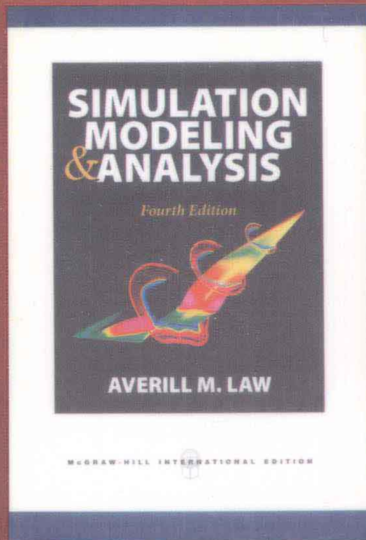
McGraw Hill Education

清华版双语教学用书



仿真建模与分析

（第4版）

Simulation Modeling and Analysis

(Fourth Edition)

Averill M. Law

清华大学出版社

Averill M. Law
EISBN: 978-0-07-125519-6

图书在版编目(CIP)数据

仿真建模与分析 = Simulation Modeling and Analysis：第 4 版：英文 /(美)劳尔(Law, A.M.)著. —北京：清华大学出版社，2009.9
(清华版双语教学用书)
ISBN 978-7-302-20406-0

Ⅰ. 仿… Ⅱ. 劳… Ⅲ. 离散系统(自动化)－系统仿真－双语教学－教材－英文 Ⅳ. TP391.9

中国版本图书馆 CIP 数据核字（2009）第 103924 号

责任编辑： 王一玲

责任印制： 孟凡玉

出版发行： 清华大学出版社　　**地　址：** 北京清华大学学研大厦 A 座
http://www.tup.com.cn　　**邮　编：** 100084
社　总　机： 010-62770175　　**邮　购：** 010-62786544
投稿与读者服务： 010-62776969, c-service@tup.tsinghua.edu.cn
质　量　反　馈： 010-62772015, zhiliang@tup.tsinghua.edu.cn
印 刷 者： 清华大学印刷厂
装 订 者： 三河市新茂装订有限公司
发 行 者： 全国新华书店
开　本： 175×245　　**印　张：** 47　　**插页：** 1
版　次： 2009 年 9 月第 1 版　　**印　次：** 2009 年 9 月第 1 次印刷
印　数： 1~3000
定　价： 69.00 元

本书如存在文字不清、漏印、缺页、倒页、脱页等印装质量问题，请与清华大学出版社出版部联系调换。联系电话：010-62770177 转 3103　　产品编号：026164-01

仿真建模与分析

第 4 版序

肖田元

仿真建模与分析(Simulation Modeling & Analysis)的第四版问世了。正如作者在序言中所言，与第三版一样，第四版对离散事件系统仿真研究的所有重要方面给出了综合性的最新论述，包括建模、仿真软件、模型校验和确认、输入建模、随机数发生器、随机变量与随机过程的产生、统计设计与仿真实验分析，以及像制造这一类主要工业领域的应用等。

那么，第四版的内容有何新变化和新特点呢？较之第三版，第四版基本保持了第三版的体系结构，因而仍具有第三版的许多特点，但在内容上做了许多调整。所有章节的相关内容的最新进展均得到补充，给出了最新论述和结果，各章的习题也做了相应的调整和补充，其中主要包括：

(1) 将第三版中所有 FORTRAN 程序删除了，以反映当前主流编程语言是 C 语言这样一种情况，使相关章节变得更为简练。对 FORTRAN 仍感兴趣的读者，可以从 www.mhhe.com/Law 网址下载相关代码。

(2) 对仿真软件的介绍进行了重新改写，以反映第三版以来，国际上流行的几种仿真软件如 Arena、Extend 等的最新进展。

(3) 近些年来，模型的校验、验证及确认技术（VV&A）得到广泛的注意并取得了许多进展，因此作者对该部分进行了重新编写，例如，第四版大大扩充了关于如何由仿真模型的输出数据来确定仿真模型的有效性，包括与已有系统的输出进行比较、与专家的意见比较，以及与其它模型进行比较等技术。

(4) 关于随机数发生器，第四版详细讨论了反馈移位寄存器发生器（第三版称为 Tausworthe 发生器）的实现，包括 LFSR、GFSR 以及 TGFSR 等。

(5) 关于随机变量的产生，第四版增加了一种新舍选法——均匀比法（ratio-of-uniforms method）。

(6) 在多系统比较方面，第四版修订了排序及选择程序（ranking and selection procedure），以允许公共随机数（CRN）用于跨系统配置等，对基于公共随机数的方差减少技术的实现给出了更为详细且实用的讨论。

(7) 第四版对实验设计和优化给出了更为详细的讨论，特别是，书中结合实例，

讨论了实际仿真如何实现实验设计和优化问题。

总之，正如我在第三版的序言中指出的，“仿真建模与分析”一书每一版都是在前一版的基础上进行进一步完善与扩充，都有反映最新成果的内容。第四版同样如此，既保留了第三版的特点，又对第三版进行了丰富与完善，相信仍然会吸引着该领域的读者。清华大学出版社适时地引进该书的第四版，对我国开展离散事件系统仿真的研究、学习来说无疑是非常有益的。

肖田元
清华大学自动化系
2008年2月

ABOUT THE AUTHOR

Averill M. Law is President of Averill M. Law & Associates, Inc. (Tucson, Arizona), a company specializing in simulation training, consulting, 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–Madison. 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 Accenture, ARCO, Boeing, Booz Allen & Hamilton, Defense Modeling and Simulation Office, Hewlett-Packard, Kaiser Aluminum, Kimberly-Clark, M&M/Mars, Navy Modeling and Simulation Office, SAIC, Sandia National Labs, Swedish Defence Materiel Administration, 3M, Tropicana, U.S. Air Force, U.S. Army, U.S. Post Office, Veteran's Administration, and Xerox. He has presented more than 400 simulation short courses in 17 countries, including in-house seminars for ALCOA, AT&T, Boeing, Caterpillar, Coca-Cola, CSX, GE, GM, IBM, Intel, Lockheed Martin, Los Alamos National Lab, Missile Defense Agency, Motorola, NASA, National Security Agency, Nortel, Northrop Grumman, 3M, Time Warner, UPS, U.S. Air Force, U.S. Army, U.S. Navy, Whirlpool, and Xerox.

He is the developer of the ExpertFit distribution-fitting software, which automates the selection of simulation input probability distributions. ExpertFit is used by more than 2000 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, operations research, statistics, manufacturing, 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. He has been the keynote speaker at simulation conferences worldwide.

PREFACE

The goal of this fourth edition of *Simulation Modeling and Analysis* remains the same as that for the first three 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, I have made available for download from the website www.mhhe.com/law a variety of teaching support materials. These include a comprehensive set of solutions to the Problems, lecture PowerPoint slides, and all the computer code for the simulation models and random-number generators in Chaps. 1, 2, and 7. 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 or by using the representative locator at www.mhhe.com.

The book can also serve as a definitive reference for simulation practitioners and researchers. To this end I have included detailed discussion of many practical examples gleaned in part from my own experiences and consulting projects. I 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 (although I 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 such as C. Occasionally I will also make use of a small amount of linear algebra or matrix theory. More advanced or technically difficult material is located in starred sections or in appendixes to chapters. At the beginning of each chapter, I suggest sections for a first reading of that chapter.

I have made numerous changes and additions to (and some deletions from) the third edition of the book to arrive at this fourth edition, but the organization has remained the same, as have the basic outline and the numbering of the chapters. Following current practice in programming languages, I have deleted FORTRAN from Chap. 1, which now contains C. (However, the FORTRAN code remains available for download from www.mhhe.com/law.) Chapter 2 on modeling complex systems has not changed. Chapter 3 has been rewritten to reflect the current state of the art in simulation software. Since Chap. 4 is basic background on probability and statistics, it is largely unchanged. The practice of model validation has improved considerably, and so Chap. 5 has been rewritten and updated to reflect this. For Chap. 6 on input modeling, I have expanded greatly my discussion of how to model a source of system randomness in the absence of corresponding data, and I also discuss current research on a number of other topics. New and greatly improved random-number generators are discussed in Chap. 7, and code is given (and can be downloaded from the website); a more comprehensive discussion of testing random-number generators is also given. I have updated the material in Chap. 8 on variate and process generation, including the introduction of the general-purpose ratio-of-uniforms method for generating random values from continuous and discrete distributions. The statistical design-and-analysis methods of Chaps. 9 through 12 have been expanded and updated extensively to reflect current practice and recent research. In particular, Chap. 9 contains a comprehensive discussion of the latest methods for estimating the steady-state mean of a simulated system, as well as new material on constructing confidence intervals for probabilities and percentiles. The discussion of ranking-and-selection procedures in Chap. 10 has been brought up to date to reflect newer methods that allow common random numbers (CRN) to be used across different system configurations. Chapter 11 gives a more detailed and practical discussion of how to implement the variance-reduction technique CRN in practice. In Chap. 12, I give a much more comprehensive and self-contained discussion of classical design of experiments and response-surface methodology, with a particular discussion of how to implement these techniques in the context of simulation modeling. Several examples of the application of simulation-based optimization are also given. The discussion of simulating manufacturing systems in Chap. 13 has been brought up to date in terms of the latest simulation-software packages. The references for all the chapters are collected together at the end of the book.

I would first like to thank my former coauthor David Kelton for his numerous contributions to the first three editions of the book; his extensive knowledge of simulation and great writing ability had a profound impact on the quality of the book. The reviewers for the fourth edition—Christos Alexopoulos (Georgia Institute of Technology), Russell Barton (Pennsylvania State University), Benita Beamon (University of Washington), Chun-Hung Chen (George Mason University), Russell Cheng (University of Southampton), Joan Donohue (University of South Carolina), Sarah Douglas (University of Oregon), Adel Elmaghraby (University of Louisville), Shane Henderson (Cornell University), Seong-Hee Kim (Georgia Institute of Technology), Turgay Korkmaż (University of Texas at San Antonio), Pierre L'Ecuyer (Université de Montréal), Robert Pavur (University of North Texas), Francisco Ramis (Universidad del Bio-Bio), Stephen Robinson (University of Wisconsin–Madison), Ihsan Sabuncuoglu (Bilkent University), Paul Savory (University of Nebraska–Lincoln), Jeffrey Smith (Auburn University), and Omer Tsimhoni (University of Michigan)—provided extremely helpful and in-depth feedback on my plans and drafts, which greatly strengthened both the content and the exposition. Knowing that I will certainly inadvertently commit grievous errors of omission, I would nonetheless like to thank the following individuals for their help in various ways: Chris Alspaugh, Sigrun Andradóttir, Jay April, Jerry Banks, A. J. Bobo, John Carson, Stephen Chick, George Fishman, Richard Fujimoto, James Gentle, Charles Harrell, James Henriksen, Wolfgang Hormann, Sheldon Jacobson, James Kelly, Jack Kleijnen, David Krahl, Eamonn Lavery, Steffi Law, Larry Leemis, Josef Leydold, Anna Marjanski, Michael McComas (deceased), Charles McLean, William Nordgren, Rochelle Price, Stuart Robinson, Paul Sanchez, Susan Sanchez, Robert Sargent, Lee Schruben, Andrew Seila, Douglas Soultz, Natalie Steiger, David Sturrock, Andrew Waller, Preston White, Frederick Wieland, Thomas Willemain, James Wilson, and Ronald Wolff.

Averill M. Law
Tucson, AZ

CONTENTS

CHAPTER 1

Basic Simulation Modeling

Recommended sections for a first reading: 1.1 through 1.4 (except 1.4.7), 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.