Simulation Modeling using @RISK

Updated for **Version 4**

Wayne L. Winston

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Preface

Many excellent simulation texts have been written during the last twenty years. Most of them concentrate on teaching students how to simulate queuing and inventory systems or other systems where bottlenecks occur. These texts also require students to write simulation programs using a language such as C or Fortran or a canned simulation program such as ARENA, PROMODEL, or GPSS. Certainly "bottleneck" simulations are of great importance, but the typical MBA will probably go into a finance or marketing job where bottleneck simulations are of little interest.

Many Fortune 500 firms are adopting simulation as the method for doing capital budgeting and analyzing the introduction of new products. Wall Street uses simulation daily to price complex, "exotic" derivatives. Fortunately most finance and marketing simulations can easily be performed in a spreadsheet using the spreadsheet add-in @RISK.

Purpose

Simulation Modeling Using @RISK introduces MBAs and advanced undergraduates to spreadsheet business simulation models. Each chapter includes a virtually self-contained discussion of an interesting business model that can be simulated with @RISK. We run the gamut from determining the price of financial derivatives to modeling the evolution of a company's brand share over time. We also give a brief treatment of spreadsheet simulation of inventory and queuing models. Each section contains step-by-step instructions on how to perform the simulation. The examples are drawn from students' course work in finance, marketing, and production.

Prior to the first edition, the book was used for four years in a highly successful elective management science course at Indiana University. Students enjoy the material, find it useful for enhancing their spreadsheet and modeling skills, and a description of the course looks good on their resumes.

The text includes a full-functioning student version of the @RISK program and all the book's models. Over 100 problems are included. A disk containing solutions to the problems is available to adopters.

New to This Edition

This new edition includes @RISK 4.0 and step-by-step instructions for each example in the book.

Potential Uses

The text is suitable for several types of situations:

1) As a supplement to a "bottleneck"-oriented simulation text in a typical one-semester simulation course.

2) Many MBA (and some undergraduate programs) are going to the eight-week class as their primary means of instruction. This book is ideally suited as a self-contained text for an eight-week course in business applications of simulation.

3) There are many exciting applications of simulation to finance. Corporate finance or investment instructors who wish to use simulation in their classes should find this book suitable as a course supplement.

4) Executives who want to understand spreadsheet simulation models should find the book an ideal vehicle for mastering spreadsheet simulation through self-study.

The only chapters that must be covered are 1–8, 13, 14, 16, and 20. Once these chapters are covered, the remaining chapters are all self-contained and may be covered in any order. During the eight weeks I spend on simulation, I cover Chapters 1–8, 10, 13, 14, and 16–22. This provides a course that emphasizes finance applications. An eight-week course emphasizing operations management applications would consist of Chapters 1–16, 20, and 22–24.

Acknowledgments

This book has been lots of fun to write. I would like to thank all my K510 students for their support of my teaching approach. The following reviewers offered valuable suggestions: Erne Houghton, The University of Sydney; Fred S. Hulme, Baylor University; Joseph McCarthy, Bryant College; Eleni Pratsini, University of Miami, Ohio; Thomas J. Schriber, University of Michigan; Carl R. Schultz, University of New Mexico; and Carlton H. Scott, University of California, Irvine. Curt Hinrichs' support of the project is greatly appreciated. Finally, I would like to thank Sam McLafferty of the Palisade Corporation for allowing us to include the great @RISK program in the book.

Please write, phone, or e-mail me if you have any questions or ideas for chapters that should be included in future editions.

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Contents

Chapter 1: What Is Simulation?

In many situations an **analytic model** exists that a decision maker can use to make an optimal decision. By an analytic model we mean a mathematical equation(s) that will, for given values of certain inputs, enable the user of the model to determine the value of important outputs. For example, consider a bank in which all customers wait in a single line for the first available teller. Consider the following inputs:

1) Average number of arrivals per hour
2) Average number of customers that a teller can serve in an hour
3) Number of servers

Under some reasonable conditions, some mathematical equations (see Chapter 22 of Winston 1994) can be derived. If we know Inputs 1–3, then these equations can be used to compute the following outputs:

1) Expected time a customer spends in line
2) Expected time a customer spends in the bank
3) Expected number of customers in line
4) For any *t*, the probability that a given customer will spend more than *t* hours in line.

We can use this model to see how the behavior of the bank responds to a change in the number of tellers or the average time a teller requires to serve a customer. This analysis can eventually lead to a decision about the number of tellers the bank should hire.

In many situations in which uncertainty is present, however, it is difficult (or impossible) to build a tractable analytic model that will yield useful information to a decision maker. For example, consider a supermarket in which customers may freely jockey between express and regular checkout lines. In this case there are no formulas that enable us to determine Outputs 1–4 from knowledge of Inputs 1–3. Simulation is used in situations like this where no tractable mathematical model exists.

In most instances, a **simulation model** is a computer model that imitates a real-life situation. The meaning of the word *imitates* will become clear to readers as they work through the examples of this book. Often the simulation model can provide a decision maker with important information.

For our supermarket illustration, a simulation model might help us answer questions such as the following:

- If an additional express lane were added, how much would the average waiting time of a customer decrease?
- Currently baggers help people load their groceries into their car. How much would the average waiting time of a customer decrease if we eliminated this practice?
- How does the number of checkout counters needed to provide adequate service vary during the day?

This information would be a great aid in scheduling employees.

A simulation can be used to determine how sensitive a system is to changes in operating conditions. For example, if the store experiences a 20% increase in business, what will happen to the average time customers must wait for service?

A simulation model also allows the user to determine an "optimal" operating policy. For example, the supermarket could use the simulation to determine the relationship between number of open registers and expected time a customer spends waiting in line. Then this relationship (along with the cost of opening a register) could be used to determine for any customer arrival rate the number of registers that need to be open to minimize the expected cost per unit time.

1.1 Actual Applications of Simulation

There are many published applications of simulation. Several are listed in the references at the end of the chapter. We now briefly describe several applications of simulation.

Burger King (see Swart and Donno 1981) developed a simulation model for its restaurants. This model was used to justify business decisions such as these:

- Should a restaurant open a second drive-through window?
- How much would customer waiting time increase if a new sandwich is added to the menu?

Many companies (Cummins Engine, Merck, Procter & Gamble, Kodak, and United Airlines, to name a few) use simulation (often referred to as **risk analysis**; see Hertz 1964) to determine which of several possible investment projects should be chosen.

Consider a situation in which a company must choose a single investment. If the future cash flows for each investment project are known with certainty, then most companies advocate choosing the investment with the largest net present value (NPV). If future cash flows are not known with certainty, however, then it is not clear how to choose among competing projects.

Using simulation, you can obtain a frequency distribution, or **histogram**, for the NPV of a project. You can answer questions such as these:

- Which project is riskiest?
- What is the probability that an investment will yield at least a 20% return?
- What is the probability that the investment will have an NPV of less than or equal to $1 billion?

As we will see in Chapter 6, contrary to what many finance textbooks assert, the investment with the largest expected net present value may not always be the best investment!

To illustrate the use of simulation in corporate finance, we refer the reader to the article "A New Tool to Help Managers" in the May 30, 1994, issue of *Fortune*. This article describes a simulation model (referred to as a Monte Carlo model) that was used by Merck (the world's largest pharmaceutical company) to determine whether Merck should pay $6.6 billion to acquire Medco, a mail-order drug company. The model contained inputs concerning the following:

- Possible futures of the U.S. health-care system such as a single-payer system, universal coverage, and so forth
- Possible future changes in the mix of generic and brand-name drugs
- A probability distribution of profit margins for each product
- Assumptions about how competitors would behave after a merger with Medco

The Merck model contained thousands of equations. A simulation was performed to see how the merger would perform under various scenarios. As Merck's CFO, Judy Lewent, said,

> Monte Carlo techniques are a very, very powerful tool to get a more intelligent look at a range of outcomes. It's almost never useful in this kind of environment to build a single bullet forecast.

Merck's model indicated that the merger with Medco would benefit Merck no matter what type of health insurance plan (if any) the federal government enacted.

1.2 What's Ahead?

In this book we will explain how to use spreadsheets to build simulation models of diverse situations. We will use the Excel add-in @RISK to perform most of our simulations. When readers have worked through the examples in the book, they should have accomplished the following:

- Set up simulation models of complex real-world situations.
- Run a simulation model with @RISK.
- Interpret the simulation output and relate it to the real-world situation that is being modeled.

The book is laid out in twenty-four chapters. In Chapter 2 we define and discuss random numbers, the building blocks of simulation. In Chapter 3 we show how to use the random number generation and data table capabilities of spreadsheets to simulate a simple newsvendor problem (e.g., how many calendars should a bookstore order in the presence of uncertain demand?). This chapter also introduces some important ideas involved in the statistical analysis of simulations.

In Chapters 4 and 5 we introduce the extensive capabilities of @RISK by using @RISK to simulate several variations of the newsvendor problem.

In Chapter 6 we show how a simulation model can be used to estimate the probability distribution of the NPV earned by an investment project. We see that the project with the highest expected NPV may not always be the best project.

All firms need to set up a cash budget. In Chapter 7 we show how simulation can help a firm answer questions such as the following:

- What is the probability that the firm will lose money this year?
- What is the probability that the firm will have to borrow more than $1 million in the next year?

All firms must determine the proper production capacity level for their products. Too little capacity results in lost profits, whereas too much capacity causes the firm to incur excessive fixed costs. In Chapter 8 we show how past sales data can be used to build a simulation model that enables a firm to determine the proper capacity level.

Suppose you are bidding on a contract against several bidders. If you bid too low you will probably get the contract, but make very little money on the contract. If you bid too high, you will probably not get the contract. How much should you bid? Bidding problems are discussed in Chapter 9.

Suppose your goal is to shoot a cannon and hit a target 1 mile away. If your first cannonball falls 20 feet short of the target, most people feel that you should adjust the settings of the cannon so that the next shot will go longer. However, this strategy usually fails. In Chapter 10 we discuss Edwards Deming's famous funnel experiment. As we shall see, the moral of the funnel experiment is "If it isn't broken, don't fix it."

Suppose one company's product meets specifications 100% of the time and another company meets specifications 95% of the time. Which company's product is of higher quality? Unless you understand the Taguchi loss function (discussed in Chapter 11), the answer may surprise you.

In Chapter 12 we show how simulation can be used to extend critical path analysis of project networks so that the following questions can be answered:

- What is the probability distribution of the time needed to complete a project?
- What is the probability that a given activity will be a critical activity?

In Chapter 13 we show how simulation can be used to determine the probability of winning for games such as craps. Also in this chapter, the student will learn how to use nested IF statements to express complex relationships.

A key decision in manufacturing is how often to replace machinery. In Chapters 14 and 15 we show how simulation can be used to analyze the effectiveness of various replacement policies. In Chapter 14 we also illustrate the use of spreadsheet LOOKUP tables.

Simulation is widely used in the investment industry. In Chapters 16–19 we show how to simulate the returns on portfolios involving stocks, options, futures, and bonds. For example, we can answer questions such as these:

- What is the probability that an investor's portfolio will earn an annual return exceeding 10%?
- What is the probability that an investor's portfolio will lose more than 20% during the course of a year?
- How do we determine the interest rate risk associated with a portfolio of bonds?

Derivatives (such as futures and stock options) are securities that derive their value from the price of an underlying asset. In Chapter 16 we show how to use simulation to determine the fair market value of a derivative such as a put or call option (see Hull 2000). In Chapter 17 we show how to use @RISK to price so-called exotic options whose value depends on the price of the stock at different points in time. For example, an Asian option's value depends on the average weekly price over a 52-week period.

A company's market share is uncertain. In Chapters 20 and 21 we show how to use simulation to determine how marketing decisions such as advertising, promotions, and product characteristics influence market share and profit. In Chapter 21 we show how @RISK can be used to generate correlated random variables.

Manufacturing companies often assess the quality of a shipment from a supplier by sampling the shipment. In Chapter 22 we show how simulation can be used to determine the effectiveness of various sampling plans.

Companies facing uncertain product demand must make two important inventory decisions:

- How low should the firm let its inventory go before it reorders the product?
- What should be the size of each order?

In Chapter 23 we show how @RISK can be used to answer these questions.

How does a customer's wait in line depend on the arrival rate of customers and the service time distribution of customers? Such questions are considered in our discussion of @RISK queuing models in Chapter 24.

After you have worked through the book, you will be able to apply simulation to a wide variety of situations involving decision making under uncertainty. You should even have gained enough expertise to formulate a model of many situations not covered in the book. We urge you to attempt as many homework problems as possible. Group A problems are fairly routine, whereas Group B problems are more difficult. Have fun!

1.3 Simulation Models Versus Analytic Models

It must be emphasized that a simulation model provides only an approximate answer to a problem. For example, in Chapter 13 we implement a spreadsheet simulation of craps. For the 900 times we played craps, we won 47.7% of the time. This is an estimate of the probability of winning at craps. By analytic methods (using the theory of Markov chains) we can show that the actual probability of winning at craps is .493. If we ran our craps simulation many, many times, it can be shown that we would closely approximate the actual probability of winning at craps, but we could never be sure we had found the exact probability of winning at craps. For this reason, an analytic solution is preferable to a simulation solution. The problem is that for many situations an analytic solution does not exist.

We have also found that most business school students have difficulty understanding the mathematical underpinnings of analytic solutions to situations involving uncertainty. Simulation, on the other hand, is a very intuitive tool that students take to easily. Whereas only the best students can develop an analytic solution to a new situation, most students have little trouble extending the simulation approach to a new situation. In fact, many students who have studied the material in this manuscript have gone on to build useful @RISK models of *real* problems facing Fortune 500 corporations. I'm sure you will follow in their footsteps!

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