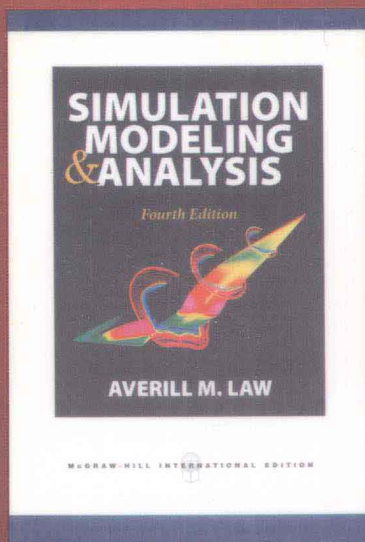


清 华 版 双 语 教 学 用 书



# 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

Copyright © 2007 by The McGraw-Hill Companies, Inc.

Original language published by The McGraw-Hill Companies, Inc. All Rights reserved. No part of this publication may be reproduced or distributed by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

Authorized English language edition jointly published by McGraw-Hill Education (Asia) Co. and Tsinghua University Press. This edition is authorized for sale only to the educational and training institutions, and within the territory of the People's Republic of China (excluding Hong Kong, Macao SAR and Taiwan). Unauthorized export of this edition is a violation of the Copyright Act. Violation of this Law is subject to Civil and Criminal Penalties.

本书英文影印版由清华大学出版社和美国麦格劳-希尔教育出版(亚洲)公司合作出版。此版本仅限在中华人民共和国境内(不包括中国香港、澳门特别行政区及中国台湾地区)针对教育及培训机构之销售。未经许可之出口,视为违反著作权法,将受法律之制裁。

未经出版者预先书面许可,不得以任何方式复制或抄袭本书的任何部分。

北京市版权局著作权合同登记号 图字: 01-2008-0566

本书封面贴有 McGraw-Hill 公司防伪标签,无标签者不得销售。

版权所有,侵权必究。侵权举报电话: 010-62782989 13701121933

### 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](http://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](http://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](http://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 appendices 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](http://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 Korkmaz (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 Krahrl, 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

---

Preface	xv
<b>Chapter 1 Basic Simulation Modeling</b>	<b>1</b>
1.1 The Nature of Simulation	1
1.2 Systems, Models, and Simulation	3
1.3 Discrete-Event Simulation	6
1.3.1 Time-Advance Mechanisms	7
1.3.2 Components and Organization of a Discrete-Event Simulation Model	9
1.4 Simulation of a Single-Server Queueing System	12
1.4.1 Problem Statement	12
1.4.2 Intuitive Explanation	18
1.4.3 Program Organization and Logic	27
1.4.4 C Program	32
1.4.5 Simulation Output and Discussion	39
1.4.6 Alternative Stopping Rules	41
1.4.7 Determining the Events and Variables	45
1.5 Simulation of an Inventory System	48
1.5.1 Problem Statement	48
1.5.2 Program Organization and Logic	50
1.5.3 C Program	53
1.5.4 Simulation Output and Discussion	60
1.6 Steps in a Sound Simulation Study	62
1.7 Other Types of Simulation	65
1.7.1 Continuous Simulation	66
1.7.2 Combined Discrete-Continuous Simulation	68
1.7.3 Monte Carlo Simulation	69
1.8 Advantages, Disadvantages, and Pitfalls of Simulation	71
Appendix 1A: A Primer on Queueing Systems	73
1A.1 Components of a Queueing System	74
1A.2 Notation for Queueing Systems	74
1A.3 Measures of Performance for Queueing Systems	75
Problems	78

<b>Chapter 2</b>	<b>Modeling Complex Systems</b>	<b>85</b>
2.1	Introduction	85
2.2	List Processing in Simulation	86
2.2.1	Approaches to Storing Lists in a Computer	86
2.2.2	Linked Storage Allocation	87
2.3	A Simple Simulation Language: simlib	93
2.4	Single-Server Queueing Simulation with simlib	102
2.4.1	Problem Statement	102
2.4.2	simlib Program	102
2.4.3	Simulation Output and Discussion	107
2.5	Time-Shared Computer Model	108
2.5.1	Problem Statement	108
2.5.2	simlib Program	109
2.5.3	Simulation Output and Discussion	117
2.6	Multiteller Bank With Jockeying	120
2.6.1	Problem Statement	120
2.6.2	simlib Program	121
2.6.3	Simulation Output and Discussion	131
2.7	Job-Shop Model	134
2.7.1	Problem Statement	134
2.7.2	simlib Program	136
2.7.3	Simulation Output and Discussion	147
2.8	Efficient Event-List Manipulation	149
	Appendix 2A: C Code for simlib	150
	Problems	163
 <b>Chapter 3</b>	 <b>Simulation Software</b>	 <b>181</b>
3.1	Introduction	181
3.2	Comparison of Simulation Packages with Programming Languages	182
3.3	Classification of Simulation Software	183
3.3.1	General-Purpose vs. Application-Oriented Simulation Packages	183
3.3.2	Modeling Approaches	184
3.3.3	Common Modeling Elements	186
3.4	Desirable Software Features	187
3.4.1	General Capabilities	187
3.4.2	Hardware and Software Requirements	189
3.4.3	Animation and Dynamic Graphics	189
3.4.4	Statistical Capabilities	191
3.4.5	Customer Support and Documentation	192

3.4.6	Output Reports and Graphics	193
3.5	General-Purpose Simulation Packages	194
3.5.1	Arena	194
3.5.2	Extend	200
3.5.3	Other General-Purpose Simulation Packages	205
3.6	Object-Oriented Simulation	206
<b>Chapter 4</b>	<b>Review of Basic Probability and Statistics</b>	208
4.1	Introduction	208
4.2	Random Variables and Their Properties	208
4.3	Simulation Output Data and Stochastic Processes	220
4.4	Estimation of Means, Variances, and Correlations	222
4.5	Confidence Intervals and Hypothesis Tests for the Mean	226
4.6	The Strong Law of Large Numbers	231
4.7	The Danger of Replacing a Probability Distribution by its Mean	232
	Appendix 4A: Comments on Covariance-Stationary Processes	233
	Problems	233
<b>Chapter 5</b>	<b>Building Valid, Credible, and Appropriately Detailed Simulation Models</b>	237
5.1	Introduction and Definitions	237
5.2	Guidelines for Determining the Level of Model Detail	240
5.3	Verification of Simulation Computer Programs	242
5.4	Techniques for Increasing Model Validity and Credibility	247
5.4.1	Collect High-Quality Information and Data on the System	247
5.4.2	Interact with the Manager on a Regular Basis	249
5.4.3	Maintain a Written Assumptions Document and Perform a Structured Walk-Through	249
5.4.4	Validate Components of the Model by Using Quantitative Techniques	251
5.4.5	Validate the Output from the Overall Simulation Model	253
5.4.6	Animation	258
5.5	Management's Role in the Simulation Process	258
5.6	Statistical Procedures for Comparing Real-World Observations and Simulation Output Data	259
5.6.1	Inspection Approach	259
5.6.2	Confidence-Interval Approach Based on Independent Data	263

5.6.3	Time-Series Approaches	266
5.6.4	Other Approaches	266
	Problems	267
<b>Chapter 6</b>	<b>Selecting Input Probability Distributions</b>	269
6.1	Introduction	269
6.2	Useful Probability Distributions	275
6.2.1	Parameterization of Continuous Distributions	275
6.2.2	Continuous Distributions	276
6.2.3	Discrete Distributions	295
6.2.4	Empirical Distributions	295
6.3	Techniques for Assessing Sample Independence	306
6.4	Activity I: Hypothesizing Families of Distributions	309
6.4.1	Summary Statistics	310
6.4.2	Histograms	312
6.4.3	Quantile Summaries and Box Plots	314
6.5	Activity II: Estimation of Parameters	320
6.6	Activity III: Determining How Representative the Fitted Distributions Are	324
6.6.1	Heuristic Procedures	324
6.6.2	Goodness-of-Fit Tests	334
6.7	The ExpertFit Software and an Extended Example	347
6.8	Shifted and Truncated Distributions	353
6.9	Bézier Distributions	355
6.10	Specifying Multivariate Distributions, Correlations, and Stochastic Processes	356
6.10.1	Specifying Multivariate Distributions	357
6.10.2	Specifying Arbitrary Marginal Distributions and Correlations	360
6.10.3	Specifying Stochastic Processes	361
6.11	Selecting a Distribution in the Absence of Data	364
6.12	Models of Arrival Processes	369
6.12.1	Poisson Processes	369
6.12.2	Nonstationary Poisson Processes	371
6.12.3	Batch Arrivals	373
6.13	Assessing the Homogeneity of Different Data Sets	374
	Appendix 6A: Tables of MLEs for the Gamma and Beta Distributions	375
	Problems	378
<b>Chapter 7</b>	<b>Random-Number Generators</b>	383
7.1	Introduction	383

7.2	Linear Congruential Generators	387
7.2.1	Mixed Generators	389
7.2.2	Multiplicative Generators	390
7.3	Other Kinds of Generators	392
7.3.1	More General Congruences	392
7.3.2	Composite Generators	393
7.3.3	Feedback Shift Register Generators	395
7.4	Testing Random-Number Generators	399
7.4.1	Empirical Tests	400
7.4.2	Theoretical Tests	404
7.4.3	Some General Observations on Testing	408
	Appendix 7A: Portable C Code for a PMMLCG	409
	Appendix 7B: Portable C Code for a Combined MRG	411
	Problems	413
<b>Chapter 8</b>	<b>Generating Random Variates</b>	<b>416</b>
8.1	Introduction	416
8.2	General Approaches to Generating Random Variates	418
8.2.1	Inverse Transform	418
8.2.2	Composition	427
8.2.3	Convolution	430
8.2.4	Acceptance-Rejection	431
8.2.5	Ratio of Uniforms	438
8.2.6	Special Properties	440
8.3	Generating Continuous Random Variates	441
8.3.1	Uniform	442
8.3.2	Exponential	442
8.3.3	$m$ -Erlang	443
8.3.4	Gamma	443
8.3.5	Weibull	446
8.3.6	Normal	447
8.3.7	Lognormal	448
8.3.8	Beta	449
8.3.9	Pearson Type V	450
8.3.10	Pearson Type VI	450
8.3.11	Log-Logistic	450
8.3.12	Johnson Bounded	450
8.3.13	Johnson Unbounded	451
8.3.14	Bézier	451
8.3.15	Triangular	451
8.3.16	Empirical Distributions	452
8.4	Generating Discrete Random Variates	453
8.4.1	Bernoulli	454
8.4.2	Discrete Uniform	454

8.4.3	Arbitrary Discrete Distribution	454
8.4.4	Binomial	459
8.4.5	Geometric	459
8.4.6	Negative Binomial	459
8.4.7	Poisson	460
8.5	Generating Random Vectors, Correlated Random Variates, and Stochastic Processes	460
8.5.1	Using Conditional Distributions	461
8.5.2	Multivariate Normal and Multivariate Lognormal	462
8.5.3	Correlated Gamma Random Variates	463
8.5.4	Generating from Multivariate Families	464
8.5.5	Generating Random Vectors with Arbitrarily Specified Marginal Distributions and Correlations	464
8.5.6	Generating Stochastic Processes	465
8.6	Generating Arrival Processes	466
8.6.1	Poisson Processes	467
8.6.2	Nonstationary Poisson Processes	467
8.6.3	Batch Arrivals	471
Appendix 8A.	Validity of the Acceptance-Rejection Method	471
Appendix 8B	Setup for the Alias Method	472
	Problems	473
<b>Chapter 9</b>	<b>Output Data Analysis for a Single System</b>	<b>479</b>
9.1	Introduction	479
9.2	Transient and Steady-State Behavior of a Stochastic Process	482
9.3	Types of Simulations with Regard to Output Analysis	484
9.4	Statistical Analysis for Terminating Simulations	488
9.4.1	Estimating Means	489
9.4.2	Estimating Other Measures of Performance	498
9.4.3	Choosing Initial Conditions	501
9.5	Statistical Analysis for Steady-State Parameters	502
9.5.1	The Problem of the Initial Transient	502
9.5.2	Replication/Deletion Approach for Means	511
9.5.3	Other Approaches for Means	513
9.5.4	Estimating Other Measures of Performance	527
9.6	Statistical Analysis for Steady-State Cycle Parameters	528
9.7	Multiple Measures of Performance	531
9.8	Time Plots of Important Variables	534
Appendix 9A.	Ratios of Expectations and Jackknife Estimators	536
	Problems	537

<b>Chapter 10</b>	<b>Comparing Alternative System Configurations</b>	<b>542</b>
10.1	Introduction	542
10.2	Confidence Intervals for the Difference Between the Expected Responses of Two Systems	546
10.2.1	A Paired- $t$ Confidence Interval	546
10.2.2	A Modified Two-Sample- $t$ Confidence Interval	548
10.2.3	Contrasting the Two Methods	549
10.2.4	Comparisons Based on Steady-State Measures of Performance	549
10.3	Confidence Intervals for Comparing More than Two Systems	551
10.3.1	Comparisons with a Standard	552
10.3.2	All Pairwise Comparisons	554
10.3.3	Multiple Comparisons with the Best	555
10.4	Ranking and Selection	555
10.4.1	Selecting the Best of $k$ Systems	556
10.4.2	Selecting a Subset of Size $m$ Containing the Best of $k$ Systems	562
10.4.3	Additional Problems and Methods	563
	Appendix 10A: Validity of the Selection Procedures	566
	Appendix 10B: Constants for the Selection Procedures	567
	Problems	569
<b>Chapter 11</b>	<b>Variance-Reduction Techniques</b>	<b>571</b>
11.1	Introduction	571
11.2	Common Random Numbers	572
11.2.1	Rationale	573
11.2.2	Applicability	574
11.2.3	Synchronization	576
11.2.4	Some Examples	580
11.3	Antithetic Variates	588
11.4	Control Variates	594
11.5	Indirect Estimation	601
11.6	Conditioning	603
	Problems	607
<b>Chapter 12</b>	<b>Experimental Design and Optimization</b>	<b>613</b>
12.1	Introduction	613
12.2	$2^k$ Factorial Designs	616
12.3	$2^{k-p}$ Fractional Factorial Designs	630
12.4	Response Surfaces and Metamodels	637
12.5	Simulation-Based Optimization	649

12.5.1 Optimum-Seeking Methods	651
12.5.2 Optimum-Seeking Packages Interfaced with Simulation Software	652
Problems	660
<b>Chapter 13 Simulation of Manufacturing Systems</b>	663
13.1 Introduction	663
13.2 Objectives of Simulation in Manufacturing	664
13.3 Simulation Software for Manufacturing	666
Applications	666
13.3.1 Flexsim	666
13.3.2 ProModel	669
13.3.3 Other Manufacturing-Oriented Simulation Packages	678
13.4 Modeling System Randomness	679
13.4.1 Sources of Randomness	679
13.4.2 Machine Downtimes	681
13.5 A Simulation Case Study of a Metal-Parts Manufacturing Facility	688
13.5.1 Description of the System	689
13.5.2 Overall Objectives and Issues to Be Investigated	689
13.5.3 Development of the Model	690
13.5.4 Model Verification and Validation	691
13.5.5 Results of the Simulation Experiments	692
13.5.6 Conclusions and Benefits	694
Problems	696
Appendix	699
References	703



# 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.