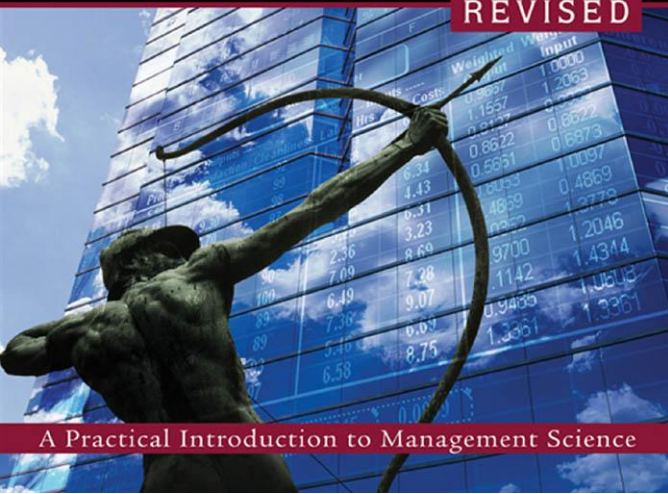


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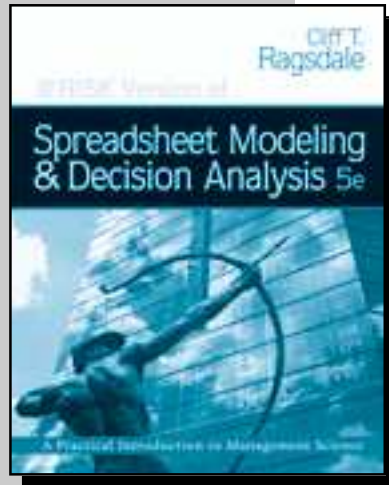
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# Spreadsheet Modeling & Decision Analysis 5e

*A Practical Introduction to Management Science*

Cliff T. Ragsdale

Virginia Polytechnic Institute  
and State University

In memory of those  
who were killed and injured  
in the noble pursuit of education  
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# Preface

Spreadsheets are one of the most popular and ubiquitous software packages on the planet. Every day, millions of business people use spreadsheet programs to build models of the decision problems they face as a regular part of their work activities. As a result, employers look for experience and ability with spreadsheets in the people they recruit.

Spreadsheets have also become the standard vehicle for introducing undergraduate and graduate students in business and engineering to the concepts and tools covered in the introductory OR/MS course. This simultaneously develops students' skills with a standard tool of today's business world and opens their eyes to how a variety of OR/MS techniques can be used in this modeling environment. Spreadsheets also capture students' interest and add a new relevance to OR/MS, as they see how it can be applied with popular commercial software being used in the business world.

*Spreadsheet Modeling & Decision Analysis* provides an introduction to the most commonly used OR/MS techniques and shows how these tools can be implemented using Microsoft® Excel. Prior experience with Excel is certainly helpful, but is not a requirement for using this text. In general, a student familiar with computers and the spreadsheet concepts presented in most introductory computer courses should have no trouble using this text. Step-by-step instructions and screen shots are provided for each example, and software tips are included throughout the text as needed.

## What's New in the Revised Fifth Edition?

This revised version of *Spreadsheet Modeling & Decision Analysis* updates the fifth edition to be compatible with Microsoft® Office 2007.

Changes in the revised fifth edition of *Spreadsheet Modeling & Decision Analysis* from the fourth edition include:

- New cases for every chapter of the book.
- A new interactive graphical tool featured in Chapters 2 and 4 to help students understand how changes in various linear programming model coefficients affect the feasible region and optimal solution.
- A new version of Crystal Ball with enhanced modeling and analysis capabilities (Chapter 12).
- New coverage of Crystal Ball's Distribution Gallery Tool, correlation tools, and efficient frontier calculation using OptQuest.
- New coverage of Crystal Ball's tornado diagrams and spider charts applied in decision analysis (Chapter 15).
- Microsoft® Office Project 2007 Win32 English 60-Day Direct Trial.
- Expanded discussion of the use of array formulas in project management models (Chapter 14).
- Numerous new and revised end-of-chapter problems throughout.

## Innovative Features

Aside from its strong spreadsheet orientation, the revised fifth edition of *Spreadsheet Modeling & Decision Analysis* contains several other unique features that distinguish it from traditional OR/MS texts.

- Algebraic formulations and spreadsheets are used side-by-side to help develop conceptual thinking skills.
- Step-by-step instructions and numerous annotated screen shots make examples easy to follow and understand.
- Emphasis is placed on model formulation and interpretation rather than on algorithms.
- Realistic examples motivate the discussion of each topic.
- Solutions to example problems are analyzed from a managerial perspective.
- Spreadsheet files for all the examples are provided on a data disk bundled with the text.
- A unique and accessible chapter covering discriminant analysis is provided.
- Sections entitled “The World of Management Science” show how each topic has been applied in a real company.
- Excel add-ins and templates are provided to support: decision trees, sensitivity analysis, discriminant analysis, queuing, simulation, and project management.

## Organization

The table of contents for *Spreadsheet Modeling & Decision Analysis* is laid out in a fairly traditional format, but topics may be covered in a variety of ways. The text begins with an overview of OR/MS in Chapter 1. Chapters 2 through 8 cover various topics in deterministic modeling techniques: linear programming, sensitivity analysis, networks, integer programming, goal programming and multiple objective optimization, and nonlinear and evolutionary programming. Chapters 9 through 11 cover predictive modeling and forecasting techniques: regression analysis, discriminant analysis, and time series analysis.

Chapters 12 and 13 cover stochastic modeling techniques: simulation (using Crystal Ball) and queuing theory. Coverage of simulation using the inherent capabilities of Excel alone is available on the textbook’s Web site, [www.thomsonedu.com/decisionsciences/ragsdale](http://www.thomsonedu.com/decisionsciences/ragsdale). Chapters 14 and 15 cover project management and decision theory, respectively.

After completing Chapter 1, a quick refresher on spreadsheet fundamentals (entering and copying formulas, basic formatting and editing, etc.) is always a good idea. Suggestions for the Excel review may be found at Thomson South-Western’s Decision Sciences Web site. Following this, an instructor could cover the material on optimization, forecasting, or simulation, depending on personal preferences. The chapters on queuing and project management make general references to simulation and, therefore, should follow the discussion of that topic.

## Ancillary Materials

New copies of the textbook include three CDs. The student CD includes Premium Solver™ for Education, several other add-ins, and data files for examples, cases and problems within the text. The other CDs provide a time-limited trial edition of Microsoft® Project. Instructions for accessing a time-limited full version of Crystal Ball® appear on a card included in this edition.

As noted on the front end-sheet of the Instructor's Edition, the 5e of *Spreadsheet Modeling & Decision Analysis* will be available in an @RISK version that comes with a student edition of The Decision Tools Suite. This product is being handled through Thomson CUSTOM and the @RISK version will not include the Crystal Ball software.

Several excellent ancillaries for the instructor accompany the revised edition of *Spreadsheet Modeling & Decision Analysis*. All instructor ancillaries are provided on CD-ROMs. Included in this convenient format are:

- **Instructor's Manual.** The Instructor's Manual, prepared by the author, contains solutions to all the text problems and cases.
- **Test Bank.** The Test Bank, prepared by Alan Olinsky of Bryant University, includes multiple choice, true/false, and short answer problems for each text chapter. It also includes mini-projects that may be assigned as take-home assignments. The Test Bank is included as Microsoft® Word files. The Test Bank also comes separately in a computerized ExamView™ format that allows instructors to use or modify the questions and create original questions.
- **PowerPoint Presentation Slides.** PowerPoint presentation slides, prepared by the author, provide ready-made lecture material for each chapter in the book.

Instructors who adopt the text for their classes may call the Thomson Learning Academic Resource Center at 1-800-423-0563 to request the Instructor's Resource CD (ISBN: 0-324-31261-X) and the ExamView testing software (ISBN 0-324-31273-3).

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Once again, I thank my dear wife, Kathy, for her unending patience, support, encouragement, and love. (You're still the one.) This book is dedicated to our sons, Thomas, Patrick, and Daniel. I will always be so glad that God let me be your daddy and the leader of the Ragsdale ragamuffin band.

## Final Thoughts

I hope you enjoy the spreadsheet approach to teaching OR/MS as much as I do and that you find this book to be very interesting and helpful. If you find creative ways to use the techniques in this book or need help applying them, I would love to hear from you. Also, any comments, questions, suggestions, or constructive criticism you have concerning this text are always welcome.

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# Chapter 1

## Introduction to Modeling and Decision Analysis

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### 1.0 Introduction

This book is titled *Spreadsheet Modeling and Decision Analysis: A Practical Introduction to Management Science*, so let's begin by discussing exactly what this title means. By the very nature of life, all of us must continually make decisions that we hope will solve problems and lead to increased opportunities for ourselves or the organizations for which we work. But making good decisions is rarely an easy task. The problems faced by decision makers in today's competitive, fast-paced business environment are often extremely complex and can be addressed by numerous possible courses of action. Evaluating these alternatives and choosing the best course of action represents the essence of decision analysis.

During the past decade, millions of business people discovered that one of the most effective ways to analyze and evaluate decision alternatives involves using electronic spreadsheets to build computer models of the decision problems they face. A **computer model** is a set of mathematical relationships and logical assumptions implemented in a computer as a representation of some real-world decision problem or phenomenon. Today, electronic spreadsheets provide the most convenient and useful way for business people to implement and analyze computer models. Indeed, most business people probably would rate the electronic spreadsheet as their most important analytical tool apart from their brain! Using a **spreadsheet model** (a computer model implemented via a spreadsheet), a business person can analyze decision alternatives before having to choose a specific plan for implementation.

This book introduces you to a variety of techniques from the field of management science that can be applied in spreadsheet models to assist in the decision-analysis process. For our purposes, we will define **management science** as a field of study that uses computers, statistics, and mathematics to solve business problems. It involves applying the methods and tools of science to management and decision making. It is the science of making better decisions. Management science is also sometimes referred to as operations research or decision science. See Figure 1.1 for a summary of how management science has been applied successfully in several real-world situations.

In the not too distant past, management science was a highly specialized field that generally could be practiced only by those who had access to mainframe computers and who possessed an advanced knowledge of mathematics and computer programming languages. However, the proliferation of powerful personal computers (PCs) and the development of easy-to-use electronic spreadsheets have made the tools of management science far more practical and available to a much larger audience. Virtually

FIGURE 1.1

Examples of  
successful  
management  
science  
applications

### Home Runs in Management Science

Over the past decade, scores of operations research and management science projects saved companies millions of dollars. Each year, the Institute For Operations Research and the Management Sciences (INFORMS) sponsors the Franz Edelman Awards competition to recognize some of the most outstanding OR/MS projects during the past year. Here are some of the “home runs” from the 2004 Edelman Awards (described in *Interfaces*, Vol. 31, No. 1, January–February, 2005).

- At the turn of the century, **Motorola** faced a crisis due to economic conditions in its marketplaces; the company needed to reduce costs dramatically and quickly. A natural target was its purchases of goods and services, as these expenses account for more than half of Motorola’s costs. Motorola decided to create an Internet-based system to conduct multi-step negotiations and auctions for supplier negotiation. The system can handle complex bids and constraints, such as bundled bids, volume-based discounts, and capacity limits. In addition, it can optimize multi-product, multi-vendor awards subject to these constraints and nonlinear price schedules. **Benefits:** In 2003, Motorola used this system to source 56 percent of its total spending, with 600 users and a total savings exceeding \$600 million.
- **Waste Management** is the leading company in North America in the waste-collection industry. The company has a fleet of over 26,000 vehicles for collecting waste from nearly 20 million residential customers, plus another two million commercial customers. To improve trash collection and make its operations more efficient, Waste Management implemented a vehicle-routing application to optimize its collection routes. **Benefits:** The successful deployment of this system brought benefits including the elimination of nearly 1,000 routes within one year of implementation and an estimated annual savings of \$44 million.
- Hong Kong has the world’s busiest port. Its largest terminal operator, **Hong Kong International Terminals (HIT)**, has the busiest container terminal in the world serving over 125 ships per week, with 10 berths at which container ships dock, and 122 yard cranes to move containers around the 227 acres of storage yard. Thousands of trucks move containers into and out of the storage yard each day. HIT implemented a decision-support system (with several embedded decision models and algorithms) to guide its operational decisions concerning the number and deployment of trucks for moving containers, the assignment of yard cranes, and the storage locations for containers. **Benefits:** The cumulative effect of this system has led to a 35 percent reduction in container handling costs, a 50 percent increase in throughput, and a 30 percent improvement in vessel turnaround time.
- The **John Deere Company** sells lawn equipment, residential and commercial mowers, and utility tractors through a network of 2,500 dealers, supported by five Deere warehouses. Each dealer stocks about 100 products, leading to approximately 250,000 product-stocking locations. Furthermore, demand is quite seasonal and stochastic. Deere implemented a system designed to optimize large-scale multi-echelon, non-stationary stochastic inventory systems. Deere runs the system each week to obtain recommended stocking levels for each product for each stocking location for each week over a 26-week planning horizon. **Benefits:** The impact of the application has been remarkable, leading to an inventory reduction of nearly one billion dollars and improving customer-service levels.

everyone who uses a spreadsheet today for model building and decision making is a practitioner of management science—whether they realize it or not.

## 1.1 The Modeling Approach to Decision Making

The idea of using models in problem solving and decision analysis is really not new, and certainly is not tied to the use of computers. At some point, all of us have used a modeling approach to make a decision. For example, if you ever have moved into a dormitory, apartment, or house, you undoubtedly faced a decision about how to arrange the furniture in your new dwelling. There probably were several different arrangements to consider. One arrangement might give you the most open space but require that you build a loft. Another might give you less space but allow you to avoid the hassle and expense of building a loft. To analyze these different arrangements and make a decision, you did not build the loft. You more likely built a **mental model** of the two arrangements, picturing what each looked like in your mind's eye. Thus, a simple mental model is sometimes all that is required to analyze a problem and make a decision.

For more complex decision problems, a mental model might be impossible or insufficient, and other types of models might be required. For example, a set of drawings or blueprints for a house or building provides a **visual model** of the real-world structure. These drawings help illustrate how the various parts of the structure will fit together when it is completed. A road map is another type of visual model because it assists a driver in analyzing the various routes from one location to another.

You probably also have seen car commercials on television showing automotive engineers using **physical models** or **scale models** to study the aerodynamics of various car designs, to find the shape that creates the least wind resistance and maximizes fuel economy. Similarly, aeronautical engineers use scale models of airplanes to study the flight characteristics of various fuselage and wing designs. And civil engineers might use scale models of buildings and bridges to study the strengths of different construction techniques.

Another common type of model is a **mathematical model**, which uses mathematical relationships to describe or represent an object or decision problem. Throughout this book we will study how various mathematical models can be implemented and analyzed on computers using spreadsheet software. But before we move to an in-depth discussion of spreadsheet models, let's look at some of the more general characteristics and benefits of modeling.

## 1.2 Characteristics and Benefits of Modeling

Although this book focuses on mathematical models implemented in computers via spreadsheets, the examples of non-mathematical models given earlier are worth discussing a bit more because they help illustrate several important characteristics and benefits of modeling in general. First, the models mentioned earlier are usually simplified versions of the object or decision problem they represent. To study the aerodynamics of a car design, we do not need to build the entire car complete with engine and stereo. Such components have little or no effect on aerodynamics. So, although a model is often

a simplified representation of reality, the model is useful as long as it is valid. A **valid** model is one that accurately represents the relevant characteristics of the object or decision problem being studied.

Second, it is often less expensive to analyze decision problems using a model. This is especially easy to understand with respect to scale models of big-ticket items such as cars and planes. Besides the lower financial cost of building a model, the analysis of a model can help avoid costly mistakes that might result from poor decision making. For example, it is far less costly to discover a flawed wing design using a scale model of an aircraft than after the crash of a fully loaded jetliner.

Frank Brock, former executive vice president of the Brock Candy Company, related the following story about blueprints his company prepared for a new production facility. After months of careful design work he proudly showed the plans to several of his production workers. When he asked for their comments, one worker responded, “It’s a fine looking building, Mr. Brock, but that sugar valve looks like it’s about twenty feet away from the steam valve.” “What’s wrong with that?” asked Brock. “Well, nothing,” said the worker, “except that I have to have my hands on both valves at the same time!”<sup>1</sup> Needless to say, it was far less expensive to discover and correct this “little” problem using a visual model before pouring the concrete and laying the pipes as originally planned.

Third, models often deliver needed information on a more timely basis. Again, it is relatively easy to see that scale models of cars or airplanes can be created and analyzed more quickly than their real-world counterparts. Timeliness is also an issue when vital data will not become available until later. In these cases, we might create a model to help predict the missing data to assist in current decision making.

Fourth, models are frequently helpful in examining things that would be impossible to do in reality. For example, human models (crash dummies) are used in crash tests to see what might happen to an actual person if a car were to hit a brick wall at a high speed. Likewise, models of DNA can be used to visualize how molecules fit together. Both of these are difficult, if not impossible, to do without the use of models.

Finally, and probably most important, models allow us to gain insight and understanding about the object or decision problem under investigation. The ultimate purpose of using models is to improve decision making. As you will see, the process of building a model can shed important light and understanding on a problem. In some cases, a decision might be made while building the model as a previously misunderstood element of the problem is discovered or eliminated. In other cases, a careful analysis of a completed model might be required to “get a handle” on a problem and gain the insights needed to make a decision. In any event, the insight gained from the modeling process ultimately leads to better decision making.

## 1.3 Mathematical Models

As mentioned earlier, the modeling techniques in this book differ quite a bit from scale models of cars and planes, or visual models of production plants. The models we will build use mathematics to describe a decision problem. We use the term “mathematics” in its broadest sense, encompassing not only the most familiar elements of math, such as algebra, but also the related topic of logic.

<sup>1</sup> Colson, Charles and Jack Eckerd, *Why America Doesn’t Work* (Denver, Colorado: Word Publishing, 1991), 146–147.

Now, let's consider a simple example of a mathematical model:

$$\text{PROFIT} = \text{REVENUE} - \text{EXPENSES} \quad 1.1$$

Equation 1.1 describes a simple relationship between revenue, expenses, and profit. It is a mathematical relationship that describes the operation of determining profit—or a mathematical model of profit. Of course, not all models are this simple, but taken piece by piece, the models we will discuss are not much more complex than this one.

Frequently, mathematical models describe functional relationships. For example, the mathematical model in equation 1.1 describes a functional relationship between revenue, expenses, and profit. Using the symbols of mathematics, this functional relationship is represented as:

$$\text{PROFIT} = f(\text{REVENUE}, \text{EXPENSES}) \quad 1.2$$

In words, the previous expression means “profit is a function of revenue and expenses.” We also could say that profit *depends* on (or is *dependent* on) revenue and expenses. Thus, the term PROFIT in equation 1.2 represents a **dependent** variable, whereas REVENUE and EXPENSES are **independent** variables. Frequently, compact symbols (such as A, B, and C) are used to represent variables in an equation such as 1.2. For instance, if we let Y, X<sub>1</sub>, and X<sub>2</sub> represent PROFIT, REVENUE, and EXPENSES, respectively, we could rewrite equation 1.2 as follows:

$$Y = f(X_1, X_2) \quad 1.3$$

The notation  $f(\bullet)$  represents the function that defines the relationship between the dependent variable Y and the independent variables X<sub>1</sub> and X<sub>2</sub>. In the case of determining PROFIT from REVENUE and EXPENSES, the mathematical form of the function  $f(\bullet)$  is quite simple:  $f(X_1, X_2) = X_1 - X_2$ . However, in many other situations we will model, the form of  $f(\bullet)$  is quite complex and might involve many independent variables. But regardless of the complexity of  $f(\bullet)$  or the number of independent variables involved, many of the decision problems encountered in business can be represented by models that assume the general form,

$$Y = f(X_1, X_2, \dots, X_k) \quad 1.4$$

In equation 1.4, the dependent variable Y represents some bottom-line performance measure of the problem we are modeling. The terms X<sub>1</sub>, X<sub>2</sub>, . . . , X<sub>k</sub> represent the different independent variables that play some role or have some effect in determining the value of Y. Again,  $f(\bullet)$  is the function (possibly quite complex) that specifies or describes the relationship between the dependent and independent variables.

The relationship expressed in equation 1.4 is very similar to what occurs in most spreadsheet models. Consider a simple spreadsheet model to calculate the monthly payment for a car loan, as shown in Figure 1.2.

The spreadsheet in Figure 1.2 contains a variety of **input** cells (for example, purchase price, down payment, trade-in, term of loan, annual interest rate) that correspond conceptually to the independent variables X<sub>1</sub>, X<sub>2</sub>, . . . , X<sub>k</sub> in equation 1.4. Similarly, a variety of mathematical operations are performed using these input cells in a manner analogous to the function  $f(\bullet)$  in equation 1.4. The results of these mathematical operations determine the value of some **output** cell in the spreadsheet (for example, monthly payment) that corresponds to the dependent variable Y in equation 1.4. Thus, there is a direct correspondence between equation 1.4 and the spreadsheet in Figure 1.2. This type of correspondence exists for most of the spreadsheet models in this book.



**FIGURE 1.2**

Example of a  
simple spreadsheet  
model

|    | A | B                                  | C               | D | E | F |
|----|---|------------------------------------|-----------------|---|---|---|
| 1  |   |                                    |                 |   |   |   |
| 2  |   | <b>Car Loan Analysis Worksheet</b> |                 |   |   |   |
| 3  |   |                                    |                 |   |   |   |
| 4  |   | <b>Purchase Price</b>              | <b>\$18,500</b> |   |   |   |
| 5  |   | <b>less:</b>                       |                 |   |   |   |
| 6  |   | <b>Down Payment</b>                | <b>\$2,000</b>  |   |   |   |
| 7  |   | <b>Trade-in</b>                    | <b>\$4,000</b>  |   |   |   |
| 8  |   | <b>Amount Financed</b>             | <b>\$12,500</b> |   |   |   |
| 9  |   |                                    |                 |   |   |   |
| 10 |   | <b>Term of loan (in years)</b>     | <b>4</b>        |   |   |   |
| 11 |   |                                    |                 |   |   |   |
| 12 |   | <b>Annual Interest Rate</b>        | <b>8.00%</b>    |   |   |   |
| 13 |   |                                    |                 |   |   |   |
| 14 |   | <b>Monthly Payment</b>             | <b>\$305.16</b> |   |   |   |
| 15 |   |                                    |                 |   |   |   |

## 1.4 Categories of Mathematical Models

Not only does equation 1.4 describe the major elements of mathematical or spreadsheet models, but it also provides a convenient means for comparing and contrasting the three categories of modeling techniques presented in this book—Prescriptive Models, Predictive Models, and Descriptive Models. Figure 1.3 summarizes the characteristics and techniques associated with each of these categories.

In some situations, a manager might face a decision problem involving a very precise, well-defined functional relationship  $f(\bullet)$  between the independent variables  $X_1, X_2, \dots, X_k$  and the dependent variable  $Y$ . If the values for the independent variables are under

**FIGURE 1.3**

Categories and  
characteristics of  
management  
science modeling  
techniques

| Category            | Model Characteristics |   | Management Science Techniques  |
|---------------------|-----------------------|---|--|
|                     | Form of $f(\bullet)$  | Values of Independent Variables         |  |
| Prescriptive Models | known, well-defined   | known or under decision maker's control | Linear Programming, Networks, Integer Programming, CPM, Goal Programming, EOQ, Nonlinear Programming |
| Predictive Models   | unknown, ill-defined  | known or under decision maker's control | Regression Analysis, Time Series Analysis, Discriminant Analysis                                     |
| Descriptive Models  | known, well-defined   | unknown or uncertain                    | Simulation, Queuing, PERT, Inventory Models  |

the decision maker's control, the decision problem in these types of situations boils down to determining the values of the independent variables  $X_1, X_2, \dots, X_k$  that produce the best possible value for the dependent variable  $Y$ . These types of models are called **Prescriptive Models** because their solutions tell the decision maker what actions to take. For example, you might be interested in determining how a given sum of money should be allocated to different investments (represented by the independent variables) to maximize the return on a portfolio without exceeding a certain level of risk.

A second category of decision problems is one in which the objective is to predict or estimate what value the dependent variable  $Y$  will take on when the independent variables  $X_1, X_2, \dots, X_k$  take on specific values. If the function  $f(\bullet)$  relating the dependent and independent variables is known, this is a very simple task—simply enter the specified values for  $X_1, X_2, \dots, X_k$  into the function  $f(\bullet)$  and compute  $Y$ . In some cases, however, the functional form of  $f(\bullet)$  might be unknown and must be estimated for the decision maker to make predictions about the dependent variable  $Y$ . These types of models are called **Predictive Models**. For example, a real estate appraiser might know that the value of a commercial property ( $Y$ ) is influenced by its total square footage ( $X_1$ ) and age ( $X_2$ ), among other things. However, the functional relationship  $f(\bullet)$  that relates these variables to one another might be unknown. By analyzing the relationship between the selling price, total square footage, and age of other commercial properties, the appraiser might be able to identify a function  $f(\bullet)$  that relates these two variables in a reasonably accurate manner.

The third category of models you are likely to encounter in the business world is called **Descriptive Models**. In these situations, a manager might face a decision problem that has a very precise, well-defined functional relationship  $f(\bullet)$  between the independent variables  $X_1, X_2, \dots, X_k$  and the dependent variable  $Y$ . However, there might be great uncertainty as to the exact values that will be assumed by one or more of the independent variables  $X_1, X_2, \dots, X_k$ . In these types of problems, the objective is to describe the outcome or behavior of a given operation or system. For example, suppose a company is building a new manufacturing facility and has several choices about the type of machines to put in the new plant, and also various options for arranging the machines. Management might be interested in studying how the various plant configurations would affect on-time shipments of orders ( $Y$ ), given the uncertain number of orders that might be received ( $X_1$ ) and the uncertain due dates ( $X_2$ ) that might be required by these orders.

## 1.5 The Problem-Solving Process

Throughout our discussion, we have said that the ultimate goal in building models is to help managers make decisions that solve problems. The modeling techniques we will study represent a small but important part of the total problem-solving process. To become an effective modeler, it is important to understand how modeling fits into the entire problem-solving process.

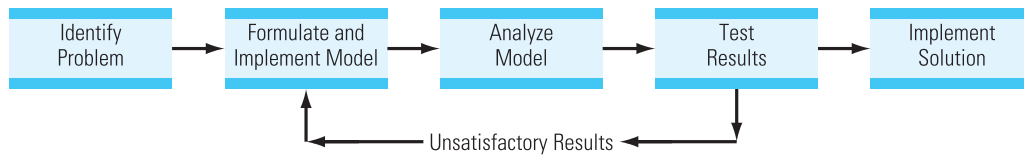
Because a model can be used to represent a decision problem or phenomenon, we might be able to create a visual model of the phenomenon that occurs when people solve problems—what we call the problem-solving process. Although a variety of models could be equally valid, the one in Figure 1.4 summarizes the key elements of the problem-solving process and is sufficient for our purposes.

The first step of the problem-solving process, identifying the problem, is also the most important. If we do not identify the correct problem, all the work that follows will amount to nothing more than wasted effort, time, and money. Unfortunately, identifying



**FIGURE 1.4**

*A visual model of the problem-solving process*



the problem to solve is often not as easy as it seems. We know that a problem exists when there is a gap or disparity between the present situation and some desired state of affairs. However, we usually are not faced with a neat, well-defined problem. Instead, we often find ourselves facing a “mess”!<sup>2</sup> Identifying the real problem involves gathering a lot of information and talking with many people to increase our understanding of the mess. We must then sift through all this information and try to identify the root problem or problems causing the mess. Thus, identifying the real problem (and not just the symptoms of the problem) requires insight, some imagination, time, and a good bit of detective work.

The end result of the problem-identification step is a well-defined statement of the problem. Simply defining a problem well will often make it much easier to solve. Having identified the problem, we turn our attention to creating or formulating a model of the problem. Depending on the nature of the problem, we might use a mental model, a visual model, a scale model, or a mathematical model. Although this book focuses on mathematical models, this does not mean that mathematical models are always applicable or best. In most situations, the best model is the simplest model that accurately reflects the relevant characteristic or essence of the problem being studied.

We will discuss several different management science modeling techniques in this book. It is important that you not develop too strong a preference for any one technique. Some people have a tendency to want to formulate every problem they face as a model that can be solved by their favorite management science technique. This simply will not work.

As indicated in Figure 1.3, there are fundamental differences in the types of problems a manager might face. Sometimes, the values of the independent variables affecting a problem are under the manager’s control; sometimes they are not. Sometimes, the form of the functional relationship  $f(\bullet)$  relating the dependent and independent variables is well-defined, and sometimes it is not. These fundamental characteristics of the problem should guide your selection of an appropriate management science modeling technique. Your goal at the model-formulation stage is to select a modeling technique that fits your problem, rather than trying to fit your problem into the required format of a pre-selected modeling technique.

After you select an appropriate representation or formulation of your problem, the next step is to implement this formulation as a spreadsheet model. We will not dwell on the implementation process now because that is the focus of the remainder of this book. After you verify that your spreadsheet model has been implemented accurately, the next step in the problem-solving process is to use the model to analyze the problem it represents. The main focus of this step is to generate and evaluate alternatives that might lead to a solution. This often involves playing out a number of scenarios or asking several “What if?” questions. Spreadsheets are particularly helpful in analyzing mathematical models in this manner. In a well-designed spreadsheet model, it should be fairly simple to change some of the assumptions in the model to see what might happen in different

<sup>2</sup> This characterization is borrowed from Chapter 5, James R. Evans, *Creative Thinking in the Decision and Management Sciences* (Cincinnati, Ohio: South-Western Publishing, 1991), 89–115.

situations. As we proceed, we will highlight some techniques for designing spreadsheet models that facilitate this type of “what if?” analysis. “What if?” analysis is also very appropriate and useful when working with nonmathematical models.

The end result of analyzing a model does not always provide a solution to the actual problem being studied. As we analyze a model by asking various “What if?” questions, it is important to test the feasibility and quality of each potential solution. The blueprints that Frank Brock showed to his production employees represented the end result of his analysis of the problem he faced. He wisely tested the feasibility and quality of this alternative before implementing it, and discovered an important flaw in his plans. Thus, the testing process can give important new insights into the nature of a problem. The testing process is also important because it provides the opportunity to double-check the validity of the model. At times, we might discover an alternative that appears to be too good to be true. This could lead us to find that some important assumption has been left out of the model. Testing the results of the model against known results (and simple common sense) helps ensure the structural integrity and validity of the model. After analyzing the model, we might discover that we need to go back and modify the model.

The last step of the problem-solving process, implementation, is often the most difficult. By their very nature, solutions to problems involve people and change. For better or for worse, most people resist change. However, there are ways to minimize the seemingly inevitable resistance to change. For example, it is wise, if possible, to involve anyone who will be affected by the decision in all steps of the problem-solving process. This not only helps develop a sense of ownership and understanding of the ultimate solution, but it also can be the source of important information throughout the problem-solving process. As the Brock Candy story illustrates, even if it is impossible to include those affected by the solution in all steps, their input should be solicited and considered before a solution is accepted for implementation. Resistance to change and new systems also can be eased by creating flexible, user-friendly interfaces for the mathematical models that often are developed in the problem-solving process.

Throughout this book, we focus mostly on the model formulation, implementation, analysis, and testing steps of the problem-solving process, summarized in Figure 1.4. Again, this does not imply that these steps are more important than the others. If we do not identify the correct problem, the best we can hope for from our modeling effort is “the right answer to the wrong question,” which does not solve the real problem. Similarly, even if we do identify the problem correctly and design a model that leads to a perfect solution, if we cannot implement the solution, then we still have not solved the problem. Developing the interpersonal and investigative skills required to work with people in defining the problem and implementing the solution are as important as the mathematical modeling skills you will develop by working through this book.

## 1.6 Anchoring and Framing Effects

At this point, some of you reading this book are probably thinking it is better to rely on subjective judgment and intuition rather than models when making decisions. Indeed, most nontrivial decision problems involve some issues that are difficult or impossible to structure and analyze in the form of a mathematical model. These unstructurable aspects of a decision problem might require the use of judgment and intuition. However, it is important to realize that human cognition is often flawed and can lead to incorrect judgments and irrational decisions. Errors in human judgment often arise because of what psychologists term **anchoring** and **framing** effects associated with decision problems.

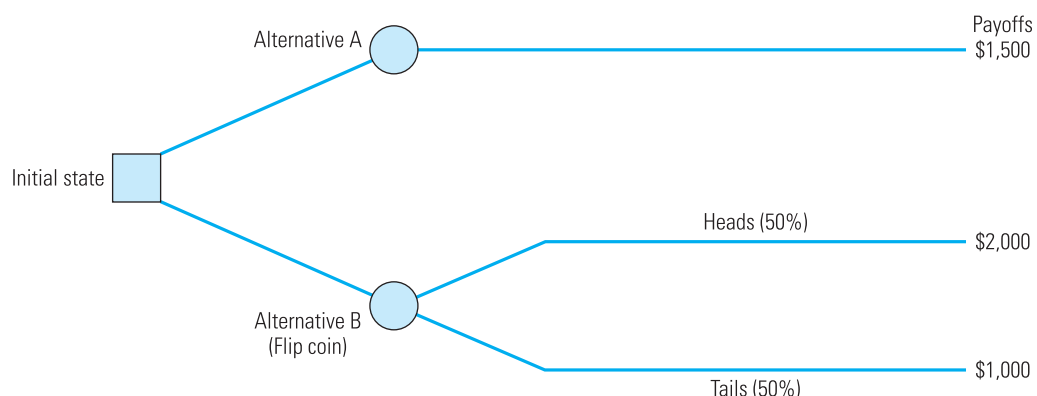
Anchoring effects arise when a seemingly trivial factor serves as a starting point (or anchor) for estimations in a decision-making problem. Decision makers adjust their estimates from this anchor but nevertheless remain too close to the anchor and usually under-adjust. In a classic psychological study on this issue, one group of subjects were asked to individually estimate the value of  $1 \times 2 \times 3 \times 4 \times 5 \times 6 \times 7 \times 8$  (without using a calculator). Another group of subjects were each asked to estimate the value of  $8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1$ . The researchers hypothesized that the first number presented (or perhaps the product of the first three or four numbers) would serve as a mental anchor. The results supported the hypothesis. The median estimate of subjects shown the numbers in ascending sequence ( $1 \times 2 \times 3 \dots$ ) was 512, whereas the median estimate of subjects shown the sequence in descending order ( $8 \times 7 \times 6 \dots$ ) was 2,250. Of course, the order of multiplication for these numbers is irrelevant and the product of both series is the same: 40,320.

Framing effects refer to how a decision maker views or perceives the alternatives in a decision problem—often involving a win/loss perspective. The way a problem is framed often influences the choices made by a decision maker and can lead to irrational behavior. For example, suppose you have just been given \$1,000 but must choose one of the following alternatives: (A<sub>1</sub>) Receive an additional \$500 with certainty, or (B<sub>1</sub>) Flip a fair coin and receive an additional \$1,000 if heads occurs or \$0 additional if tails occurs. Here, alternative A<sub>1</sub> is a “sure win” and is the alternative most people prefer. Now suppose you have been given \$2,000 and must choose one of the following alternatives: (A<sub>2</sub>) Give back \$500 immediately, or (B<sub>2</sub>) Flip a fair coin and give back \$0 if heads occurs or \$1,000 if tails occurs. When the problem is framed this way, alternative A<sub>2</sub> is a “sure loss” and many people who previously preferred alternative A<sub>1</sub> now opt for alternative B<sub>2</sub> (because it holds a chance of avoiding a loss). However, Figure 1.5 shows a single decision tree for these two scenarios making it clear that, in both cases, the “A” alternative guarantees a total payoff of \$1,500, whereas the “B” alternative offers a 50% chance of a \$2,000 total payoff and a 50% chance of a \$1,000 total payoff. (Decision trees will be covered in greater detail in a later chapter.) A purely rational decision maker should focus on the consequences of his or her choices and consistently select the same alternative, regardless of how the problem is framed.

Whether we want to admit it or not, we are all prone to make errors in estimation due to anchoring effects and may exhibit irrationality in decision making due to framing effects. As a result, it is best to use computer models to do what they are best at (i.e., modeling structurable portions of a decision problem) and let the human brain do what it is best at (i.e., dealing with the unstructurable portion of a decision problem).

**FIGURE 1.5**

*Decision tree for framing effects*



## 1.7 Good Decisions vs. Good Outcomes

The goal of the modeling approach to problem solving is to help individuals make good decisions. But good decisions do not always result in good outcomes. For example, suppose the weather report on the evening news predicts a warm, dry, sunny day tomorrow. When you get up and look out the window tomorrow morning, suppose there is not a cloud in sight. If you decide to leave your umbrella at home and subsequently get soaked in an unexpected afternoon thundershower, did you make a bad decision? Certainly not. Unforeseeable circumstances beyond your control caused you to experience a bad outcome, but it would be unfair to say that you made a bad decision. Good decisions sometimes result in bad outcomes. See Figure 1.6 for the story of another good decision having a bad outcome.

The modeling techniques presented in this book can help you make good decisions, but cannot guarantee that good outcomes will always occur as a result of those decisions. Even when a good decision is made, luck often plays a role in determining whether a good or bad outcome occurs. However, using a structured, modeling approach to decision making should produce good outcomes more frequently than making decisions in a more haphazard manner.

## 1.8 Summary

This book introduces you to a variety of techniques from the field of management science that can be applied in spreadsheet models to assist in decision analysis and problem solving. This chapter discussed how spreadsheet models of decision problems can be used to analyze the consequences of possible courses of action before a particular alternative is selected for implementation. It described how models of decision problems differ in several important characteristics and how you should select a modeling technique that is most appropriate for the type of problem being faced. Finally, it discussed how spreadsheet modeling and analysis fit into the problem-solving process.

**FIGURE 1.6**

*A good decision  
with a bad  
outcome*

Andre-Francois Raffray thought he had a great deal in 1965 when he agreed to pay a 90-year-old woman named Jeanne Calment \$500 a month until she died to acquire her grand apartment in Arles, northwest of Marseilles in the south of France—a town Vincent Van Gogh once roamed. Buying apartments “for life” is common in France. The elderly owner gets to enjoy a monthly income from the buyer who gambles on getting a real estate bargain—betting the owner doesn’t live too long. Upon the owner’s death, the buyer inherits the apartment regardless of how much was paid. But in December of 1995, Raffray died at age 77, having paid more than \$180,000 for an apartment he never got to live in.

On the same day, Calment, then the world’s oldest living person at 120, dined on foie gras, duck thighs, cheese, and chocolate cake at her nursing home near the sought-after apartment. And she does not need to worry about losing her \$500 monthly income. Although the amount Raffray already paid is twice the apartment’s current market value, his widow is obligated to keep sending the monthly check to Calment. If Calment also outlives her, then the Raffray children will have to pay. “In life, one sometimes makes bad deals,” said Calment of the outcome of Raffray’s decision. (Source: *The Savannah Morning News*, 12/29/95.)

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### THE WORLD OF MANAGEMENT SCIENCE

#### *"Business Analysts Trained in Management Science Can Be a Secret Weapon in a CIO's Quest for Bottom-Line Results."*

Efficiency nuts. These are the people you see at cocktail parties explaining how the host could disperse that crowd around the popular shrimp dip if he would divide it into three bowls and place them around the room. As she draws the improved traffic flow on a paper napkin, you notice that her favorite word is "optimize"—a tell-tale sign that she has studied the field of "operations research" or "management science" (also known as OR/MS).

OR/MS professionals are driven to solve logistics problems. This trait might not make them the most popular people at parties, but it is exactly what today's information systems (IS) departments need to deliver more business value. Experts say that smart IS executives will learn to exploit the talents of these mathematical wizards in their quest to boost a company's bottom line.

According to Ron J. Ponder, chief information officer (CIO) at Sprint Corp. in Kansas City, Mo., and former CIO at Federal Express Corp., "If IS departments had more participation from operations research analysts, they would be building much better, richer IS solutions." As someone who has a Ph.D. in operations research and who built the renowned package-tracking systems at Federal Express, Ponder is a true believer in OR/MS. Ponder and others say analysts trained in OR/MS can turn ordinary information systems into money-saving, decision-support systems, and are ideally suited to be members of the business process reengineering team. "I've always had an operations research department reporting to me, and it's been invaluable. Now I'm building one at Sprint," says Ponder.

#### The Beginnings

OR/MS got its start in World War II, when the military had to make important decisions about allocating scarce resources to various military operations. One of the first business applications for computers in the 1950s was to solve operations research problems for the petroleum industry. A technique called linear programming was used to figure out how to blend gasoline for the right flash point, viscosity, and octane in the most economical way. Since then, OR/MS has spread throughout business and government, from designing efficient drive-thru window operations for Burger King Corp. to creating ultrasophisticated computerized stock trading systems.

A classic OR/MS example is the crew scheduling problem faced by all major airlines. How do you plan the itineraries of 8,000 pilots and 17,000 flight attendants



when there is an astronomical number of combinations of planes, crews, and cities? The OR/MS analysts at United Airlines came up with a scheduling system called Paragon that attempts to minimize the amount of paid time that crews spend waiting for flights. Their model factors in constraints such as labor agreement provisions and Federal Aviation Administration regulations, and is projected to save the airline at least \$1 million a year.

### OR/MS and IS

Somewhere in the 1970s, the OR/MS and IS disciplines went in separate directions. "The IS profession has had less and less contact with the operations research folks . . . and IS lost a powerful intellectual driver," says Peter G. W. Keen, executive director of the International Center for Information Technologies in Washington, D.C. However, many feel that now is an ideal time for the two disciplines to rebuild some bridges.

Today's OR/MS professionals are involved in a variety of IS-related fields, including inventory management, electronic data interchange, supply chain management, IT security, computer-integrated manufacturing, network management, and practical applications of artificial intelligence. Furthermore, each side needs something the other side has: OR/MS analysts need corporate data to plug into their models, and the IS folks need to plug the OR/MS models into their strategic information systems. At the same time, CIOs need intelligent applications that enhance the bottom line and make them heroes with the chief executive officer.

OR/MS analysts can develop a model of how a business process works now and simulate how it could work more efficiently in the future. Therefore, it makes sense to have an OR/MS analyst on the interdisciplinary team that tackles business process reengineering projects. In essence, OR/MS professionals add more value to the IS infrastructure by building "tools that really help decision makers analyze complex situations," says Andrew B. Whinston, director of the Center for Information Systems Management at the University of Texas at Austin.

Although IS departments typically believe their job is done if they deliver accurate and timely information, Thomas M. Cook, president of American Airlines Decision Technologies, Inc. says that adding OR/MS skills to the team can produce intelligent systems that actually recommend solutions to business problems. One of the big success stories at Cook's operations research shop is a "yield management" system that decides how much to overbook and how to set prices for each seat so that a plane is filled up and profits are maximized. The yield management system deals with more than 250 decision variables and accounts for a significant amount of American Airlines' revenue.

### Where to Start

So how can the CIO start down the road toward collaboration with OR/MS analysts? If the company already has a group of OR/MS professionals, the IS department can draw on their expertise as internal consultants. Otherwise, the CIO can simply hire a few OR/MS wizards, throw a problem at them, and see what happens. The payback may come surprisingly quickly. As one former OR/MS professional put it: "If I couldn't save my employer the equivalent of my own salary in the first month of the year, then I wouldn't feel like I was doing my job."

**Adapted from:** Mitch Betts, "Efficiency Einsteins," *ComputerWorld*, March 22, 1993, p. 64.

## Questions and Problems

1. What is meant by the term decision analysis?
2. Define the term computer model.
3. What is the difference between a spreadsheet model and a computer model?
4. Define the term management science.
5. What is the relationship between management science and spreadsheet modeling?
6. What kinds of spreadsheet applications would not be considered management science?
7. In what ways do spreadsheet models facilitate the decision-making process?
8. What are the benefits of using a modeling approach to decision making?
9. What is a dependent variable?
10. What is an independent variable?
11. Can a model have more than one dependent variable?
12. Can a decision problem have more than one dependent variable?
13. In what ways are prescriptive models different from descriptive models?
14. In what ways are prescriptive models different from predictive models?
15. In what ways are descriptive models different from predictive models?
16. How would you define the words description, prediction, and prescription? Carefully consider what is unique about the meaning of each word.
17. Identify one or more mental models you have used. Can any of them be expressed mathematically? If so, identify the dependent and independent variables in your model.
18. Consider the spreadsheet model shown in Figure 1.2. Is this model descriptive, predictive, or prescriptive in nature, or does it not fall into any of these categories?
19. What are the steps in the problem-solving process?
20. Which step in the problem-solving process do you think is most important? Why?
21. Must a model accurately represent every detail of a decision situation to be useful? Why or why not?
22. If you were presented with several different models of a given decision problem, which would you be most inclined to use? Why?
23. Describe an example in which business or political organizations may use anchoring effects to influence decision making.
24. Describe an example in which business or political organizations may use framing effects to influence decision making.
25. Suppose sharks have been spotted along the beach where you are vacationing with a friend. You and your friend have been informed of the shark sightings and are aware of the damage a shark attack can inflict on human flesh. You both decide (individually) to go swimming anyway. You are promptly attacked by a shark while your friend has a nice time body surfing in the waves. Did you make a good or bad decision? Did your friend make a good or bad decision? Explain your answer.
26. Describe an example in which a well-known business, political, or military leader made a good decision that resulted in a bad outcome, or a bad decision that resulted in a good outcome.

### CASE 1.1

## Patrick's Paradox

Patrick's luck had changed overnight—but not his skill at mathematical reasoning. The day after graduating from college he used the \$20 that his grandmother had given him



as a graduation gift to buy a lottery ticket. He knew that his chances of winning the lottery were extremely low and it probably was not a good way to spend this money. But he also remembered from the class he took in management science that bad decisions sometimes result in good outcomes. So he said to himself, "What the heck? Maybe this bad decision will be the one with a good outcome." And with that thought, he bought his lottery ticket.

The next day Patrick pulled the crumpled lottery ticket out of the back pocket of his blue jeans and tried to compare his numbers to the winning numbers printed in the paper. When his eyes finally came into focus on the numbers they also just about popped out of his head. He had a winning ticket! In the ensuing days he learned that his share of the jackpot would give him a lump sum payout of about \$500,000 after taxes. He knew what he was going to do with part of the money: buy a new car, pay off his college loans, and send his grandmother on an all-expenses-paid trip to Hawaii. But he also knew that he couldn't continue to hope for good outcomes to arise from more bad decisions. So he decided to take half of his winnings and invest it for his retirement.

A few days later, Patrick was sitting around with two of his fraternity buddies, Josh and Peyton, trying to figure out how much money his new retirement fund might be worth in 30 years. They were all business majors in college and remembered from their finance class that if you invest  $p$  dollars for  $n$  years at an annual interest rate of  $i$  percent then in  $n$  years you would have  $p(1 + i)^n$  dollars. So they figure that if Patrick invested \$250,000 for 30 years in an investment with a 10% annual return then in 30 years he would have \$4,362,351 (that is,  $\$250,000(1 + 0.10)^{30}$ ).

But after thinking about it a little more, they all agreed that it would be unlikely for Patrick to find an investment that would produce a return of exactly 10% each and every year for the next 30 years. If any of this money is invested in stocks then some years the return might be higher than 10% and some years it would probably be lower. So to help account for the potential variability in the investment returns Patrick and his friends came up with a plan; they would assume he could find an investment that would produce an annual return of 17.5% seventy percent of the time and a return (or actually a loss) of -7.5% thirty percent of the time. Such an investment should produce an average annual return of  $0.7(17.5\%) + 0.3(-7.5\%) = 10\%$ . Josh felt certain that this meant Patrick could still expect his \$250,000 investment to grow to \$4,362,351 in 30 years (because  $\$250,000(1 + 0.10)^{30} = \$4,362,351$ ).

After sitting quietly and thinking about it for a while, Peyton said that he thought Josh was wrong. The way Peyton looked at it, Patrick should see a 17.5% return in 70% of the 30 years (or  $0.7(30) = 21$  years) and a -7.5% return in 30% of the 30 years (or  $0.3(30) = 9$  years). So, according to Peyton, that would mean Patrick should have  $\$250,000(1 + 0.175)^{21}(1 - 0.075)^9 = \$3,664,467$  after 30 years. But that's \$697,884 less than what Josh says Patrick should have.

After listening to Peyton's argument, Josh said he thought Peyton was wrong because his calculation assumes that the "good" return of 17.5% would occur in each of the first 21 years and the "bad" return of -7.5% would occur in each of the last 9 years. But Peyton countered this argument by saying that the order of good and bad returns does not matter. The commutative law of arithmetic says that when you add or multiply numbers, the order doesn't matter (that is,  $X + Y = Y + X$  and  $X \times Y = Y \times X$ ). So Peyton says that because Patrick can expect 21 "good" returns and 9 "bad" returns and it doesn't matter in what order they occur, then the expected outcome of the investment should be \$3,664,467 after 30 years.

Patrick is now really confused. Both of his friends' arguments seem to make perfect sense logically—but they lead to such different answers, and they can't both be right. What really worries Patrick is that he is starting his new job as a business analyst in a couple of weeks. And if he can't reason his way to the right answer in a relatively simple problem like this, what is he going to do when he encounters the more difficult problems awaiting him the business world? Now he really wishes he had paid more attention in his management sciences class.

So what do you think? Who is right, Josh or Peyton? And more important, why?

# Chapter 2

## Introduction to Optimization and Linear Programming

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### 2.0 Introduction

Our world is filled with limited resources. The amount of oil we can pump out of the earth is limited. The amount of land available for garbage dumps and hazardous waste is limited and, in many areas, diminishing rapidly. On a more personal level, each of us has a limited amount of time in which to accomplish or enjoy the activities we schedule each day. Most of us have a limited amount of money to spend while pursuing these activities. Businesses also have limited resources. A manufacturing organization employs a limited number of workers. A restaurant has a limited amount of space available for seating.

Deciding how best to use the limited resources available to an individual or a business is a universal problem. In today's competitive business environment, it is increasingly important to make sure that a company's limited resources are used in the most efficient manner possible. Typically, this involves determining how to allocate the resources in such a way as to maximize profits or minimize costs. **Mathematical programming** (MP) is a field of management science that finds the optimal, or most efficient, way of using limited resources to achieve the objectives of an individual or a business. For this reason, mathematical programming often is referred to as **optimization**.

### 2.1 Applications of Mathematical Optimization

To help you understand the purpose of optimization and the types of problems for which it can be used, let's consider several examples of decision-making situations in which MP techniques have been applied.

**Determining Product Mix.** Most manufacturing companies can make a variety of products. However, each product usually requires different amounts of raw materials and labor. Similarly, the amount of profit generated by the products varies. The manager of such a company must decide how many of each product to produce to maximize profits or to satisfy demand at minimum cost.

**Manufacturing.** Printed circuit boards, like those used in most computers, often have hundreds or thousands of holes drilled in them to accommodate the different electrical components that must be plugged into them. To manufacture these boards, a computer-controlled drilling machine must be programmed to drill in a given location, then move

the drill bit to the next location and drill again. This process is repeated hundreds or thousands of times to complete all the holes on a circuit board. Manufacturers of these boards would benefit from determining the drilling order that minimizes the total distance the drill bit must be moved.

**Routing and Logistics.** Many retail companies have warehouses around the country that are responsible for keeping stores supplied with merchandise to sell. The amount of merchandise available at the warehouses and the amount needed at each store tends to fluctuate, as does the cost of shipping or delivering merchandise from the warehouses to the retail locations. Large amounts of money can be saved by determining the least costly method of transferring merchandise from the warehouses to the stores.

**Financial Planning.** The federal government requires individuals to begin withdrawing money from individual retirement accounts (IRAs) and other tax-sheltered retirement programs no later than age 70.5. There are various rules that must be followed to avoid paying penalty taxes on these withdrawals. Most individuals want to withdraw their money in a manner that minimizes the amount of taxes they must pay while still obeying the tax laws.

### Optimization Is Everywhere

Going to Disney World this summer? Optimization will be your ubiquitous companion, scheduling the crews and planes, pricing the airline tickets and hotel rooms, even helping to set capacities on the theme park rides. If you use Orbitz to book your flights, an optimization engine sifts through millions of options to find the cheapest fares. If you get directions to your hotel from MapQuest, another optimization engine figures out the most direct route. If you ship souvenirs home, an optimization engine tells UPS which truck to put the packages on, exactly where on the truck the packages should go to make them fastest to load and unload, and what route the driver should follow to make his deliveries most efficiently.

(Adapted from: V. Postrel, "Operation Everything," *The Boston Globe*, June 27, 2004.)

## 2.2 Characteristics of Optimization Problems

These examples represent just a few areas in which MP has been used successfully. We will consider many other examples throughout this book. However, these examples give you some idea of the issues involved in optimization. For instance, each example involves one or more *decisions* that must be made: How many of each product should be produced? Which hole should be drilled next? How much of each product should be shipped from each warehouse to the various retail locations? How much money should an individual withdraw each year from various retirement accounts?

Also, in each example, restrictions, or *constraints*, are likely to be placed on the alternatives available to the decision maker. In the first example, when determining the number of products to manufacture, a production manager probably is faced with a limited amount of raw materials and a limited amount of labor. In the second example, the drill never should return to a position where a hole has already been drilled. In the

third example, there is a physical limitation on the amount of merchandise a truck can carry from one warehouse to the stores on its route. In the fourth example, laws determine the minimum and maximum amounts that can be withdrawn from retirement accounts without incurring a penalty. There might be many other constraints for these examples. Indeed, it is not unusual for real-world optimization problems to have hundreds or thousands of constraints.

A final common element in each of the examples is the existence of some goal or *objective* that the decision maker considers when deciding which course of action is best. In the first example, the production manager can decide to produce several different product mixes given the available resources, but the manager probably will choose the mix of products that maximizes profits. In the second example, a large number of possible drilling patterns can be used, but the ideal pattern probably will involve moving the drill bit the shortest total distance. In the third example, there are numerous ways merchandise can be shipped from the warehouses to supply the stores, but the company probably will want to identify the routing that minimizes the total transportation cost. Finally, in the fourth example, individuals can withdraw money from their retirement accounts in many ways without violating the tax laws, but they probably want to find the method that minimizes their tax liability.

## 2.3 Expressing Optimization Problems Mathematically

From the preceding discussion, we know that optimization problems involve three elements: decisions, constraints, and an objective. If we intend to build a mathematical model of an optimization problem, we will need mathematical terms or symbols to represent each of these three elements.

### 2.3.1 DECISIONS

The decisions in an optimization problem often are represented in a mathematical model by the symbols  $X_1, X_2, \dots, X_n$ . We will refer to  $X_1, X_2, \dots, X_n$  as the **decision variables** (or simply the variables) in the model. These variables might represent the quantities of different products the production manager can choose to produce. They might represent the amount of different pieces of merchandise to ship from a warehouse to a certain store. They might represent the amount of money to be withdrawn from different retirement accounts.

The exact symbols used to represent the decision variables are not particularly important. You could use  $Z_1, Z_2, \dots, Z_n$  or symbols like Dog, Cat, and Monkey to represent the decision variables in the model. The choice of which symbols to use is largely a matter of personal preference and might vary from one problem to the next.

### 2.3.2 CONSTRAINTS

The constraints in an optimization problem can be represented in a mathematical model in several ways. Three general ways of expressing the possible constraint relationships in an optimization problem are:

|  |                                  |
|--|----------------------------------|
| A “less than or equal to” constraint:    | $f(X_1, X_2, \dots, X_n) \leq b$ |
| A “greater than or equal to” constraint: | $f(X_1, X_2, \dots, X_n) \geq b$ |
| An “equal to” constraint:                | $f(X_1, X_2, \dots, X_n) = b$    |

In each case, the **constraint** is some function of the decision variables that must be less than or equal to, greater than or equal to, or equal to some specific value (represented above by the letter  $b$ ). We will refer to  $f(X_1, X_2, \dots, X_n)$  as the left-hand-side (LHS) of the constraint and to  $b$  as the right-hand-side (RHS) value of the constraint.

For example, we might use a “less than or equal to” constraint to ensure that the total labor used in producing a given number of products does not exceed the amount of available labor. We might use a “greater than or equal to” constraint to ensure that the total amount of money withdrawn from a person’s retirement accounts is at least the minimum amount required by the IRS. You can use any number of these constraints to represent a given optimization problem depending on the requirements of the situation.

### 2.3.3 OBJECTIVE

The objective in an optimization problem is represented mathematically by an objective function in the general format:

$$\text{MAX (or MIN): } f(X_1, X_2, \dots, X_n)$$

The **objective function** identifies some function of the decision variables that the decision maker wants to either MAXimize or MINimize. In our earlier examples, this function might be used to describe the total profit associated with a product mix, the total distance the drill bit must be moved, the total cost of transporting merchandise, or a retiree’s total tax liability.

The mathematical formulation of an optimization problem can be described in the general format:

$$\text{MAX (or MIN): } f_0(X_1, X_2, \dots, X_n) \quad 2.1$$

$$\text{Subject to: } f_1(X_1, X_2, \dots, X_n) \leq b_1 \quad 2.2$$

:

$$f_k(X_1, X_2, \dots, X_n) \geq b_k \quad 2.3$$

:

$$f_m(X_1, X_2, \dots, X_n) = b_m \quad 2.4$$

This representation identifies the objective function (equation 2.1) that will be maximized (or minimized) and the constraints that must be satisfied (equations 2.2 through 2.4). Subscripts added to the  $f$  and  $b$  in each equation emphasize that the functions describing the objective and constraints can all be different. The goal in optimization is to find the values of the decision variables that maximize (or minimize) the objective function without violating any of the constraints.

## 2.4 Mathematical Programming Techniques

Our general representation of an MP model is just that—general. You can use many kinds of functions to represent the objective function and the constraints in an MP model. Of course, you always should use functions that accurately describe the objective and constraints of the problem you are trying to solve. Sometimes, the functions in a model are linear in nature (that is, they form straight lines or flat surfaces); other times,



they are nonlinear (that is, they form curved lines or curved surfaces). Sometimes, the optimal values of the decision variables in a model must take on integer values (whole numbers); other times, the decision variables can assume fractional values.

Given the diversity of MP problems that can be encountered, many techniques have been developed to solve different types of MP problems. In the next several chapters, we will look at these MP techniques and develop an understanding of how they differ and when each should be used. We will begin by examining a technique called **linear programming** (LP), which involves creating and solving optimization problems with linear objective functions and linear constraints. LP is a very powerful tool that can be applied in many business situations. It also forms a basis for several other techniques discussed later and is, therefore, a good starting point for our investigation into the field of optimization.

## 2.5 An Example LP Problem

We will begin our study of LP by considering a simple example. You should not interpret this to mean that LP cannot solve more complex or realistic problems. LP has been used to solve extremely complicated problems, saving companies millions of dollars. However, jumping directly into one of these complicated problems would be like starting a marathon without ever having gone out for a jog—you would get winded and could be left behind very quickly. So we'll start with something simple.

Blue Ridge Hot Tubs manufactures and sells two models of hot tubs: the Aqua-Spa and the Hydro-Lux. Howie Jones, the owner and manager of the company, needs to decide how many of each type of hot tub to produce during his next production cycle. Howie buys prefabricated fiberglass hot tub shells from a local supplier and adds the pump and tubing to the shells to create his hot tubs. (This supplier has the capacity to deliver as many hot tub shells as Howie needs.) Howie installs the same type of pump into both hot tubs. He will have only 200 pumps available during his next production cycle. From a manufacturing standpoint, the main difference between the two models of hot tubs is the amount of tubing and labor required. Each Aqua-Spa requires 9 hours of labor and 12 feet of tubing. Each Hydro-Lux requires 6 hours of labor and 16 feet of tubing. Howie expects to have 1,566 production labor hours and 2,880 feet of tubing available during the next production cycle. Howie earns a profit of \$350 on each Aqua-Spa he sells and \$300 on each Hydro-Lux he sells. He is confident that he can sell all the hot tubs he produces. The question is, how many Aqua-Spas and Hydro-Luxes should Howie produce if he wants to maximize his profits during the next production cycle?

## 2.6 Formulating LP Models

The process of taking a practical problem—such as determining how many Aqua-Spas and Hydro-Luxes Howie should produce—and expressing it algebraically in the form of an LP model is known as **formulating** the model. Throughout the next several chapters, you will see that formulating an LP model is as much an art as a science.

### 2.6.1 STEPS IN FORMULATING AN LP MODEL

There are some general steps you can follow to help make sure your formulation of a particular problem is accurate. We will walk through these steps using the hot tub example.



1. **Understand the problem.** This step appears to be so obvious that it hardly seems worth mentioning. However, many people have a tendency to jump into a problem and start writing the objective function and constraints before they really understand the problem. If you do not fully understand the problem you face, it is unlikely that your formulation of the problem will be correct.

The problem in our example is fairly easy to understand: How many Aqua-Spas and Hydro-Luxes should Howie produce to maximize his profit, while using no more than 200 pumps, 1,566 labor hours, and 2,880 feet of tubing?

2. **Identify the decision variables.** After you are sure you understand the problem, you need to identify the decision variables. That is, what are the fundamental decisions that must be made to solve the problem? The answers to this question often will help you identify appropriate decision variables for your model. Identifying the decision variables means determining what the symbols  $X_1, X_2, \dots, X_n$  represent in your model.

In our example, the fundamental decision Howie faces is this: How many Aqua-Spas and Hydro-Luxes should be produced? In this problem, we will let  $X_1$  represent the number of Aqua-Spas to produce and  $X_2$  represent the number of Hydro-Luxes to produce.

3. **State the objective function as a linear combination of the decision variables.** After determining the decision variables you will use, the next step is to create the objective function for the model. This function expresses the mathematical relationship between the decision variables in the model to be maximized or minimized.

In our example, Howie earns a profit of \$350 on each Aqua-Spa ( $X_1$ ) he sells and \$300 on each Hydro-Lux ( $X_2$ ) he sells. Thus, Howie's objective of maximizing the profit he earns is stated mathematically as:

$$\text{MAX: } 350X_1 + 300X_2$$

For whatever values might be assigned to  $X_1$  and  $X_2$ , the previous function calculates the associated total profit that Howie would earn. Obviously, Howie wants to maximize this value.

4. **State the constraints as linear combinations of the decision variables.** As mentioned earlier, there are usually some limitations on the values that can be assumed by the decision variables in an LP model. These restrictions must be identified and stated in the form of constraints.

In our example, Howie faces three major constraints. Because only 200 pumps are available and each hot tub requires one pump, Howie cannot produce more than a total of 200 hot tubs. This restriction is stated mathematically as:

$$1X_1 + 1X_2 \leq 200$$

This constraint indicates that each unit of  $X_1$  produced (that is, each Aqua-Spa built) will use one of the 200 pumps available—as will each unit of  $X_2$  produced (that is, each Hydro-Lux built). The total number of pumps used (represented by  $1X_1 + 1X_2$ ) must be less than or equal to 200.

Another restriction Howie faces is that he has only 1,566 labor hours available during the next production cycle. Because each Aqua-Spa he builds (each unit of  $X_1$ ) requires 9 labor hours and each Hydro-Lux (each unit of  $X_2$ ) requires 6 labor hours, the constraint on the number of labor hours is stated as:

$$9X_1 + 6X_2 \leq 1,566$$

The total number of labor hours used (represented by  $9X_1 + 6X_2$ ) must be less than or equal to the total labor hours available, which is 1,566.

The final constraint specifies that only 2,880 feet of tubing is available for the next production cycle. Each Aqua-Spa produced (each unit of  $X_1$ ) requires 12 feet of tubing, and each Hydro-Lux produced (each unit of  $X_2$ ) requires 16 feet of tubing. The following constraint is necessary to ensure that Howie's production plan does not use more tubing than is available:

$$12X_1 + 16X_2 \leq 2,880$$

The total number of feet of tubing used (represented by  $12X_1 + 16X_2$ ) must be less than or equal to the total number of feet of tubing available, which is 2,880.

5. **Identify any upper or lower bounds on the decision variables.** Often, simple upper or lower bounds apply to the decision variables. You can view upper and lower bounds as additional constraints in the problem.

In our example, there are simple lower bounds of zero on the variables  $X_1$  and  $X_2$  because it is impossible to produce a negative number of hot tubs. Therefore, the following two constraints also apply to this problem:

$$X_1 \geq 0$$

$$X_2 \geq 0$$

Constraints like these are often referred to as nonnegativity conditions and are quite common in LP problems.

## 2.7 Summary of the LP Model for the Example Problem

The complete LP model for Howie's decision problem can be stated as:

|             |                            |      |
|-------------|----------------------------|------|
| MAX:        | $350X_1 + 300X_2$          | 2.5  |
| Subject to: | $1X_1 + 1X_2 \leq 200$     | 2.6  |
|             | $9X_1 + 6X_2 \leq 1,566$   | 2.7  |
|             | $12X_1 + 16X_2 \leq 2,880$ | 2.8  |
|             | $1X_1 \geq 0$              | 2.9  |
|             | $1X_2 \geq 0$              | 2.10 |

In this model, the decision variables  $X_1$  and  $X_2$  represent the number of Aqua-Spas and Hydro-Luxes to produce, respectively. Our goal is to determine the values for  $X_1$  and  $X_2$  that maximize the objective in equation 2.5 while simultaneously satisfying all the constraints in equations 2.6 through 2.10.

## 2.8 The General Form of an LP Model

The technique of linear programming is so named because the MP problems to which it applies are linear in nature. That is, it must be possible to express all the functions in an

LP model as some weighted sum (or linear combination) of the decision variables. So, an LP model takes on the general form:

$$\text{MAX (or MIN):} \quad c_1X_1 + c_2X_2 + \cdots + c_nX_n \quad 2.11$$

$$\text{Subject to:} \quad a_{11}X_1 + a_{12}X_2 + \cdots + a_{1n}X_n \leq b_1 \quad 2.12$$

$$\quad \quad \quad \vdots$$

$$a_{k1}X_1 + a_{k2}X_2 + \cdots + a_{kn}X_n \geq b_k \quad 2.13$$

$$\quad \quad \quad \vdots$$

$$a_{m1}X_1 + a_{m2}X_2 + \cdots + a_{mn}X_n = b_m \quad 2.14$$

Up to this point, we have suggested that the constraints in an LP model represent some type of limited resource. Although this is frequently the case, in later chapters you will see examples of LP models in which the constraints represent things other than limited resources. The important point here is that *any* problem that can be formulated in the above fashion is an LP problem.

The symbols  $c_1, c_2, \dots, c_n$  in equation 2.11 are called **objective function coefficients** and might represent the marginal profits (or costs) associated with the decision variables  $X_1, X_2, \dots, X_n$ , respectively. The symbol  $a_{ij}$  found throughout equations 2.12 through 2.14 represents the numeric coefficient in the  $i$ th constraint for variable  $X_j$ . The objective function and constraints of an LP problem represent different weighted sums of the decision variables. The  $b_i$  symbols in the constraints, once again, represent values that the corresponding linear combination of the decision variables must be less than or equal to, greater than or equal to, or equal to.

You should now see a direct connection between the LP model we formulated for Blue Ridge Hot Tubs in equations 2.5 through 2.10 and the general definition of an LP model given in equations 2.11 through 2.14. In particular, note that the various symbols used in equations 2.11 through 2.14 to represent numeric constants (that is, the  $c_j$ ,  $a_{ij}$ , and  $b_i$ ) were replaced by actual numeric values in equations 2.5 through 2.10. Also, note that our formulation of the LP model for Blue Ridge Hot Tubs did not require the use of “equal to” constraints. Different problems require different types of constraints, and you should use whatever types of constraints are necessary for the problem at hand.

## 2.9 Solving LP Problems: An Intuitive Approach

After an LP model has been formulated, our interest naturally turns to solving it. But before we actually solve our example problem for Blue Ridge Hot Tubs, what do you think is the optimal solution to the problem? Just by looking at the model, what values for  $X_1$  and  $X_2$  do you think would give Howie the largest profit?

Following one line of reasoning, it might seem that Howie should produce as many units of  $X_1$  (Aqua-Spas) as possible because each of these generates a profit of \$350, whereas each unit of  $X_2$  (Hydro-Luxes) generates a profit of only \$300. But what is the maximum number of Aqua-Spas that Howie could produce?

Howie can produce the maximum number of units of  $X_1$  by making no units of  $X_2$  and devoting all his resources to the production of  $X_1$ . Suppose we let  $X_2 = 0$  in the model in equations 2.5 through 2.10 to indicate that no Hydro-Luxes will be produced.

What then is the largest possible value of  $X_1$ ? If  $X_2 = 0$ , then the inequality in equation 2.6 tells us:

$$X_1 \leq 200 \quad 2.15$$

So we know that  $X_1$  cannot be any greater than 200 if  $X_2 = 0$ . However, we also have to consider the constraints in equations 2.7 and 2.8. If  $X_2 = 0$ , then the inequality in equation 2.7 reduces to:

$$9X_1 \leq 1,566 \quad 2.16$$

If we divide both sides of this inequality by 9, we find that the previous constraint is equivalent to:

$$X_1 \leq 174 \quad 2.17$$

Now consider the constraint in equation 2.8. If  $X_2 = 0$ , then the inequality in equation 2.8 reduces to:

$$12X_1 \leq 2,880 \quad 2.18$$

Again, if we divide both sides of this inequality by 12, we find that the previous constraint is equivalent to:

$$X_1 \leq 240 \quad 2.19$$

So, if  $X_2 = 0$ , the three constraints in our model imposing upper limits on the value of  $X_1$  reduce to the values shown in equations 2.15, 2.17, and 2.19. The most restrictive of these constraints is equation 2.17. Therefore, the maximum number of units of  $X_1$  that can be produced is 174. In other words, 174 is the largest value  $X_1$  can take on and still satisfy all the constraints in the model.

If Howie builds 174 units of  $X_1$  (Aqua-Spas) and 0 units of  $X_2$  (Hydro-Luxes), he will have used all of the labor that is available for production ( $9X_1 = 1,566$  if  $X_1 = 174$ ). However, he will have 26 pumps remaining ( $200 - X_1 = 26$  if  $X_1 = 174$ ) and 792 feet of tubing remaining ( $2,880 - 12X_1 = 792$  if  $X_1 = 174$ ). Also, notice that the objective function value (or total profit) associated with this solution is:

$$\$350X_1 + \$300X_2 = \$350 \times 174 + \$300 \times 0 = \$60,900$$

From this analysis, we see that the solution  $X_1 = 174$ ,  $X_2 = 0$  is a *feasible solution* to the problem because it satisfies all the constraints of the model. But is it the *optimal solution*? In other words, is there any other possible set of values for  $X_1$  and  $X_2$  that also satisfies all the constraints *and* results in a higher objective function value? As you will see, the intuitive approach to solving LP problems that we have taken here cannot be trusted because there actually is a *better* solution to Howie's problem.

## 2.10 Solving LP Problems: A Graphical Approach

The constraints of an LP model define the set of feasible solutions—or the **feasible region**—for the problem. The difficulty in LP is determining which point or points in the feasible region correspond to the best possible value of the objective function. For simple problems with only two decision variables, it is fairly easy to sketch the feasible region for the LP model and locate the optimal feasible point graphically. Because the graphical approach can be used only if there are two decision variables, it has limited practical use. However, it is an extremely good way to develop a basic understanding of

the strategy involved in solving LP problems. Therefore, we will use the graphical approach to solve the simple problem faced by Blue Ridge Hot Tubs. Chapter 3 shows how to solve this and other LP problems using a spreadsheet.

To solve an LP problem graphically, first you must plot the constraints for the problem and identify its feasible region. This is done by plotting the *boundary lines* of the constraints and identifying the points that will satisfy all the constraints. So, how do we do this for our example problem (repeated below)?

$$\text{MAX:} \quad 350X_1 + 300X_2 \quad 2.20$$

$$\text{Subject to:} \quad 1X_1 + 1X_2 \leq 200 \quad 2.21$$

$$9X_1 + 6X_2 \leq 1,566 \quad 2.22$$

$$12X_1 + 16X_2 \leq 2,880 \quad 2.23$$

$$1X_1 \geq 0 \quad 2.24$$

$$1X_2 \geq 0 \quad 2.25$$

### 2.10.1 PLOTTING THE FIRST CONSTRAINT

The boundary of the first constraint in our model, which specifies that no more than 200 pumps can be used, is represented by the straight line defined by the equation:

$$X_1 + X_2 = 200 \quad 2.26$$

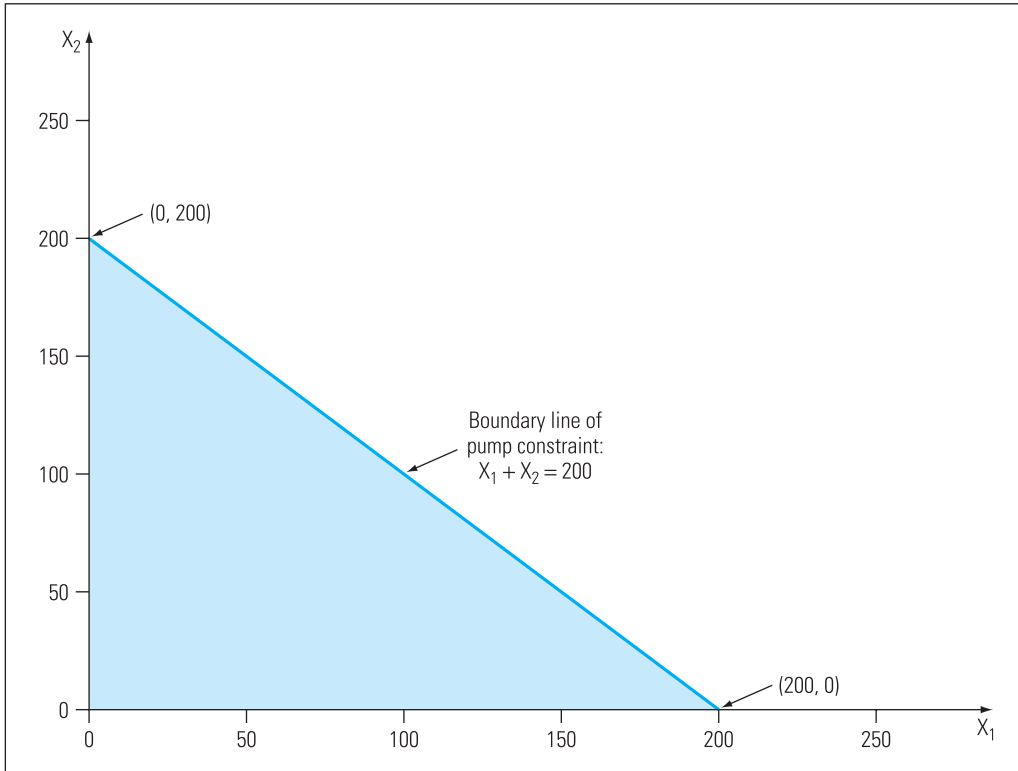
If we can find any two points on this line, the entire line can be plotted easily by drawing a straight line through these points. If  $X_2 = 0$ , we can see from equation 2.26 that  $X_1 = 200$ . Thus, the point  $(X_1, X_2) = (200, 0)$  must fall on this line. If we let  $X_1 = 0$ , from equation 2.26, it is easy to see that  $X_2 = 200$ . So, the point  $(X_1, X_2) = (0, 200)$  also must fall on this line. These two points are plotted on the graph in Figure 2.1 and connected to form the straight line representing equation 2.26.

Note that the graph of the line associated with equation 2.26 actually extends beyond the  $X_1$  and  $X_2$  axes shown in Figure 2.1. However, we can disregard the points beyond these axes because the values assumed by  $X_1$  and  $X_2$  cannot be negative (because we also have the constraints given by  $X_1 \geq 0$  and  $X_2 \geq 0$ ).

The line connecting the points  $(0, 200)$  and  $(200, 0)$  in Figure 2.1 identifies the points  $(X_1, X_2)$  that satisfy the equality  $X_1 + X_2 = 200$ . But recall that the first constraint in the LP model is the inequality  $X_1 + X_2 \leq 200$ . Thus, after plotting the boundary line of a constraint, we must determine which area on the graph corresponds to feasible solutions for the original constraint. This can be done easily by picking an arbitrary point on either side of (*i.e.*, not on) the boundary line and checking whether it satisfies the original constraint. For example, the point  $(X_1, X_2) = (0, 0)$  is not on the boundary line of the first constraint and also satisfies the first constraint. Therefore, the area of the graph on the same side of the boundary line as the point  $(0, 0)$  corresponds to the feasible solutions of our first constraint. This area of feasible solutions is shaded in Figure 2.1.

### 2.10.2 PLOTTING THE SECOND CONSTRAINT

Some of the feasible solutions to one constraint in an LP model usually will not satisfy one or more of the other constraints in the model. For example, the point  $(X_1, X_2) = (200, 0)$  satisfies the first constraint in our model, but it does not satisfy the second constraint, which requires that no more than 1,566 labor hours be used (because  $9 \times 200 + 6 \times 0 = 1,800$ ). So, what values for  $X_1$  and  $X_2$  will satisfy both of these

**FIGURE 2.1**

*Graphical representation of the pump constraint*

constraints simultaneously? To answer this question, we also need to plot the second constraint on the graph. This is done in the same manner as before—by locating two points on the boundary line of the constraint and connecting these points with a straight line.

The boundary line for the second constraint in our model is given by:

$$9X_1 + 6X_2 = 1,566 \quad 2.27$$

If  $X_1 = 0$  in equation 2.27, then  $X_2 = 1,566/6 = 261$ . So, the point  $(0, 261)$  must fall on the line defined by equation 2.27. Similarly, if  $X_2 = 0$  in equation 2.27, then  $X_1 = 1,566/9 = 174$ . So, the point  $(174, 0)$  also must fall on this line. These two points are plotted on the graph and connected with a straight line representing equation 2.27, as shown in Figure 2.2.

The line drawn in Figure 2.2 representing equation 2.27 is the boundary line for our second constraint. To determine the area on the graph that corresponds to feasible solutions to the second constraint, we again need to test a point on either side of this line to see if it is feasible. The point  $(X_1, X_2) = (0, 0)$  satisfies  $9X_1 + 6X_2 \leq 1,566$ . Therefore, all points on the same side of the boundary line satisfy this constraint.

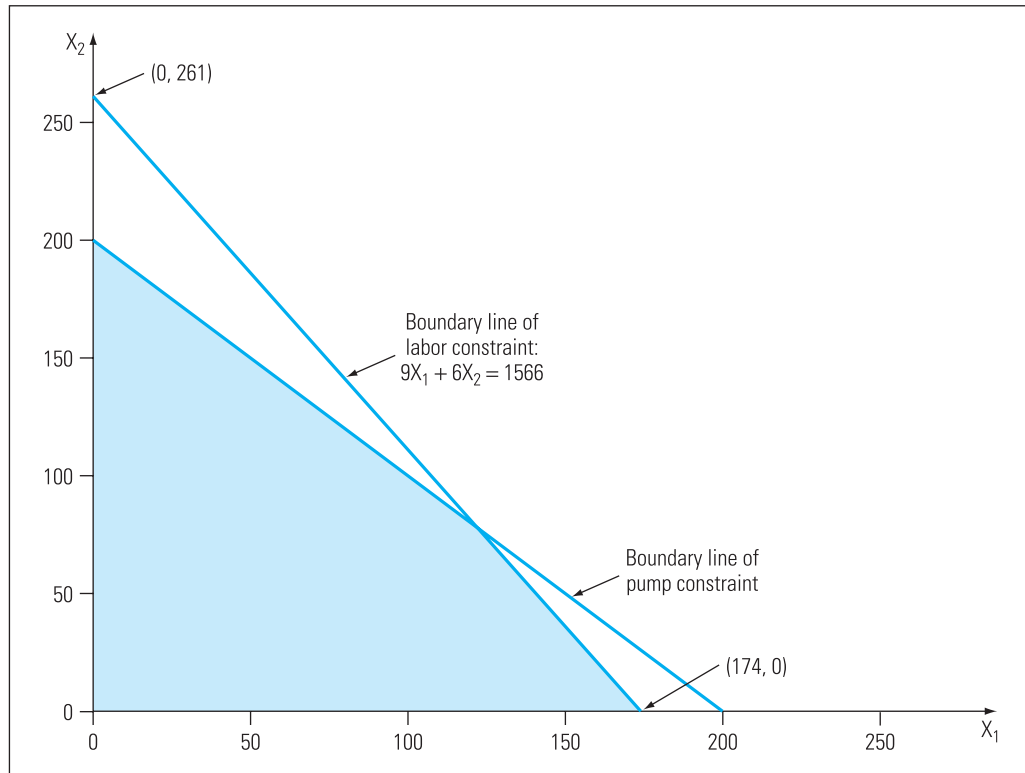
### 2.10.3 PLOTTING THE THIRD CONSTRAINT

To find the set of values for  $X_1$  and  $X_2$  that satisfies all the constraints in the model, we need to plot the third constraint. This constraint requires that no more than 2,880 feet of tubing be used in producing the hot tubs. Again, we will find two points on the graph that fall on the boundary line for this constraint and connect them with a straight line.



**FIGURE 2.2**

Graphical representation of the pump and labor constraints



The boundary line for the third constraint in our model is:

$$12X_1 + 16X_2 = 2,880 \quad 2.28$$

If  $X_1 = 0$  in equation 2.28, then  $X_2 = 2,880/16 = 180$ . So, the point  $(0, 180)$  must fall on the line defined by equation 2.28. Similarly, if  $X_2 = 0$  in equation 2.28, then  $X_1 = 2,880/12 = 240$ . So, the point  $(240, 0)$  also must fall on this line. These two points are plotted on the graph and connected with a straight line representing equation 2.28, as shown in Figure 2.3.

Again, the line drawn in Figure 2.3 representing equation 2.28 is the boundary line for our third constraint. To determine the area on the graph that corresponds to feasible solutions to this constraint, we need to test a point on either side of this line to see if it is feasible. The point  $(X_1, X_2) = (0, 0)$  satisfies  $12X_1 + 16X_2 \leq 2,880$ . Therefore, all points on the same side of the boundary line satisfy this constraint.

#### 2.10.4 THE FEASIBLE REGION

It is now easy to see which points satisfy all the constraints in our model. These points correspond to the shaded area in Figure 2.3, labeled “Feasible Region.” The **feasible region** is the set of points or values that the decision variables can assume and simultaneously satisfy all the constraints in the problem. Take a moment now to carefully compare the graphs in Figures 2.1, 2.2, and 2.3. In particular, notice that when we added the second constraint in Figure 2.2, some of the feasible solutions associated with the first constraint were eliminated because these solutions did not satisfy the second constraint. Similarly, when we added the third constraint in Figure 2.3, another portion of the feasible solutions for the first constraint was eliminated.