

CONTENTS

List of Symbols	xvii
Preface	xix
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 FORTRAN Program	32
1.4.5 C Program	41
1.4.6 Simulation Output and Discussion	49
1.4.7 Alternative Stopping Rules	51
1.4.8 Determining the Events and Variables	57
1.5 Simulation of an Inventory System	60
1.5.1 Problem Statement	60
1.5.2 Program Organization and Logic	62
1.5.3 FORTRAN Program	66
1.5.4 C Program	73
1.5.5 Simulation Output and Discussion	78
1.6 Alternative Approaches to Modeling and Coding Simulations	80
1.6.1 Parallel and Distributed Simulation	80
1.6.2 Simulation across the Internet and Web-Based Simulation	83
1.7 Steps in a Sound Simulation Study	83
1.8 Other Types of Simulation	87
1.8.1 Continuous Simulation	87

1.8.2	Combined Discrete-Continuous Simulation	89
1.8.3	Monte Carlo Simulation	90
1.9	Advantages, Disadvantages, and Pitfalls of Simulation	91
	Appendix 1A: Fixed-Increment Time Advance	93
	Appendix 1B: A Primer on Queueing Systems	94
	1B.1 Components of a Queueing System	95
	1B.2 Notation for Queueing Systems	95
	1B.3 Measures of Performance for Queueing Systems	96
	Problems	99

Chapter 2 Modeling Complex Systems 106

2.1	Introduction	106
2.2	List Processing in Simulation	107
	2.2.1 Approaches to Storing Lists in a Computer	107
	2.2.2 Linked Storage Allocation	108
2.3	A Simple Simulation Language: simlib	114
2.4	Single-Server Queueing Simulation with simlib	123
	2.4.1 Problem Statement	123
	2.4.2 simlib Program	123
	2.4.3 Simulation Output and Discussion	128
2.5	Time-Shared Computer Model	129
	2.5.1 Problem Statement	129
	2.5.2 simlib Program	130
	2.5.3 Simulation Output and Discussion	138
2.6	Multiteller Bank with Jockeying	141
	2.6.1 Problem Statement	141
	2.6.2 simlib Program	142
	2.6.3 Simulation Output and Discussion	152
2.7	Job-Shop Model	155
	2.7.1 Problem Statement	155
	2.7.2 simlib Program	157
	2.7.3 Simulation Output and Discussion	168
2.8	Efficient Event-List Manipulation	170
	Appendix 2A: C Code for simlib	171
	Problems	184

Chapter 3 Simulation Software 202

3.1	Introduction	202
3.2	Comparison of Simulation Packages with Programming Languages	203
3.3	Classification of Simulation Software	204
	3.3.1 General-Purpose Versus Application-Oriented Simulation Packages	204

3.3.2	Modeling Approaches	205
3.3.3	Common Modeling Elements	207
3.4	Desirable Software Features	208
3.4.1	General Capabilities	208
3.4.2	Hardware and Software Requirements	210
3.4.3	Animation and Dynamic Graphics	210
3.4.4	Statistical Capabilities	212
3.4.5	Customer Support and Documentation	213
3.4.6	Output Reports and Graphics	214
3.5	General-Purpose Simulation Packages	215
3.5.1	Arena	215
3.5.2	Extend	219
3.5.3	Other General-Purpose Simulation Packages	225
3.6	Object-Oriented Simulation	227
3.6.1	MODSIM III	228
3.7	Examples of Application-Oriented Simulation Packages	233
Chapter 4	Review of Basic Probability and Statistics	235
4.1	Introduction	235
4.2	Random Variables and Their Properties	235
4.3	Simulation Output Data and Stochastic Processes	247
4.4	Estimation of Means, Variances, and Correlations	249
4.5	Confidence Intervals and Hypothesis Tests for the Mean	253
4.6	The Strong Law of Large Numbers	259
4.7	The Danger of Replacing a Probability Distribution by its Mean	260
	Appendix 4A: Comments on Covariance-Stationary Processes	260
	Problems	261
Chapter 5	Building Valid, Credible, and Appropriately Detailed Simulation Models	264
5.1	Introduction and Definitions	264
5.2	Guidelines for Determining the Level of Model Detail	267
5.3	Verification of Simulation Computer Programs	269
5.4	Techniques for Increasing Model Validity and Credibility	273
5.4.1	Collect High-Quality Information and Data on the System	274
5.4.2	Interact with the Manager on a Regular Basis	275
5.4.3	Maintain an Assumptions Document and Perform a Structured Walk-Through	276
5.4.4	Validate Components of the Model by Using Quantitative Techniques	277

5.4.5	Validate the Output from the Overall Simulation Model	279
5.4.6	Animation	282
5.5	Management's Role in the Simulation Process	282
5.6	Statistical Procedures for Comparing Real-World Observations and Simulation Output Data	283
5.6.1	Inspection Approach	283
5.6.2	Confidence-Interval Approach Based on Independent Data	287
5.6.3	Time-Series Approaches	289
	Problems	290

Chapter 6	Selecting Input Probability Distributions	292
6.1	Introduction	292
6.2	Useful Probability Distributions	298
6.2.1	Parameterization of Continuous Distributions	298
6.2.2	Continuous Distributions	299
6.2.3	Discrete Distributions	318
6.2.4	Empirical Distributions	318
6.3	Techniques for Assessing Sample Independence	329
6.4	Activity I: Hypothesizing Families of Distributions	332
6.4.1	Summary Statistics	333
6.4.2	Histograms	335
6.4.3	Quantile Summaries and Box Plots	337
6.5	Activity II: Estimation of Parameters	343
6.6	Activity III: Determining How Representative the Fitted Distributions Are	347
6.6.1	Heuristic Procedures	347
6.6.2	Goodness-of-Fit Tests	356
6.7	The ExpertFit Software and an Extended Example	370
6.8	Shifted and Truncated Distributions	376
6.9	Bézier Distributions	378
6.10	Specifying Multivariate Distributions, Correlations, and Stochastic Processes	378
6.10.1	Specifying Multivariate Distributions	380
6.10.2	Specifying Arbitrary Marginal Distributions and Correlations	383
6.10.3	Specifying Stochastic Processes	384
6.11	Selecting a Distribution in the Absence of Data	386
6.12	Models of Arrival Processes	389
6.12.1	Poisson Processes	389
6.12.2	Nonstationary Poisson Processes	390
6.12.3	Batch Arrivals	393
6.13	Assessing the Homogeneity of Different Data Sets	394

Appendix 6A: Tables of MLEs for the Gamma and Beta Distributions	395
Problems	397
Chapter 7 Random-Number Generators	402
7.1 Introduction	402
7.2 Linear Congruential Generators	406
7.2.1 Mixed Generators	409
7.2.2 Multiplicative Generators	410
7.3 Other Kinds of Generators	412
7.3.1 More General Congruences	413
7.3.2 Composite Generators	414
7.3.3 Tausworthe and Related Generators	416
7.4 Testing Random-Number Generators	417
7.4.1 Empirical Tests	418
7.4.2 Theoretical Tests	423
7.4.3 Some General Observations on Testing	426
Appendix 7A: Portable Computer Codes for a PMMLCG	427
7A.1 FORTRAN	428
7A.2 C	430
7A.3 Obtaining Initial Seeds for the Streams	431
Appendix 7B: Portable C Code for a Combined MRG	432
Problems	435
Chapter 8 Generating Random Variates	437
8.1 Introduction	437
8.2 General Approaches to Generating Random Variates	439
8.2.1 Inverse Transform	440
8.2.2 Composition	448
8.2.3 Convolution	451
8.2.4 Acceptance-Rejection	452
8.2.5 Special Properties	459
8.3 Generating Continuous Random Variates	459
8.3.1 Uniform	460
8.3.2 Exponential	460
8.3.3 m -Erlang	461
8.3.4 Gamma	461
8.3.5 Weibull	464
8.3.6 Normal	465
8.3.7 Lognormal	466
8.3.8 Beta	467
8.3.9 Pearson Type V	468
8.3.10 Pearson Type VI	468
8.3.11 Log-Logistic	468

8.3.12	Johnson Bounded	468
8.3.13	Johnson Unbounded	469
8.3.14	Bézier	469
8.3.15	Triangular	469
8.3.16	Empirical Distributions	470
8.4	Generating Discrete Random Variates	471
8.4.1	Bernoulli	472
8.4.2	Discrete Uniform	472
8.4.3	Arbitrary Discrete Distribution	472
8.4.4	Binomial	477
8.4.5	Geometric	477
8.4.6	Negative Binomial	477
8.4.7	Poisson	478
8.5	Generating Random Vectors, Correlated Random Variates, and Stochastic Processes	478
8.5.1	Using Conditional Distributions	479
8.5.2	Multivariate Normal and Multivariate Lognormal	480
8.5.3	Correlated Gamma Random Variates	481
8.5.4	Generating from Multivariate Families	482
8.5.5	Generating Random Vectors with Arbitrarily Specified Marginal Distributions and Correlations	482
8.5.6	Generating Stochastic Processes	483
8.6	Generating Arrival Processes	484
8.6.1	Poisson Processes	485
8.6.2	Nonstationary Poisson Processes	485
8.6.3	Batch Arrivals	489
	Appendix 8A: Validity of the Acceptance-Rejection Method	489
	Appendix 8B: Setup for the Alias Method Problems	490
		491
Chapter 9	Output Data Analysis for a Single System	496
9.1	Introduction	496
9.2	Transient and Steady-State Behavior of a Stochastic Process	499
9.3	Types of Simulations with Regard to Output Analysis	502
9.4	Statistical Analysis for Terminating Simulations	505
9.4.1	Estimating Means	506
9.4.2	Estimating Other Measures of Performance	515
9.4.3	Choosing Initial Conditions	518
9.5	Statistical Analysis for Steady-State Parameters	518
9.5.1	The Problem of the Initial Transient	519
9.5.2	Replication/Deletion Approaches for Means	525
9.5.3	Other Approaches for Means	527
9.5.4	Estimating Other Measures of Performance	537

9.6	Statistical Analysis for Steady-State Cycle Parameters	539
9.7	Multiple Measures of Performance	542
9.8	Time Plots of Important Variables	545
	Appendix 9A: Ratios of Expectations and Jackknife Estimators	545
	Problems	547
Chapter 10	Comparing Alternative System Configurations	553
10.1	Introduction	553
10.2	Confidence Intervals for the Difference Between the Expected Responses of Two Systems	557
10.2.1	A Paired- t Confidence Interval	557
10.2.2	A Modified Two-Sample- t Confidence Interval	559
10.2.3	Contrasting the Two Methods	560
10.2.4	Comparisons Based on Steady-State Measures of Performance	560
10.3	Confidence Intervals for Comparing More than Two Systems	562
10.3.1	Comparisons with a Standard	563
10.3.2	All Pairwise Comparisons	564
10.3.3	Multiple Comparisons with the Best	566
10.4	Ranking and Selection	566
10.4.1	Selecting the Best of k Systems	567
10.4.2	Selecting a Subset of Size m Containing the Best of k Systems	569
10.4.3	Selecting the m Best of k Systems	570
10.4.4	Additional Problems and Methods	572
	Appendix 10A: Validity of the Selection Procedures	575
	Appendix 10B: Constants for the Selection Procedures	576
	Problems	579
Chapter 11	Variance-Reduction Techniques	581
11.1	Introduction	581
11.2	Common Random Numbers	582
11.2.1	Rationale	583
11.2.2	Applicability	584
11.2.3	Synchronization	586
11.2.4	Some Examples	590
11.3	Antithetic Variates	598
11.4	Control Variates	604
11.5	Indirect Estimation	611
11.6	Conditioning	613
	Problems	617

Chapter 12	Experimental Design, Sensitivity Analysis, and Optimization	622
12.1	Introduction	622
12.2	2^k Factorial Designs	625
12.3	Coping with Many Factors	637
12.3.1	2^{k-p} Fractional Factorial Designs	638
12.3.2	Factor-Screening Strategies	644
12.4	Response Surfaces and Metamodels	646
12.5	Sensitivity and Gradient Estimation	655
12.6	Optimum Seeking	657
12.6.1	Optimum-Seeking Methods	659
12.6.2	Optimum-Seeking Packages Interfaced with Simulation Software	662
	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
13.4	Modeling System Randomness	675
13.4.1	Sources of Randomness	675
13.4.2	Machine Downtimes	678
13.5	An Extended Example	684
13.5.1	Problem Description and Simulation Results	684
13.5.2	Statistical Calculations	693
13.6	A Simulation Case Study of a Metal-Parts Manufacturing Facility	695
13.6.1	Description of the System	695
13.6.2	Overall Objectives and Issues to Be Investigated	696
13.6.3	Development of the Model	696
13.6.4	Model Verification and Validation	697
13.6.5	Results of the Simulation Experiments	699
13.6.6	Conclusions and Benefits	701
	Problems	702
	Appendix	707
	References	711
	Subject Index	745