

Contents



Preface xi

PART ONE Introduction to Discrete-Event System Simulation 1

1 Introduction to Simulation 3

- 1.1 When is Simulation the Appropriate Tool? 4
- 1.2 Advantages and Disadvantages of Simulation 4
- 1.3 Areas of Application 6
 - Manufacturing Systems 6
 - Public Systems 7
 - Transportation Systems 7
 - Construction Systems 7
 - Restaurant and Entertainment Systems 8
 - Business Process Reengineering 8
 - Food Processing 8
 - Computer System Performance 8
- 1.4 Systems and System Environment 8
- 1.5 Components of a System 8
- 1.6 Discrete and Continuous Systems 9
- 1.7 Model of a System 11
- 1.8 Types of Models 12
- 1.9 Discrete-Event System Simulation 13
- 1.10 Steps in a Simulation Study 13
- References 18
- Exercises 19

2 Simulation Examples 21

- 2.1 Simulation of Queueing Systems 22
- 2.2 Simulation of Inventory Systems 36
- 2.3 Other Examples of Simulation 42

2.4	Summary	49
	References	50
	Exercises	50

3 General Principles 59

3.1	Concepts in Discrete-Event Simulation	60
3.1.1	The Event Scheduling/Time Advance Algorithm	63
3.1.2	World Views	67
3.1.3	Manual Simulation Using Event Scheduling	70
3.2	List Processing	80
3.2.1	Lists: Basic Properties and Operations	80
3.2.2	Using Arrays for List Processing	82
3.2.3	Using Dynamic Allocation and Linked Lists	84
3.2.4	Advanced Techniques	86
3.3	Summary	87
	References	87
	Exercises	87

4 Programming Languages 89

4.1	Simulation in FORTRAN	91
4.2	Simulation in GPSS	103
4.3	Simulation in SIMAN V	111
4.4	Simulation in SIMSCRIPT II.5	116
4.5	Simulation in SLAM II Using SLAMSYSTEM	122
4.6	Simulation in MODSIM III	128
4.6.1	Object Oriented Programming	128
4.6.2	Messages and Behaviors	131
4.6.3	Inheritance	132
4.6.4	Object Oriented Simulation	133
4.7	Summary and Advice on Software Selection	138
	References	140
	Exercises	140

5 Simulation of Manufacturing and Material Handling Systems 153

5.1	Manufacturing and Material Handling Simulations	154
5.1.1	Modeling of Manufacturing Systems	154
5.1.2	Models of Material Handling Systems	155
5.1.3	Some Common Material Handling Equipment	156
5.2	Goals and Performance Measures	157
5.3	Issues in Manufacturing and Material Handling Simulations	158
5.3.1	Modeling Downtimes and Failures	158
5.3.2	Trace-driven Models	162
5.4	Case Studies of the Simulations of Manufacturing and Material Handling Systems	164

5.5	Simulators and Languages for Manufacturing and Material Handling	166
5.5.1	SIMFACTORY II.5	166
5.5.2	ProModel	167
5.5.3	AutoMod	168
5.5.4	Taylor II	169
5.5.5	Witness	170
5.5.6	AIM	171
5.5.7	Arena	172
5.6	Summary	173
	References	173
	Exercises	174
PART TWO Mathematical and Statistical Models		183
6	Statistical Models in Simulation	185
6.1	Review of Terminology and Concepts	186
6.2	Useful Statistical Models	192
6.3	Discrete Distributions	196
6.4	Continuous Distributions	201
6.5	Poisson Process	220
6.6	Empirical Distributions	223
6.7	Summary	225
	References	226
	Exercises	226
7	Queueing Models	233
7.1	Characteristics of Queueing Systems	234
7.1.1	The Calling Population	235
7.1.2	System Capacity	236
7.1.3	The Arrival Process	236
7.1.4	Queue Behavior and Queue Discipline	238
7.1.5	Service Times and the Service Mechanism	238
7.2	Queueing Notation	240
7.3	Transient and Steady-State Behavior of Queues	241
7.4	Long-Run Measures of Performance of Queueing Systems	246
7.4.1	Time-Average Number in System L	246
7.4.2	Average Time Spent in System Per Customer w	248
7.4.3	The Conservation Equation: $L = \lambda w$	249
7.4.4	Server Utilization	250
7.4.5	Costs in Queueing Problems	255
7.5	Steady-State Behavior of Infinite-Population Markovian Models	257
7.5.1	Single-Server Queues with Poisson Arrivals and Unlimited Capacity: M/G/1	258

7.5.2	Single-Server Queues with Poisson Arrivals and Limited Capacity: $M/M/1/N/\infty$	267
7.5.3	Multiserver Queue: $M/M/c/\infty/\infty$	269
7.6	Steady-State Behavior of Finite-Population Models ($M/M/c/K/K$)	275
7.7	Networks of Queues	278
7.8	Summary	279
	References	281
	Exercises	282
PART THREE Random Numbers		287
8	Random-Number Generation	289
8.1	Properties of Random Numbers	289
8.2	Generation of Pseudo-Random Numbers	290
8.3	Techniques for Generating Random Numbers	292
8.3.1	Linear Congruential Method	292
8.3.2	Combined Linear Congruential Generators	296
8.4	Tests for Random Numbers	297
8.4.1	Frequency Tests	299
8.4.2	Runs Tests	303
8.4.3	Tests for Autocorrelation	311
8.4.4	Gap Test	313
8.4.5	Poker Test	316
8.5	Summary	316
	References	317
	Exercises	318
9	Random Variate Generation	321
9.1	Inverse Transform Technique	322
9.1.1	Exponential Distribution	322
9.1.2	Uniform Distribution	325
9.1.3	Weibull Distribution	326
9.1.4	Triangular Distribution	327
9.1.5	Empirical Continuous Distributions	328
9.1.6	Continuous Distributions without a Closed-Form Inverse	334
9.1.7	Discrete Distributions	335
9.2	Direct Transformation for the Normal Distribution	341
9.3	Convolution Method	343
9.3.1	Erlang Distribution	343
9.4	Acceptance-Rejection Technique	344
9.4.1	Poisson Distribution	345
9.4.2	Gamma Distribution	348
9.5	Summary	349

References	349
Exercises	350

PART FOUR Analysis of Simulation Data 353

10 Input Modeling 355

10.1	Data Collection	356
10.2	Identifying the Distribution with Data	358
	10.2.1 Histograms	359
	10.2.2 Selecting the Family of Distributions	362
	10.2.3 Quantile-Quantile Plots	365
10.3	Parameter Estimation	367
	10.3.1 Preliminary Statistics: Sample Mean and Sample Variance	367
	10.3.2 Suggested Estimators	369
10.4	Goodness-of-Fit Tests	375
	10.4.1 Chi-Square Test	375
	10.4.2 Chi-Square Test with Equal Probabilities	378
	10.4.3 Kolmogorov-Smirnov Goodness-of-Fit Test	382
10.5	Selecting Input Models without Data	384
10.6	Multivariate and Time-Series Input Models	385
	10.6.1 Covariance and Correlation	386
	10.6.2 Multivariate Input Models	386
	10.6.3 Time-Series Input Models	388
10.7	Summary	390
	References	391
	Exercises	392

11 Verification and Validation of Simulation Models 399

11.1	Model Building, Verification, and Validation	400
11.2	Verification of Simulation Models	401
11.3	Calibration and Validation of Models	406
	11.3.1 Face Validity	407
	11.3.2 Validation of Model Assumptions	408
	11.3.3 Validating Input-Output Transformations	409
	11.3.4 Input-Output Validation: Using Historical Input Data	419
	11.3.5 Input-Output Validation: Using a Turing Test	423
11.4	Summary	424
	References	425
	Exercises	426

12 Output Analysis for a Single Model 428

12.1	Stochastic Nature of Output Data	429
12.2	Types of Simulations with Respect to Output Analysis	433

12.3	Measures of Performance and Their Estimation	436
12.3.1	Point Estimation	436
12.3.2	Interval Estimation	438
12.4	Output Analysis for Terminating Simulations	443
12.4.1	Confidence Interval Estimation for a Fixed Number of Replications	444
12.4.2	Confidence Intervals with Specified Precision	446
12.5	Output Analysis for Steady-State Simulations	449
12.5.1	Initialization Bias in Steady-State Simulations	450
12.5.2	Replication Method for Steady-State Simulations	457
12.5.3	Sample Size in Steady-State Simulations	460
12.5.4	Batch Means for Interval Estimation in Steady-State Simulations	462
12.6	Summary	465
	References	465
	Exercises	466
13	Comparison and Evaluation of Alternative System Designs	475
13.1	Comparison of Two System Designs	476
13.1.1	Independent Sampling with Equal Variances	479
13.1.2	Independent Sampling with Unequal Variances	481
13.1.3	Correlated Sampling, or Common Random Numbers	481
13.1.4	Confidence Intervals with Specified Precision	490
13.2	Comparison of Several System Designs	491
13.2.1	Bonferroni Approach to Multiple Comparisons	492
13.2.2	Bonferroni Approach to Selecting the Best	497
13.3	Statistical Models for Estimating the Effect of Design Alternatives	499
13.3.1	Purposes of the Statistical Design of Experiments	500
13.3.2	Single-Factor Completely Randomized Experimental Designs	502
13.3.3	Factorial Designs with Two Factors	508
13.3.4	Other Experimental Design Models	513
13.4	Metamodeling	513
13.4.1	Simple Linear Regression	514
13.4.2	Testing for Significance of Regression	518
13.4.3	Multiple Linear Regression	521
13.4.4	Random-Number Assignment for Regression	521
13.5	Summary	522
	References	523
	Exercises	524
Appendix A	529	
Index	543	