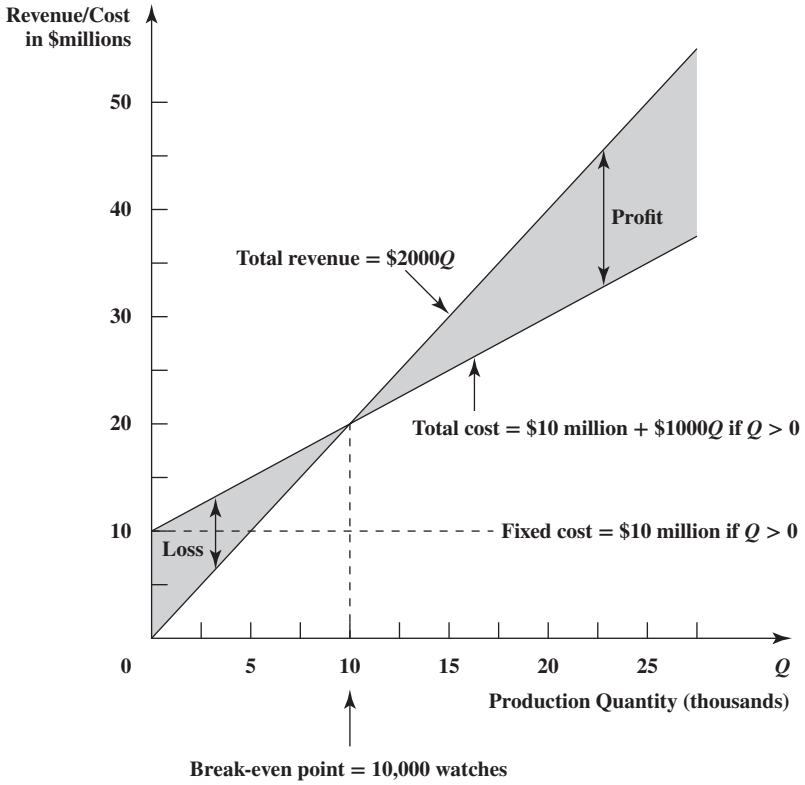

FIGURE 1.2
Break-even analysis for the Special Products Company shows that the cost line and revenue line intersect at $Q = 10{,}000$ watches, so this is the break-even point for the proposed new product.

value of Q means a loss (negative profit) for the company, whereas a sufficiently large value would generate a positive profit for the company. For example, look at the difference between $Q = 2{,}000$ and $Q = 20{,}000$.

$$\text{Profit} = -\$10 \text{ million} + \$1{,}000\,(2{,}000) = -\$8 \text{ million} \qquad \text{if } Q = 2{,}000$$
$$\text{Profit} = -\$10 \text{ million} + \$1{,}000\,(20{,}000) = \$10 \text{ million} \qquad \text{if } Q = 20{,}000$$

Figure 1.2 plots both the company's total cost and total revenue for the various values of Q. Note that the cost line and the revenue line intersect at $Q = 10{,}000$. For any value of $Q < 10{,}000$, cost exceeds revenue, so the gap between the two lines represents the *loss* to the company. For any $Q > 10{,}000$, revenue exceeds cost, so the gap between the two lines now shows positive profit. At $Q = 10{,}000$, the profit is 0. Since 10,000 units is the production and sales volume at which the company would break even on the proposed new product, this volume is referred to as the **break-even point**. This is the point that must be exceeded to make it worthwhile to introduce the product. Therefore, the crucial question is whether the sales forecast for how many watches can be sold is above or below the break-even point.

Figure 1.2 illustrates the *graphical procedure* for finding the break-even point. Another alternative is to use an *algebraic procedure* to solve for the point. Because the profit is 0 at this point, the procedure consists of solving the following equation for the unknown Q.

$$\text{Profit} = -\$10 \text{ million} + \$1{,}000Q = 0$$

Thus,

$$\$1{,}000Q = \$10 \text{ million}$$
$$Q = \frac{\$10 \text{ million}}{\$1{,}000}$$
$$Q = 10{,}000$$

A Complete Mathematical Model for the Problem

The preceding analysis of the problem made use of a basic mathematical model that consisted of the equation for profit expressed in terms of Q. However, implicit in this analysis were some additional factors that can be incorporated into a complete mathematical model for the problem.