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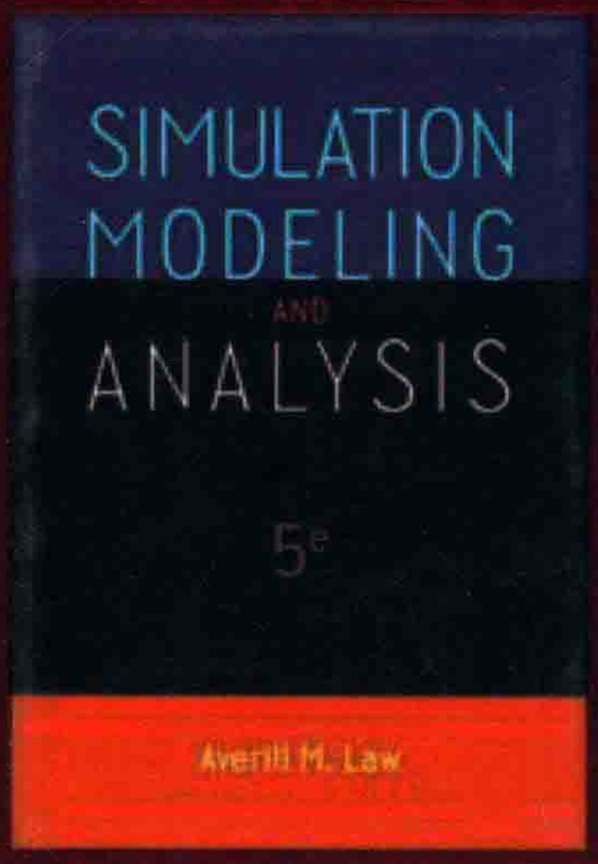

仿真建模与分析

（第5版）

Simulation Modeling and Analysis

Fifth Edition

[美] Averill M. Law 著

范文慧 选译

清华大学出版社

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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 presented more than 525 simulation and statistics short courses in 19 countries, including onsite seminars for ALCOA, AT&T, Boeing, Caterpillar, Coca-Cola, CSX, Defence Research and Development Canada, GE, GM, IBM, Intel, Lockheed Martin, Los Alamos National Lab, Missile Defense Agency, Motorola, NASA, National Security Agency, NATO (Netherlands), Northrop Grumman, Norwegian Defence Research Establishment, Sasol Technology (South Africa), 3M, Time Warner, UPS, U.S. Air Force, U.S. Army, U.S. Forces Korea, U.S. Navy, Verizon, Whirlpool, and Xerox. He has been a simulation consultant to organizations such as Accenture, Boeing, Booz Allen & Hamilton, ConocoPhillips, Defense Modeling and Simulation Office, Hewlett-Packard, Kaiser Aluminum, Kimberly-Clark, M&M/Mars, SAIC, Sandia National Labs, Swedish Defence Materiel Administration, 3M, Tropicana, U.S. Air Force, U.S. Army, U.S. Marine Corps, U.S. Navy, Veteran's Administration, 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 was awarded the INFORMS Simulation Society Lifetime Professional Achievement Award in 2009. He 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, namely, *Operations Research*. 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 eight 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.

For Steffi, Heather, Adam, and Brian, and in memory of Sallie and David.

前　言

《仿真建模与分析(第5版)》的目标和前4版仍然保持一致：提供仿真研究的所有重要方面综合的与最新的进展，包括建模、仿真软件、模型校验与确认、输入建模、随机数发生器、随机变量与过程的产生、统计设计与仿真实验的分析，以及像制造这样的最重要的应用领域。本书力图促进直观理解仿真与建模，并以技术上正确但更清晰的方式来阐述它们。全书有许多例子和习题，并有广泛的仿真参考文献和著作以用于进一步研究。

本书可作为各种课程的主教材，例如：

(1) 工程、制造、商业或计算机科学专业的大学三年级、高年级或新入学的研究生水平的第一门仿真课(第1章到第4章以及第5章到第9章和第13章的一部分)。在结束该课程时，学生要准备进行完整而有效的仿真学习，并进行高级仿真课程的学习。

(2) 上述任意学科的研究生的第二门仿真课程(第5章到第12章的大部分)。完成该课程后，学生应该熟悉仿真学习中更高级的方法学问题，还应该准备理解并进行仿真研究。

(3) 仿真导论，作为运筹学和管理科学中通用课程的一部分(第1章、第3章、第5章、第6章、第9章及第13章的一部分)。

对用本书作为教材的教师来说，可以从网址 www. mhhe. com/law 下载各种教学辅助支撑资料。这些资料包括习题答案的全集，第1章、第2章和第7章中的全部仿真模型和随机数发生器的计算机代码。采用此书的教师应该与本地的 McGraw-Hill 代表联系获得登录标识和密码，以便能访问该网址的资料。

本书还可以作为仿真产业和研究人员的权威参考书。为此目的，本书对许多来自作者本人实践和咨询项目的实际例子进行了详细讨论。作者还做了巨大努力将主题与相关的研究文献联系起来，既有文字的，也有网上的，并保持这些材料实时更新。理解本书的前提是基本的基于计算的概率与统计学知识(虽然在第4章会复习这些主题)，以及对计算技术有一定了解。对第1章和第2章，读者还应该熟悉通用编程语言，例如 C 语言。偶尔也会用到少量的线性代数或矩阵理论。较深或有技术难度的内容放在标有星号的节中或放在各章的附录中。在每章的开头，给出了应首先阅读该章哪些节的建议。

本书第5版对第4版的内容进行了大量的改动和添加，但结构绝大部分仍然保持相同。我在第一章中删除了第4版其他类型仿真的内容，并将其移到了后面第13章中进行讨论。第2章关于复杂系统建模已经更新，反映了有效事件列表管理的最新研究内容。第3章进行了重写和扩展，反映了仿真软件的最新进展，给出了三个用通用

仿真软件包实现的一个通用的仿真案例。第4章讨论了置信区间与假设检验,做了很大的强化和补充,这一章的概率与统计学的基础知识为后面章节提供了基础。第5章对经常容易误解的校验和标定,做了更为清楚的区别。第6章说明了输入模型和模型到达过程的不确定性的最新进展。第7章提供了最有用的随机数发生器。第8章少量更新了关于随机变量和过程产生的内容。第9章到第12章对许多统计设计与分析方法进行了扩展和更新,以反映当前的实际和近期的研究进展。特别是,第9章综合讨论了用于估计被仿真系统的稳态均值的固定样本长度和序贯最新方法。更新了第10章中排序与选择程序的讨论以反映其较新的、有效的方法,而不是基于传统的一致区间方法。第11章方差减少技术仅有少量改动。在第12章中,给出了广泛得多且独立的经典实验设计与元模型的讨论,还特别强调了元模型和仿真模型。第14章是关于制造系统仿真,内容在本书的网站上,而不是在这本书里,其中关于制造系统仿真应用和最新仿真软件包已经进行了更新。本书增加了第13章,讨论了基于agent的仿真和系统动力学仿真,以及第4版第1章中讨论的其他类型的仿真。本书网站提供了学生版的ExpertFit分布拟合软件,它可以被用来分析第6章中相关例子和问题的数据集。为了方便读者阅读和材料压缩,书后列出了所有参考文献。一个大而全的主题索引增强了本书作为参考用书的价值。

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首先应该感谢本人以前的合作者David Kelton,他对本书的前3版做出了巨大贡献。第5版的评审人员分别阅读了新加的以及重点变化的章节提出了许多有价值的建议,这些在内容和表达两个方面都得到了极大的加强。这些评审人员有:Christos Alexopoulos(佐治亚理工学院),Russell Barton(宾夕法尼亚州立大学),Chun-Hung Chen(乔治梅森大学),Shane Henderson(康奈尔大学),Jack Kleijnen(蒂尔堡大学),Pierre L'Ecuyer(蒙特利尔大学),Charles Macal(阿贡国家实验室),Michael North(阿贡国家实验室)和Douglas Samuelson(InfoLogix公司)。众所周知,本书一定会有不少因疏忽而产生的令人遗憾的错误,虽然如此,本人应该感谢以各种方式给予帮助的以下人员:Wayne Adams, Mark Anderson, Sigrun Andradóttir, Jay April, Robert Axtell, Emmett Beeker, Marco Better, Edmund Bitinas, A. J. Bobo, Andrei Borshchev, Nathanael Brown, John Carson, Loren Cobb, Eric Frisco, David Galligan, Nigel Gilbert, Fred Glover, David Goldsman, Daniel Green, Charles Harrell, Thomas Hayson, James Henriksen, Raymond Hill, Kathryn Hoad, Terril Hurst, Andrew Ilachinski, Jeffrey Joines, Harry King, David Krahl, Emily Lada, Michael Lauren, Steffi Law, Thomas Lucas,

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埃佛里尔 M. 劳

于亚利桑那州图森市

PREFACE

The goal of this fifth edition of *Simulation Modeling and Analysis* remains the same as that for the first four 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 and 13). 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, 9, and 13).

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 number of teaching support materials. These include a comprehensive set of solutions to the Problems 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 a 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 the fourth edition of the book to arrive at this fifth edition, but the organization has remained mostly the same. I have moved the material on other types of simulation from Chap. 1 to a new Chap. 13, which is discussed below. Chapter 2 on modeling complex systems has been updated to reflect the latest research on efficient event-list management. Chapter 3 has been rewritten and expanded to reflect the current state of the art in simulation software. A common example is now given in three of the leading general-purpose simulation packages. The discussion of confidence intervals and hypothesis tests in Chap. 4 has been greatly enhanced, making the chapter a much more self-contained treatment of the basic probability and statistics needed for the remainder of the book. Chapter 5 makes clearer the distinction between validating and calibrating a model, which is often misunderstood. For Chap. 6 on input modeling, the latest developments in accounting for input-model uncertainty and in modeling arrival processes are discussed. Chapter 7 provides recommendations on the best-available random-number generators. Chapter 8 on generating random variates and processes has only had minor updates. Many of 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 fixed-sample-size and sequential methods for estimating the steady-state mean of a simulated system. The discussion of ranking-and-selection procedures in Chap. 10 has been expanded to include newer and more efficient methods that are not based on the classical indifference-zone approach. Chapter 11 on variance-reduction techniques has only had minor changes. In Chap. 12, I give a much more comprehensive and self-contained discussion of design of experiments and metamodeling, with a particular emphasis on what designs and metamodels to use specifically for simulation modeling. The discussion of simulating manufacturing systems is now in a new Chap. 14, which is available on the book's website www.mhhe.com/law, rather than in the book itself. It has been brought up to date in terms of the latest simulation-software packages and uses of simulation for manufacturing applications. There is a *new* Chap. 13 that discusses agent-based simulation and system dynamics, as well as other types of simulation that were previously discussed in Chap. 1 of the fourth edition. A student version of the ExpertFit distribution-fitting software is now available on the book's website; it can be used to analyze the data sets corresponding to the examples and problems in Chap. 6. The references for all the chapters are collected together at the end of the book, to make this material more compact and convenient to the reader. A large and thorough subject index enhances the book's value as a reference.

This text is available as an eBook at www.CourseSmart.com. At CourseSmart you can take advantage of significant savings off the cost of a print textbook, reduce their impact on the environment, and gain access to powerful web tools for learning. CourseSmart eBooks can be viewed online or downloaded to a computer. The eBooks allow readers to do full text searches, add highlighting and notes, and share notes with others. CourseSmart has the largest selection of eBooks available anywhere. Visit www.CourseSmart.com to learn more and to try a sample chapter.

I would first like to thank my former coauthor David Kelton for his numerous contributions to the first three editions of the book. The formal reviewers for the fifth edition were Christos Alexopoulos (Georgia Institute of Technology), Russell Barton (Pennsylvania State University), Chun-Hung Chen (George Mason University), Shane Henderson (Cornell University), Jack Kleijnen (Tilberg University), Pierre L'Ecuyer (Université de Montréal), Charles Macal (Argonne National Lab), Michael North (Argonne National Lab), and Douglas Samuelson (InfoLogix). They each read one new or significantly changed chapter in great detail and made many valuable suggestions. 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: Wayne Adams, Mark Anderson, Sigrun Andradóttir, Jay April, Robert Axtell, Emmett Beeker, Marco Better, Edmund Bitinas, A. J. Bobo, Andrei Borshchev, Nathanael Brown, John Carson, Loren Cobb, Eric Frisco, David Galligan, Nigel Gilbert, Fred Glover, David Goldsman, Daniel Green, Charles Harrell, Thomas Hayson, James Henriksen, Raymond Hill, Kathryn Hoad, Terril Hurst, Andrew Ilachinski, Jeffrey Joines, Harry King, David Krahl, Emily Lada, Michael Lauren, Steffi Law, Thomas Lucas, Gregory McIntosh, Janet McLeavey, Anup Mokashi, Daniel Muller, Rodney Myers, William Nordgren, Ernie Page, Dennis Pegden, David Peterson, Stuart Robinson, Paul Sanchez, Susan Sanchez, Lee Schruben, David Siebert, Jeffrey Smith, David Sturrock, Ali Tafazzoli, Andrew Waller, Hong Wan, Robert Weber, Preston White, and James Wilson.

Averill M. Law
Tucson, AZ

LIST OF SYMBOLS

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