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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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Simulation Modeling and Analysis

THIRD EDITION

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国际知名大学原版教材

——信息技术学科和电气工程学科系列

出 版 说 明

郑大钟

清华大学信息科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在的“课程体系老化，内容落伍时代，本研层次不清”的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济体制的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1)书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2)教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3)教材属于在近5年内所出版的新书或新版书。(4)教材适合于作为我国大学相应课程的教材或主要教学参考书。(5)每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6)教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版。为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工

程师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

"Simulation Modeling and Analysis"

(第3版)

影印版序

凡是从事离散事件系统仿真的人员对 Averill M. Law 与 W. David Kelton 合著的"Simulation Modeling and Analysis"一书应该不会陌生。该书从 1982 年第一版问世以来,随着计算机技术与仿真技术的发展,不断修订发行。继 1991 年第二版发行,9 年后即 2000 年第三版又由 McGraw-Hill Higher Education 正式发行。

由于每一版都是在前一版基础上的进一步完善与扩充,都有反映最新成果的内容,因而始终吸引着该领域的读者。据我从美国同行了解,该书是美国许多大学相关课程教学的主要参考书之一,也是进入该领域的研究人员最畅销的自学教材之一。

该书(第三版)分为13章。从体系结构上可分为四部分。第一部分(第1~3章)从系统角度介绍了离散事件系统仿真的概念、建模方法以及实现技术(商用仿真软件),使读者不但对这类系统的仿真建模有一个总体了解,并从应用角度掌握这门技术。为使读者深入系统地理解与掌握离散事件系统仿真技术,第二部分(第4~8章)讨论离散事件系统仿真建模的基础理论和方法,包括数学基础(概率与数理统计),如何由观测数据确定随机变量模型,如何产生仿真模型中的随机变量等。离散事件系统仿真输出分析一直是该书的最具特色的内容,这反映在第三部分(第9~12章)。由于离散事件系统的随机性,任何一次仿真运行只是随机系统随机动态过程的一次模拟。该部分首先讨论了所谓"单系统"的输出数据分析,然后讨论了所谓"多系统"的分析比较技术,进而讨论就该类系统仿真的实验设计技术。第四部分(第13章)是综合应用,以制造系统为例,讨论如何将前面各章讨论的内容用于制造系统的仿真。

该书的主要特点是:

(1)通用:与许多其他类似的书籍不同,该书着眼于离散事件系统仿真的原理、方法学的阐述,而不依赖于某一种商业化的仿真软件,因此适宜于作为教材使用。

(2)体系结构合理:该书从基本概念出发,通过实际例子加以阐述与讨论,由浅入深,逐渐展开,符合认识规律。在每一章,书中明确哪些是基本的,哪些

是需进一步掌握的，便于读者选择。

(3)内容丰富、详略适宜：对于基本概念、方法、技术，力求深入；对最新的技术发展，则着眼于方向性说明。

(4)富有特色：如前所述，离散事件系统仿真输出分析技术是该书最具特色的部分，作者将该领域的各类问题从理论、方法、技术以及实验进行了系统的介绍，而这是离散事件系统仿真与连续系统仿真技术的主要区别之一，往往也是一般读者易于进入的误区。

(5)适于教学与自学：每章内容有大量的例题，且均附有大量的练习题，这对于教学及学生理解与掌握是非常必要而重要的。

较之第一、第二版，第三版不但从章节的编排、内容的组织方面作了较大的调整，而且新增加了不少内容，如并行仿真、分布式仿真、跨因特网基于 Web 的仿真，在模型的校验(verification)、致效(validation)、致信(credible)、方差减少技术(variance reduction)等方面都有不少新的研究成果充实到该版中。

肖田元

清华大学自动化系

2000 年 10 月

ABOUT THE AUTHORS

Averill M. Law is President of Averill M. Law & Associates, Inc. (Tucson, Arizona), a company specializing in simulation consulting, training, and software. He was previously Professor of Decision Sciences at the University of Arizona and Associate Professor of Industrial Engineering at the University of Wisconsin. He has a Ph.D. and an M.S. in industrial engineering and operations research from the University of California at Berkeley, an M.A. in mathematics from California State University at Long Beach, and a B.S. in mathematics from Pennsylvania State University.

Dr. Law has been a simulation consultant to organizations such as Andersen Consulting, ARCO, Boeing, Booz Allen & Hamilton, Cellular One, Compaq, Defense Modeling and Simulation Office, Kaiser Aluminum, Kimberly-Clark, M&M/Mars, SAIC, Sandia National Labs, 3M, Tropicana, U.S. Air Force, U.S. Army, U.S. Post Office, Veteran's Administration, and Xerox. He has presented more than 320 simulation short courses in 17 countries, including in-house seminars for ALCOA, AT&T, Coca-Cola, CSX, GE, GM, IBM, Intel, Lockheed Martin, Lucent Technologies, MCI, Motorola, NASA, National Security Agency, Nortel, 3M, Time Warner, UPS, U.S. Air Force, U.S. Army, U.S. Navy, Whirlpool, and Xerox.

He is the codeveloper of the ExpertFit distribution-fitting software, which automates the selection of simulation input probability distributions. ExpertFit is used by more than 1600 organizations worldwide. He also developed the videotapes *Simulation of Manufacturing Systems* and *How to Conduct a Successful Simulation Study*.

Dr. Law is the author (or coauthor) of three books and numerous papers on simulation, manufacturing, operations research, statistics, and communications networks. His article "Statistical Analysis of Simulation Output Data" was the first invited feature paper on simulation to appear in a major research journal. His series of papers on the simulation of manufacturing systems won the 1988 Institute of Industrial Engineers' best publication award. During his academic career, the Office of Naval Research supported his simulation research for 8 consecutive years. He was President of the INFORMS College on Simulation. He wrote a regular column on simulation for *Industrial Engineering* during 1990 and 1991. In 1994 he was the keynote speaker at the first major simulation conference held in Asia (Tokyo).

W. David Kelton is Professor of Quantitative Analysis and Operations Management in the College of Business Administration at the University of Cincinnati, where he teaches courses in simulation, stochastic processes, operations research, and statistics. He received a B.A. in mathematics from the University of Wisconsin-Madison, an M.S. in mathematics from Ohio University, and M.S. and Ph.D. degrees in industrial engineering from Wisconsin. He was formerly on the faculty at the University of Minnesota, The University of Michigan, and Kent State University. Visiting posts have included Wisconsin, the Institute for Advanced Studies in Vienna, and the Warsaw School of Economics.

His research interests and publications are in the probabilistic and statistical aspects of simulation, applications of simulation, statistical quality control, and stochastic models. His papers have appeared in *Operations Research, Management Science*, the *INFORMS Journal on Computing, IIE Transactions, Naval Research Logistics*, and the *Journal of the American Statistical Association*, among others. In addition to this book, he is co-author of *Simulation with Arena*, with Randall P. Sadowski and Deborah A. Sadowski, published by WCB/McGraw-Hill in 1998. Grants have come from General Motors, Ford, Standard Oil, Cray Research, Apple Computer, Hennepin County (Minnesota), the Minneapolis Citizens Council on Crime and Justice, the Minnesota Center for Urban and Regional Affairs, Vaughn Communications, Cincinnati Sub-Zero, Omnicare Inc., University of Cincinnati Hospitals, Revco Drug Stores, McKesson Automated Pharmacy Systems, Select Tool & Die Corporation, and the U.S. Department of Education.

He is Editor-in-Chief of the *INFORMS Journal on Computing*, has served as Simulation Area Editor for *Operations Research* and the *INFORMS Journal on Computing*, Simulation Department Co-Editor for *IIE Transactions*, Associate Editor for *Operations Research*, the *Journal of Manufacturing Systems*, and *Simulation*, and was Guest Co-Editor for a special simulation issue of *IIE Transactions*. He regularly reviews for many journals, NSF, and NSERC. In 1994 he received the IIE Operations Research Division Award, in 1997 a Meritorious Service Award from *Operations Research*, and in 1998 the INFORMS College on Simulation Distinguished Service Award. He was President of the TIMS College on Simulation, and has served as the INFORMS co-representative to the Winter Simulation Conference Board of Directors, where he served as Board Chair for 1998. In 1987 he was Program Chair for the WSC, and in 1991 was General Chair. He has consulted for NASA, Volvo, General Dynamics, Harper-Grace Hospitals, Pillsbury, 3M, Johnson Controls, Systems Modeling, SuperValu, SEMATECH, the Minneapolis Public Housing Authority, and the Vienna (Austria) Chamber of Commerce.

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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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Simulation Modeling and Analysis

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