

CONTENTS

List of Symbols	xv
Preface	xvii
Chapter 1 Basic Simulation Modeling	1
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 Parallel/Distributed Simulation and the High Level Architecture	61
1.6.1 Parallel Simulation	62
1.6.2 Distributed Simulation and the High Level Architecture	64
1.7 Steps in a Sound Simulation Study	66
1.8 Other Types of Simulation	70
1.8.1 Continuous Simulation	70
1.8.2 Combined Discrete-Continuous Simulation	72
1.8.3 Monte Carlo Simulation	73
1.8.4 Spreadsheet Simulation	74

1.9	Advantages, Disadvantages, and Pitfalls of Simulation	76
	Appendix 1A: Fixed-Increment Time Advance	78
	Appendix 1B: A Primer on Queueing Systems	79
1B.1	Components of a Queueing System	80
1B.2	Notation for Queueing Systems	80
1B.3	Measures of Performance for Queueing Systems	81
	Problems	84
Chapter 2	Modeling Complex Systems	91
2.1	Introduction	91
2.2	List Processing in Simulation	92
2.2.1	Approaches to Storing Lists in a Computer	92
2.2.2	Linked Storage Allocation	93
2.3	A Simple Simulation Language: simlib	99
2.4	Single-Server Queueing Simulation with simlib	108
2.4.1	Problem Statement	108
2.4.2	simlib Program	108
2.4.3	Simulation Output and Discussion	113
2.5	Time-Shared Computer Model	114
2.5.1	Problem Statement	114
2.5.2	simlib Program	115
2.5.3	Simulation Output and Discussion	123
2.6	Multiteller Bank With Jockeying	126
2.6.1	Problem Statement	126
2.6.2	simlib Program	127
2.6.3	Simulation Output and Discussion	137
2.7	Job-Shop Model	140
2.7.1	Problem Statement	140
2.7.2	simlib Program	142
2.7.3	Simulation Output and Discussion	153
2.8	Efficient Event-List Manipulation	155
	Appendix 2A: C Code for simlib	156
	Problems	169
Chapter 3	Simulation Software	187
3.1	Introduction	187
3.2	Comparison of Simulation Packages with Programming Languages	188
3.3	Classification of Simulation Software	189
3.3.1	General-Purpose vs. Application-Oriented Simulation Packages	189

3.3.2	Modeling Approaches	190
3.3.3	Common Modeling Elements	192
3.4	Desirable Software Features	193
3.4.1	General Capabilities	193
3.4.2	Hardware and Software Requirements	195
3.4.3	Animation and Dynamic Graphics	195
3.4.4	Statistical Capabilities	197
3.4.5	Customer Support and Documentation	198
3.4.6	Output Reports and Graphics	199
3.5	General-Purpose Simulation Packages	200
3.5.1	Arena	200
3.5.2	Extend	206
3.5.3	Other General-Purpose Simulation Packages	211
3.6	Object-Oriented Simulation	212
3.7	Examples of Application-Oriented Simulation Packages	213
Chapter 4	Review of Basic Probability and Statistics	214
4.1	Introduction	214
4.2	Random Variables and Their Properties	214
4.3	Simulation Output Data and Stochastic Processes	226
4.4	Estimation of Means, Variances, and Correlations	228
4.5	Confidence Intervals and Hypothesis Tests for the Mean	232
4.6	The Strong Law of Large Numbers	237
4.7	The Danger of Replacing a Probability Distribution by its Mean	238
	Appendix 4A: Comments on Covariance-Stationary Processes	239
	Problems	239
Chapter 5	Building Valid, Credible, and Appropriately Detailed Simulation Models	243
5.1	Introduction and Definitions	243
5.2	Guidelines for Determining the Level of Model Detail	246
5.3	Verification of Simulation Computer Programs	248
5.4	Techniques for Increasing Model Validity and Credibility	253
5.4.1	Collect High-Quality Information and Data on the System	253
5.4.2	Interact with the Manager on a Regular Basis	255
5.4.3	Maintain a Written Assumptions Document and Perform a Structured Walk-Through	255
5.4.4	Validate Components of the Model by Using Quantitative Techniques	257

5.4.5	Validate the Output from the Overall Simulation Model	259
5.4.6	Animation	264
5.5	Management's Role in the Simulation Process	264
5.6	Statistical Procedures for Comparing Real-World Observations and Simulation Output Data	265
5.6.1	Inspection Approach	265
5.6.2	Confidence-Interval Approach Based on Independent Data	269
5.6.3	Time-Series Approaches	272
5.6.4	Other Approaches	272
	Problems	273
Chapter 6	Selecting Input Probability Distributions	275
6.1	Introduction	275
6.2	Useful Probability Distributions	281
6.2.1	Parameterization of Continuous Distributions	281
6.2.2	Continuous Distributions	282
6.2.3	Discrete Distributions	301
6.2.4	Empirical Distributions	301
6.3	Techniques for Assessing Sample Independence	312
6.4	Activity I: Hypothesizing Families of Distributions	315
6.4.1	Summary Statistics	316
6.4.2	Histograms	318
6.4.3	Quantile Summaries and Box Plots	320
6.5	Activity II: Estimation of Parameters	326
6.6	Activity III: Determining How Representative the Fitted Distributions Are	330
6.6.1	Heuristic Procedures	330
6.6.2	Goodness-of-Fit Tests	340
6.7	The ExpertFit Software and an Extended Example	353
6.8	Shifted and Truncated Distributions	359
6.9	Bézier Distributions	361
6.10	Specifying Multivariate Distributions, Correlations, and Stochastic Processes	362
6.10.1	Specifying Multivariate Distributions	363
6.10.2	Specifying Arbitrary Marginal Distributions and Correlations	366
6.10.3	Specifying Stochastic Processes	367
6.11	Selecting a Distribution in the Absence of Data	370
6.12	Models of Arrival Processes	375
6.12.1	Poisson Processes	375
6.12.2	Nonstationary Poisson Processes	377
6.12.3	Batch Arrivals	379

6.13	Assessing the Homogeneity of Different Data Sets	380
	Appendix 6A: Tables of MLEs for the Gamma and Beta Distributions	381
	Problems	384
Chapter 7	Random-Number Generators	389
7.1	Introduction	389
7.2	Linear Congruential Generators	393
	7.2.1 Mixed Generators	395
	7.2.2 Multiplicative Generators	396
7.3	Other Kinds of Generators	398
	7.3.1 More General Congruences	398
	7.3.2 Composite Generators	399
	7.3.3 Feedback Shift Register Generators	401
7.4	Testing Random-Number Generators	405
	7.4.1 Empirical Tests	406
	7.4.2 Theoretical Tests	410
	7.4.3 Some General Observations on Testing	414
	Appendix 7A: Portable C Code for a PMMLCG	415
	Appendix 7B: Portable C Code for a Combined MRG	417
	Problems	419
Chapter 8	Generating Random Variates	422
8.1	Introduction	422
8.2	General Approaches to Generating Random Variates	424
	8.2.1 Inverse Transform	424
	8.2.2 Composition	433
	8.2.3 Convolution	436
	8.2.4 Acceptance-Rejection	437
	8.2.5 Ratio of Uniforms	444
	8.2.6 Special Properties	446
8.3	Generating Continuous Random Variates	447
	8.3.1 Uniform	448
	8.3.2 Exponential	448
	8.3.3 m -Erlang	449
	8.3.4 Gamma	449
	8.3.5 Weibull	452
	8.3.6 Normal	453
	8.3.7 Lognormal	454
	8.3.8 Beta	455
	8.3.9 Pearson Type V	456
	8.3.10 Pearson Type VI	456
	8.3.11 Log-Logistic	456

8.3.12	Johnson Bounded	456
8.3.13	Johnson Unbounded	457
8.3.14	Bézier	457
8.3.15	Triangular	457
8.3.16	Empirical Distributions	458
8.4	Generating Discrete Random Variates	459
8.4.1	Bernoulli	460
8.4.2	Discrete Uniform	460
8.4.3	Arbitrary Discrete Distribution	460
8.4.4	Binomial	465
8.4.5	Geometric	465
8.4.6	Negative Binomial	465
8.4.7	Poisson	466
8.5	Generating Random Vectors, Correlated Random Variates, and Stochastic Processes	466
8.5.1	Using Conditional Distributions	467
8.5.2	Multivariate Normal and Multivariate Lognormal	468
8.5.3	Correlated Gamma Random Variates	469
8.5.4	Generating from Multivariate Families	470
8.5.5	Generating Random Vectors with Arbitrarily Specified Marginal Distributions and Correlations	470
8.5.6	Generating Stochastic Processes	471
8.6	Generating Arrival Processes	472
8.6.1	Poisson Processes	473
8.6.2	Nonstationary Poisson Processes	473
8.6.3	Batch Arrivals	477
	Appendix 8A: Validity of the Acceptance-Rejection Method	477
	Appendix 8B: Setup for the Alias Method	478
	Problems	479
Chapter 9	Output Data Analysis for a Single System	485
9.1	Introduction	485
9.2	Transient and Steady-State Behavior of a Stochastic Process	488
9.3	Types of Simulations with Regard to Output Analysis	490
9.4	Statistical Analysis for Terminating Simulations	494
9.4.1	Estimating Means	495
9.4.2	Estimating Other Measures of Performance	504
9.4.3	Choosing Initial Conditions	507
9.5	Statistical Analysis for Steady-State Parameters	508
9.5.1	The Problem of the Initial Transient	508
9.5.2	Replication/Deletion Approach for Means	517
9.5.3	Other Approaches for Means	519
9.5.4	Estimating Other Measures of Performance	533

9.6	Statistical Analysis for Steady-State Cycle Parameters	534
9.7	Multiple Measures of Performance	537
9.8	Time Plots of Important Variables	540
	Appendix 9A: Ratios of Expectations and Jackknife Estimators	542
	Problems	543
Chapter 10	Comparing Alternative System Configurations	548
10.1	Introduction	548
10.2	Confidence Intervals for the Difference Between the Expected Responses of Two Systems	552
10.2.1	A Paired- t Confidence Interval	552
10.2.2	A Modified Two-Sample- t Confidence Interval	554
10.2.3	Contrasting the Two Methods	555
10.2.4	Comparisons Based on Steady-State Measures of Performance	555
10.3	Confidence Intervals for Comparing More than Two Systems	557
10.3.1	Comparisons with a Standard	558
10.3.2	All Pairwise Comparisons	560
10.3.3	Multiple Comparisons with the Best	561
10.4	Ranking and Selection	561
10.4.1	Selecting the Best of k Systems	562
10.4.2	Selecting a Subset of Size m Containing the Best of k Systems	568
10.4.3	Additional Problems and Methods	569
	Appendix 10A: Validity of the Selection Procedures	572
	Appendix 10B: Constants for the Selection Procedures	573
	Problems	575
Chapter 11	Variance-Reduction Techniques	577
11.1	Introduction	577
11.2	Common Random Numbers	578
11.2.1	Rationale	579
11.2.2	Applicability	580
11.2.3	Synchronization	582
11.2.4	Some Examples	586
11.3	Antithetic Variates	594
11.4	Control Variates	600
11.5	Indirect Estimation	607
11.6	Conditioning	609
	Problems	613

Chapter 12	Experimental Design and Optimization	619
12.1	Introduction	619
12.2	2^k Factorial Designs	622
12.3.	2^{k-p} Fractional Factorial Designs	636
12.4	Response Surfaces and Metamodels	643
12.5	Simulation-Based Optimization	655
12.5.1	Optimum-Seeking Methods	657
12.5.2	Optimum-Seeking Packages Interfaced with Simulation Software	658
	Problems	666
Chapter 13	Simulation of Manufacturing Systems	669
13.1	Introduction	669
13.2	Objectives of Simulation in Manufacturing	670
13.3	Simulation Software for Manufacturing Applications	672
13.3.1	Flexsim	672
13.3.2	ProModel	675
13.3.3	Other Manufacturing-Oriented Simulation Packages	684
13.4	Modeling System Randomness	685
13.4.1	Sources of Randomness	685
13.4.2	Machine Downtimes	687
13.5	An Extended Example	694
13.5.1	Problem Description and Simulation Results	694
13.5.2	Statistical Calculations	703
13.6	A Simulation Case Study of a Metal-Parts Manufacturing Facility	704
13.6.1	Description of the System	705
13.6.2	Overall Objectives and Issues to Be Investigated	705
13.6.3	Development of the Model	706
13.6.4	Model Verification and Validation	707
13.6.5	Results of the Simulation Experiments	708
13.6.6	Conclusions and Benefits	711
	Problems	712
	Appendix	715
	References	719
	Subject Index	751