THE FRANK J. FABOZZI SERIES

SIMULATION AND OPTIMIZATION IN FINANCE

+ Web Site

Modeling with MATLAB, @RISK, or VBA

DESSISLAVA A. PACHAMANOVA • FRANK J. FABOZZI

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Pachamanova and Frank J. Fabozzi

Simulation and Optimization in Finance

Modeling with MATLAB, @RISK, or VBA

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Dessislava A. Pachamanova
To my husband, Christian, and my children,
Anna and Coleman

Frank J. Fabozzi
To my wife, Donna, and my children, Patricia,
Karly, and Francesco

Preface

Simulation and Optimization in Finance: Modeling with MATLAB, @RISK, or VBA is an introductio to two quantitative modeling tools—simulation and optimization—and their applications in financi risk management. In addition to laying a solid theoretical foundation and discussing the practic implications of applying simulation and optimization techniques, the book uses simulation an optimization as a means to clarify difficult concepts in traditional risk models in finance, and explain how to build financial models with software. The book covers a wide range of applications and written in a theoretically rigorous way, which will make it of interest to both practitioners an academics. It can be used as a self-study aid by finance practitioners and students who have som fundamental background in calculus and statistics, or as a textbook in finance and quantitativ methods courses. In addition, this book is accompanied by a web site where readers can go download an array of supplementary materials. Please see the “Companion Web Site” section towar the end of this Preface

CENTRAL THEMES

Simulation and Optimization in Finance contains 18 chapters in five parts. Part One, Fundament Concepts, provides background on the most important finance, simulation, optimization, an optimization under uncertainty concepts that are necessary to understand the financial applications later parts of the book. Part Two, Portfolio Optimization and Risk Measures, reviews the theory an practice of equity and fixed income portfolio management, from classical frameworks, such as mean variance optimization, to recent advances in the theory of risk measurement, such as value-at-risk an conditional value-at-risk estimation. Part Three, Asset Pricing Models, discusses classical static an dynamic models for asset pricing, such as factor models and different types of random walks. Pa Four, Derivative Pricing and Use, introduces important types of financial derivatives, shows how the value can be determined by simulation, reviews advanced simulation methods for efficie implementation of pricing algorithms, and discusses how derivatives can be employed for portfol risk management and return enhancement purposes. Part Five, Capital Budgeting Decisions, review capital budgeting decision models, including real options, and discusses applications of simulatio and optimization in capital budgeting under uncertainty.

It is important to note that there often are multiple numerical methods that can be used to handle particular problem in finance. Many of the topics listed here, especially asset and derivative pricin models, however, have traditionally been out of reach for readers without advanced degrees mathematics because understanding the theory behind the models and the advanced methods f modeling requires years of training. Simulation and optimization formulations provide a framewor within which very challenging concepts can be explained through simple visualization and hands-o implementation, which makes the material accessible to readers with little background in advance mathematics.

SOFTWARE

In our experience, teaching and learning cannot be effective without examples and hands- ~~implementation. Most of the chapters in this book have "Software Hints" sections that explain how~~ use the applications under discussion. The examples themselves are posted on the companion web si discussed later in the Preface.

In *Simulation and Optimization in Finance*, we assume basic familiarity with spreadsheets a Microsoft Excel, and use two different platforms to implement concepts and algorithms: the Palisa Decision Tools Suite and other Excel-based software (@RISK[1], Solver[2], VBA[3]), and MATLAB Readers do not need to learn both; they can choose one or the other, depending on their level familiarity and comfort with spreadsheet programs and their add-ins versus programmi environments such as MATLAB. Specifically, users with finance and social science backgroun typically prefer an Excel-based implementation, whereas users with engineering and quantitati backgrounds prefer MATLAB. Some tasks and implementations are easier in one environment than the other, and students who have used this book in the form of lecture notes in the past have felt the benefitted from learning about both platforms. Basic introductions to the software used in the book a provided in Appendices B through D, which can be accessed at the companion web site.

Although Excel and other programs are used extensively in this book, we were wary of turning into a software tutorial. Our goal was to combine concepts and tools for implementing them in effective manner without necessarily covering every aspect of working in a specific softwa environment.

We have, of course, attempted to implement all examples correctly. That said, the code is provide "as is" and is intended only to illustrate the concepts in this book. Readers who use the code f financial decision making are doing so at their own risk. For full information on the terms of use the code, please see the licensing information in each file on the companion web site.

The following web sites provide useful information about Palisade Decision Tools Suite a MATLAB. Readers can download trial versions or purchase the software.

- Palisade Decision Tools Suite, http://www.palisade.com
- MATLAB, http://www.mathworks.com

TEACHING

Simulation and Optimization in Finance: Modeling with MATLAB, @RISK, or VBA covers finance a applied quantitative methods theory, as well as a wide range of applications. It can be used as textbook for upper-level undergraduate or lower-level graduate (such as MBA or Master's) courses applied quantitative methods, operations research, decision sciences, or financial engineering, finan courses in derivatives, investments or corporate finance with an emphasis on modeling, or as supplement in a special topics course in quantitative methods or finance. In addition, the book can used as a self-study aid by students, or serve as a reference for student projects.

The book assumes that the reader has no background in finance or advanced quantitative metho except for basic calculus and statistics. Most quantitative concepts necessary for understanding t notation or applications are introduced and explained in endnotes, software hints, and onli appendices. This makes the book suitable for readers with a wide range of backgrounds a particularly so as a textbook for classes with mixed audiences (such as engineering and busine students). In fact, the idea for this book project matured after years of searching for an appropria text for a course with a mixed audience that needed a good reference for both finance and quantitativ methods topics.

Every chapter follows the same basic outline. The concepts are introduced in the main body of tl chapter, and illustrations are provided. At the end of each chapter, there is a summary that contains tl most important discussion points. A Software Hints section provides instructions and code fo implementing the examples in the chapter with both Excel-based software and MATLAB.

On the companion web site, there are practice sections for selected chapters. These sections featu examples that complement those found in their respective chapters. Some practice sections conta cases as well. The cases are more in-depth exercises that focus on a particular practical application n necessarily covered in the chapter, but possible to address with the tools introduced in that chapter.

We recommend that before proceeding with the main body of this book, readers consult the fou appendices on the companion web site, namely Appendix A, Basic Linear Algebra Concept Appendix B, Introduction to @RISK; Appendix C, Introduction to MATLAB; and Appendix I Introduction to Visual Basic for Applications. They provide background on basic mathematical ar programming concepts that enable readers to understand the implementation and the code provided the Software Hints sections.

The chapters that introduce fundamental concepts all contain code that can be found on tl companion web site. Some more advanced chapters do not; the idea is that at that point students a sufficiently familiar with the applications and models to put together examples on their own based (the code provided in previous chapters. The material in the advanced chapters can be used also templates for student course projects.

A typical course may start with the material in Chapters 2 through 6. It can then cover the materi in Chapters 7 through 9, which focus on applications of optimization for single-period optim portfolio allocation and risk management. The course then proceeds with Chapters 11 through 1 which introduce static and dynamic asset pricing models through simulation as well as derivativ pricing by simulation, and ends with Chapters 17 and 18, which discuss applications of simulation ar optimization in capital budgeting. Chapters 10, 15, and 16 represent good assignments for fin projects because they use concepts similar to other chapters, but in a different context and without much implementation detail.

Depending on the nature of the course, only some of Chapters 2 through 6 will need to be covere explicitly; but the information in these chapters is useful in case the instructor would like to assign tl chapters as reading for students who lack some of the necessary background for the course.

COMPANION WEB SITE

Additional material for *Simulation and Optimization in Finance* can be downloaded by visitir www.wiley.com/go/pachamanova. **Please log in to the web site using this password: finance12** The files on this companion web site are organized in the following folders: Appendices, Code, ar Practice. The Appendices directory contains Appendix A through D. The Practice directory contair practice problems and cases indexed by chapter. (Practice problems are present for Chapters 4–16, 1 and Appendix D, as a bonus to the content in the book. Please note, however, that only problems ar offered without solutions.) The Code directory has Excel and MATLAB subdirectories that contai files for use with the corresponding software. The latter files are referenced in the main body of tl book and the Software Hints sections for selected chapters.

The companion web site is a great resource for readers interested in actually implementing t ~~concepts in the book. Such readers should begin by reading the applicable appendix on the companio~~ web site with information about the software they intend to use, then read the main body of a chapte the chapter’s Software Hints, and, finally, the Excel model files or MATLAB code in the cod directory on the companion web site.

NOTES

1 An Excel add-in for simulation.

2 An Excel add-in for optimization that comes standard with Excel.

3 Visual Basic for Applications—a programming language that can be used to automate tasks in Excel.

4 A programming environment for mathematical and engineering applications that provides users with tools for number array manipulation, statistical estimation, simulation, optimization, and others.

About the Authors

Dessislava A. Pachamanova is an Associate Professor of Operations Research at Babson Colleg where she holds the Zwerling Term Chair. Her research interests lie in the areas of portfolio ris management, simulation, high-performance optimization, and financial engineering. She h published a number of articles in operations research, finance, and engineering journals, an coauthored the Wiley title *Robust Portfolio Optimization and Management* (2007). Dessislava academic research is supplemented by consulting and previous work in the financial industr including projects with quantitative strategy groups at WestLB and Goldman Sachs. She holds an A in mathematics from Princeton University and a PhD in operations research from the Sloan School Management at MIT.

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CHAPTER 1

Introduction

Finance is the application of economic principles to decision making, and involves the allocation money under conditions of uncertainty. Investors allocate their funds among financial assets in ord to accomplish their objectives. Business entities and government at all levels raise funds by issui claims in the form of debt (e.g., loans and bonds) or equity (e.g., common stock) and, in turn, inve those funds. Finance provides the framework for making decisions as to how those funds should obtained and then invested.

The field of finance has three specialty areas: (1) capital markets and capital market theory, (financial management, and (3) portfolio management. The specialty field of *capital markets* a *capital market theory* focuses on the study of the financial system, the structure of interest rates, a the pricing of risky assets. *Financial management*, sometimes called *business finance*, is the special area of finance concerned with financial decision making within a business entity. Although we ofte refer to financial management as *corporate finance*, the principles of financial management also app to other forms of business and to government entities. Moreover, not all nongovernment busine enterprises are corporations. Financial managers are primarily concerned with investment decisio and financing decisions within business. Making investment decisions that involve long-term capit expenditures is called *capital budgeting. Portfolio management* deals with the management individual or institutional funds. This specialty area of finance—also commonly referred to *investment management*, *asset management*, and *money management*—involves selecting investment strategy and then selecting the specific assets to be included in a portfolio.

A critical element common to all three specialty areas in finance is the concept of risk. Measuri and quantifying risk is critical for the fair valuation of an asset, the selection of capital budgeti projects in financial management, the selection of individual asset holdings, and portfol construction in portfolio management. The field of *risk management* includes the identificatio measurement, and control of risk in a business entity or a portfolio.

Sophisticated mathematical tools have been employed in order to deal with the risks associated wi individual assets, capital budgeting projects, and selecting assets in portfolio construction. The use such tools is now commonplace in the financial industry. For example, in portfolio manageme practitioners run statistical routines to identify risk factors that drive asset returns, scenario analys to evaluate the risk of their positions, and algorithms to find the optimal way to allocate assets execute a trade.

This book focuses on two quantitative tools—optimization and simula-tion—and discusses the applications in finance. In this chapter, we briefly introduce these two techniques, and provide overview of the structure of the book.

OPTIMIZATION

Optimization is an area in applied mathematics that, most generally, deals with efficient algorithm for ~~finding an optimal solution among a set of solutions that satisfy given constraints.~~ The fir application of optimization in finance was suggested by Harry Markowitz in 1952, in a seminal pap that outlined his mean-variance optimization framework for optimal asset allocation. Some oth classical problems in finance that can be solved by optimization algorithms include:

- Is there a possibility to make riskless profit given market prices of related securities? (Thi opportunity is called an *arbitrage opportunity* and is discussed in Chapter 13.)
- How should trades be executed so as to reach a target allocation with minimum transaction costs?
- Given a limited capital budget, which capital budgeting projects should be selected?
- Given estimates for the costs and benefits of a multistage capital budgeting project, at wha stage should the project be expanded/abandoned?

Traditional optimization modeling assumes that the inputs to the algorithms are certain, but there also a branch of optimization that studies the optimal decision under uncertainty about the paramete of the problem. Fast and reliable algorithms exist for many classes of optimization problems, an advances in computing power have made optimization techniques a viable and useful part of th standard toolset of the financial modeler.

SIMULATION

Simulation is a technique for replicating uncertain processes, and evaluating decisions under uncerta conditions. Perhaps the earliest application of simulation in finance was in financial managemen Hertz (1964) argued that traditional valuation methods for investments omitted from consideration important component: the fact that many of the inputs were inaccurate. He suggested modeling th uncertainty through probability-weighted scenarios, which would allow for obtaining a range outcomes for the value of the investments and associated probabilities for each outcome. These ide were forgotten for a while, but have experienced tremendous growth in the last two decade Simulation is now used not only in financial management, but also in risk management and pricing different financial instruments. In portfolio management, for example, the correlated behavior different factors over time is simulated in order to estimate measures of portfolio risk. In pricin financial options or complex securities, such as mortgage-backed securities, paths for the underlyin risk factors are simulated; and the fair price of the securities is estimated as the average of th discounted payoffs over those paths. We will see numerous examples of such simulation application in this book.

Simulation bears some resemblance to an intuitive tool for modifying original assumptions financial models—what-if analysis—which has been used for a long time in financial applications. *what-if analysis*, each uncertain input in a model is assigned a range of possible values—typicall best, worst, and most likely value—and the modeler analyzes what happens to the decision under the scenarios. The important additional component in simulation modeling, however, is that there a probabilities associated with the different outcomes. This allows for obtaining an additional piece information compared to what-if analysis: the probabilities that specific final outcomes will happe Probability theory is so fundamental to understanding the nature of simulation analysis, that w include a chapter (Chapter 3) on the most important aspects of probability theory that are relevant f simulation modeling.

OUTLINE OF TOPICS

The book is organized as follows. Part One (Chapters 2 through 6) provides a background on th fundamental concepts used in the rest of the book. Part Two (Chapters 7 through 10) introduces th classical underpinnings of modern portfolio theory, and discusses the role of simulation an optimization in recent developments. Part Three (Chapters 11 and 12) summarizes important mode for asset pricing and asset price dynamics. Understanding how to implement these models is prerequisite for the material in Part Four (Chapters 13 through 16), which deals with the pricing financial derivatives, mortgage-backed securities, advanced portfolio management, and advance simulation methods. Part Five (Chapters 17 and 18) discusses applications of simulation an optimization in capital budgeting and real option valuation. The four appendices (on the companio web site) feature introductions to linear algebra concepts, @RISK, MATLAB, and Visual Basic fo Applications in Microsoft Excel.

We begin by listing important finance terminology in Chapter 2. This includes basic theory o interest; terminology associated with equities, fixed income securities, and trading; calculation of ra of return; and useful concepts in fixed income, such as spot rates, forward rates, yield, duration, an convexity.

Chapter 3 is an introduction to probability theory, distributions, and basic statistics. We revie important probability distributions, such as the normal distribution and the binomial distributio measures of central tendency and variability, and measures of strength of codependence betwee random variables. Understanding these concepts is paramount to understanding the simulation mode discussed in the book.

Chapter 4 introduces simulation as a methodology. We discuss determining inputs for an interpreting output from simulation models, and explain the methodology behind generating rando numbers from different probability distributions. We also touch upon recent developments in efficien random number generation, which provides the foundation for the advanced simulation methods f financial derivative pricing discussed in Part Four of the book.

In Chapter 5 we provide a practical introduction to optimization. We discuss the most commonl encountered types of optimization problems in finance, and elaborate on the concept of “difficul versus “easy” optimization problems. We introduce optimization duality and describe intuitively ho optimization algorithms work. Illustrations of simple finance problems that can be handled wi optimization techniques are provided, including examples of optimal portfolio allocation and cas flow matching from the field of portfolio management, and capital budgeting from the field financial management. We also discuss dynamic programming—a technique for solving optimizatio problems over multiple stages. Multistage optimization is used in Chapters 13 and 18. Finally, v review available software for different types of optimization problems and portfolio optimization particular.

Classical optimization methods treat the parameters in optimization problems as deterministic an accurate. In reality, however, these parameters are typically estimated through error-prone statistic procedures or based on subjective evaluation, resulting in estimates with significant estimation error The output of optimization routines based on poorly estimated inputs can be at best useless and worst seriously misleading. It is important to know how to treat uncertainty in the estimates of inp parameters in optimization problems. Chapter 6 provides a taxonomy of methods for optimizatio ~~under uncertainty. We review the main ideas behind dynamic programming under uncertainty~~ stochastic programming, and robust optimization, and illustrate the methods with examples. We wi encounter these methods in applications in Chapters 9, 13, 14, and 18.

Chapter 7 uses the concept of optimization to introduce the mean-variance framework that is th foundation of modern portfolio theory. We also present an alternative framework for optimal decisio making in investments—expected utility maximization—and explain its relationship to mea variance optimization.

Chapter 8 extends the classical mean-variance portfolio optimization theory to a more gener mean-risk setting. We cover the most commonly used alternative risk measures that are generall better suited than variance for describing investor preferences when asset return distributions a skewed or fat-tailed. We focus on two popular portfolio risk measures— value-at-risk and condition value-at-risk—and show how to estimate them using simulation. We also formulate the problems o optimal asset allocation under these risk measures using optimization.

Chapter 9 provides an overview of practical considerations in implementing portfolio optimizatio We review constraints that are most commonly faced by portfolio managers, and show how t formulate them as part of optimization problems. We also show how the classical framework fo portfolio allocation can be extended to include transaction costs, and discuss index trackin optimization of trades across multiple client accounts, and robust portfolio optimization techniques minimize estimation error.

While Chapter 9 focuses mostly on equity portfolio management, Chapter 10 discusses th specificities of fixed income (bond) portfolio management. Many of the same concepts are used equity and fixed income portfolio management (which are defined in Chapter 2); however, fixe income securities have some fundamental differences from equities, so the concepts cannot always b applied in the same way in which they would be applied for stock portfolios. We review classic measures of bond portfolio risk, such as duration, key rate duration, and spread duration. We discus bond portfolio optimization relative to a benchmark index. We also give examples of ho optimization can be used in liability-driven bond portfolio strategies such as immunization and cas flow matching.

Chapter 11 transitions from the topic of portfolio management to the topic of asset pricing, an introduces standard financial models for explaining asset returns—the Capital Asset Pricing Mod (CAPM), which is based on the mean-variance framework described in Chapter 7, the Arbitrag Pricing Theory (APT), and factor models. Such models are widely used in portfolio management- they not only help to model the processes that drive asset prices, but also substantially reduce th computational burden for statistical estimation and asset allocation optimization algorithms.

Chapter 12 focuses on dynamic asset pricing models, which are based on random processes. W examine the most commonly used types of random walks, and illustrate their behavior throug simulation. The models discussed include arithmetic, geometric, different types of mean-revertin random walks, and more advanced hybrid models. In our presentation in the chapter, we assume th changes in asset prices happen at discrete time intervals. At the end of the chapter, we extend th concept of a random walk to a random process in continuous time.

The concepts introduced in Chapter 12 are reused multiple times when we discuss valuation complex securities and multistage investments in Parts Four and Five of the book. The first chapter Part Four, Chapter 13, is an introduction to the topic of financial derivatives. It lists the main class

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