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Simulation Modeling and Analysis

Third Edition

仿真建模与分析

第 3 版

Averill M. Law
W. David Kelton

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PREFACE

The goal of this third edition of *Simulation Modeling and Analysis* remains the same as for the first two editions: To give a comprehensive and state-of-the-art treatment of all the important aspects of a simulation study, including modeling, simulation software, model verification and validation, input modeling, random-number generators, generating random variates and processes, statistical design and analysis of simulation experiments, and to highlight major application areas such as manufacturing. The book strives to motivate intuition about simulation and modeling, as well as to present them in a technically correct yet clear manner. There are many examples and problems throughout, as well as extensive references to the simulation and related literature for further study.

The book can serve as the primary text for a variety of courses; for example:

- A first course in simulation at the junior, senior, or beginning-graduate-student level in engineering, manufacturing, business, or computer science (Chaps. 1 through 4, and parts of Chaps. 5 through 9). At the end of such a course, the student will be prepared to carry out complete and effective simulation studies, and to take advanced simulation courses.
- A second course in simulation for graduate students in any of the above disciplines (most of Chaps. 5 through 12). After completing this course, the student should be familiar with the more advanced methodological issues involved in a simulation study, and should be prepared to understand and conduct simulation research.
- An introduction to simulation as part of a general course in operations research or management science (parts of Chaps. 1, 3, 5, 6, and 9).

For instructors who have adopted the book for use in a course, we have made available for download from the web site http://www.mhhe.com/lawkelton a variety of teaching support materials. These include a comprehensive set of solutions to the Problems, lecture slides, and all the computer code (including all the simulation models) in the book. Adopting instructors should contact their local McGraw-Hill representative for login identification and a password to gain access to the material on this site; local representatives can be identified by calling 1-800-338-3987, sending e-mail to mhcom@mcgraw-hill.com, or by the representative locator at http://www.mhhe.com.

The book can also serve as a definitive reference for simulation practitioners and researchers. To this end we have included detailed discussion of many practical examples gleaned in part from our own experiences and applications. We have also made major efforts to link subjects to the relevant research literature, both in print and on the web, and to keep this material up to date.

Prerequisites for understanding the book are knowledge of basic calculus-based probability and statistics (though we give a review of these topics in Chap. 4), and some experience with computing. For Chaps. 1 and 2 the reader should also be familiar with a general-purpose programming language like FORTRAN or C. Occasionally we will also make use of a small amount of linear algebra or matrix theory. More advanced or technically difficult material is in starred sections or in appendixes to chapters. At the beginning of each chapter we suggest sections for a first reading of that chapter.

We have made many changes and additions to (and some deletions from) the second edition of the book to arrive at this third edition, but the organization has remained the same, as has the basic outline and numbering of the chapters. Following current practice in programming languages, we have deleted Pascal from Chap. 1 (though the Pascal code remains available for download from http://www.mhhe.com/lawkelton), which now contains FORTRAN 77 and C; we have also moved the code in Chap. 2 from FORTRAN 77 to C (again, the older FORTRAN 77 programs are on the above web site), with the help of Dr. Gregory Glockner's C version of the original FORTRAN SIMLIB code from the first two editions of this book, on which our C version of simlib in Chap. 2 is based. Because simulation software has made great advances since the second edition, Chap. 3 has been completely rewritten to make it current. Since Chap. 4 is basic background on probability and statistics, it is largely unchanged. The practice of model validation has improved markedly, and so Chap. 5 has been extensively rewritten and updated to reflect this. For Chap. 6 on input modeling, we have introduced some important new distributions, included discussion of recent developments in modeling and estimating correlated structures and processes, as well as discussed other recent research. New and greatly improved random-number generators are discussed in Chap. 7, and code is given (and can be downloaded from the web site). We have updated the material in Chap. 8 on variate and process generation, including recent work on generating correlated structures and processes corresponding to their specification as discussed in Chap. 6. The statistical design-and-analysis methods of Chaps. 9 through 12 have been expanded and updated to reflect current practice and recent research, including a much-enhanced discussion of optimizing simulation models in Chap. 12. The discussion of simulating manufacturing systems in Chap. 13 has been brought up to date in terms of current practice and new software. Unlike the first two editions, we have collected the references for all the chapters together at the end of the book, to make this material more compact and convenient to the reader; we have also listed with each reference the page number(s) in the book on which each reference item is cited, to aid the reader in identifying potentially helpful linkages between topics in different parts of the book (and to eliminate the need for a separate author index). A large and thorough subject index enhances the book's value as a reference.

Going back over 20 years ago to our beginning work on the first edition of this book, and coming right up to the present day with our efforts on this third edition, there have been many, many talented and generous people and supportive organizations who have provided significant (sometimes essential) help to us in writing, rewriting, and maintaining this book. Especially for preparation of this third edition, we are deeply grateful to Mr. Michael G. McComas of Averill M. Law & Associates for his invaluable input to many different aspects of the book, including modeling, analysis, research, computing, and reading our sometimes-very-rough drafts. Substantial and valuable support for preparation of this edition, and of earlier editions, has come from the Defense Modeling and Simulation Office, the University of Cincinnati's Department of Quantitative Analysis and Operations Management, the University of Minnesota Supercomputer Institute, the Office of Naval Research, and the Army Research Office's funding of the Mathematics Research Center at the University of Wisconsin. The reviewers for this edition, Ken Bauer (Air Force Institute of Technology), Jeff Cochran (Arizona State University), Dave Goldsman (Georgia Tech), and Mansooreh Mollaghasemi (University of Central Florida), provided extremely helpful and in-depth feedback on our plans and drafts, which greatly strengthened both content and exposition; this added to the already-valuable reviews of earlier editions done by Osman Balci (Virginia Tech), Wafik Iskander (West Virginia University), Barry Nelson (Northwestern University), James Riggs (deceased), Pirooz Vakilli (Boston University), and Frank Wolf (Western Michigan University). Knowing that we will certainly inadvertently commit grievous errors of omission, we would nonetheless like to thank the following individuals for their help in various ways: Kaushik Balakrishnan, Russ Barton, Aarti Bhaté-Felsheim, Bill Biles, Diane Bischak, Eberhard Blümel, Jason Boesel, Dan Brunner, Jeff Camm, Marne Cario, John Carson, John Charnes, Jack Chen, Russell Cheng, Youngsoo Chun, Bob Crain, Bob Diamond, Ed Dudewicz, George Fishman, Paul Fishwick, Ben Fox, Mike Fu, Richard Fujimoto, Fred Glover, Jorge Haddock, Phil Heidelberger, Jim Henriksen, Sheldon Jacobson, Mark Johnson, Doug Jones, Peter Kalish, Jim Kelly, Steve Kimbrough, Jack Kleijnen, Gary Kochenberger, Lloyd Koenig, Manuel Laguna, Steve Lavenberg, Pierre L'Ecuyer, Marty Levy, Peter Lorenz, Herb Morgan, Doug Morrice, Joe Murray, Dick Nance, David Nicol, Bill Nordgren, David Norman, Jean O'Reilly, Jim Palmer, Dennis Pegden, Tyler Phillips, Alan Pritsker, John Ramberg, Ian Rawles, Chuck Reilly, Steve Roberts, Ralph Rogers, Ed Russell, Deb Sadowski, Randy Sadowski, Safi Safizadeh, Paul Sanchez, Susan Sanchez, Bob Sargent, Bruce Schmeiser, Tom Schriber, Lee Schruben, Thomas Schulze, Murali Shanker, Bob Shannon, Marlene Smith, Karen Stanley, Dave Sturrock, Jim Swain, Mike Taaffe, Laurel Travis, Kerim Tumay, Brian Unger, Willem Van Groenendaal, Thomas Varley, Ed Watson, Peter Welch, Jim Wilson, Brian Wood, Simone Youngblood, and Enver Yücesan.

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CHAPTER 1

Basic Simulation Modeling

Recommended sections for a first reading: 1.1 through 1.4 (except 1.4.8), 1.7, 1.9

1.1 THE NATURE OF SIMULATION

This is a book about techniques for using computers to imitate, or *simulate*, the operations of various kinds of real-world facilities or processes. The facility or process of interest is usually called a *system*, and in order to study it scientifically we often have to make a set of assumptions about how it works. These assumptions, which usually take the form of mathematical or logical relationships, constitute a *model* that is used to try to gain some understanding of how the corresponding system behaves.

If the relationships that compose the model are simple enough, it may be possible to use mathematical methods (such as algebra, calculus, or probability theory) to obtain *exact* information on questions of interest; this is called an *analytic* solution. However, most real-world systems are too complex to allow realistic models to be evaluated analytically, and these models must be studied by means of simulation. In a *simulation* we use a computer to evaluate a model *numerically*, and data are gathered in order to *estimate* the desired true characteristics of the model.

As an example of the use of simulation, consider a manufacturing company that is contemplating building a large extension onto one of its plants but is not sure if the potential gain in productivity would justify the construction cost. It certainly would not be cost-effective to build the extension and then remove it later if it does not work out. However, a careful simulation study could shed some light on the question by simulating the operation of the plant as it currently exists and as it *would* be *if* the plant were expanded.