

Contents

Preface

vii

1	Simulation in Perspective	1
1.1	Discrete-Event Systems	5
1.2	Open- and Closed-Loop Systems	8
1.3	Time Averages	10
1.3.1	Exceedance Probabilities	13
1.4	Example: Reducing Waiting Time for Photocopying	14
1.5	Example: Increasing Throughput at an Incinerator	19
1.6	Why Discrete-Event Simulation	23
1.6.1	Detail	24
1.6.2	Modeling Dangers	26
1.7	Technical Attractions of Simulation	26
1.8	Medium for Modeling	27
1.9	Discrete-Event Simulation Programming Languages	29
1.9.1	Special Features	31
1.9.2	Object-Oriented Programming	31

1.9.3	Web-Based Discrete-Event Simulation	33
1.9.4	No Programming	34
1.9.5	Teaching Discrete-Event Simulation	34
1.10	References	35
2	Modeling Concepts	36
2.1	Next-Event Time Advance	39
2.2	Arithmetic and Logical Relationships	40
2.3	Event-Scheduling Approach	41
2.3.1	Priority Order	52
2.4	Process-Interaction Approach	52
2.5	Active Processes and Passive Resources	57
2.6	Telecommunications Network Modeling	58
2.7	Lessons Learned	62
2.8	Exercises	64
2.9	References	69
3	Data Collection and Averages	70
3.1	Performance Statistics	72
3.1.1	Queue Length	74
3.1.2	Resource Utilization	76
3.1.3	Waiting Time	77
3.2	Statistical Accuracy	78
3.2.1	System State	79
3.3	Conditional and Equilibrium Distributions	81
3.3.1	Initial Conditions	82
3.3.2	Warm-Up Interval and Convergence	84
3.3.3	Queue Length, Resource Utilization, and Convergence	85
3.3.4	Finite Sample-Path Length	88
3.4	Terminating Execution	90
	Option A	90
	Option B	91
3.5	Waiting Time	92
3.5.1	Little's Law	93
3.6	Summary	94
3.7	Periodic Data Collection	94
3.8	Lessons Learned	96
3.9	References	97
4	Programming and Execution	98
4.1	Modalities for Programming	100
4.2	SIMSCRIPT II.5	103

4.3	Entities	111
4.4	Event Notices	111
4.5	Summary Statistics	112
4.6	Traffic Intensity	115
4.7	Pseudorandom Number Generation	116
4.8	Warm-Up and Path-Length Parameters	118
4.9	Event Management	119
4.10	Starting and Stopping Execution	119
4.11	CALL Event	120
4.12	END_MESSAGE Event	121
4.13	Filing Priorities	121
4.14	COMPLETION Event	122
4.15	Getting an Executable Program	125
4.16	A First Run	127
4.17	Collecting Data	131
4.18	Process-Interaction Approach	131
4.19	Processes and Resources in SIMSCRIPT II.5	132
4.20	Using Processes Exclusively	133
4.21	Using Processes and Resources	137
4.22	Common Pseudorandom Numbers	142
	4.22.1 Other Variance-Reducing Methods	148
4.23	Point-Click-Drag-Drop-Connect Approach	149
4.24	M/M/1 Arena Example	151
	4.24.1 SIMAN Statements	154
	Blocks	154
	Elements	155
4.25	Arena/SIMAN Airline Reservation Example	156
	4.25.1 Modeling with the BAAT Panels	162
4.26	Events in SIMAN and SLAM	162
4.27	Macromodules	163
	What is the sequencing discipline?	163
	What can the bridge crane do?	164
	Module Opaqueness	165
4.28	Lessons Learned	165
4.29	Exercises	166
4.30	References	173
5	Search, Space, and Time	176
5.1	Memory Space Needs and Computing Time: A Simplified Perspective	178
	5.1.1 FES Management Time per Job	183
	5.1.2 Reducing the Size of the FES	183
	Protocol A	184

	Protocol B	184
	Protocol C	185
5.2	List Processing	186
5.2.1	Insertion and Deletion	189
5.3	Dynamic Space Management	190
	Algorithm SPACE_FINDER	191
	Algorithm SPACE_RELEASER	191
	Algorithm SPACE_FINDER*	194
	Algorithm SPACE_RELEASER*	195
5.3.1	Aggregating Record Classes	195
5.3.2	Resizing	196
	Algorithm SPACE_FINDER**	197
5.4	Future-Event Set	197
5.4.1	Single Linear Event List	199
	Efficiency	201
5.4.2	Multiple Linear Event Lists	201
	Scheduling	201
	Selecting the Next Event	201
5.4.3	Heaps	203
	Algorithm SIFTUP(x)	204
	Algorithm SIFTDOWN(x)	204
	Space	205
5.4.4	Henriksen's Algorithm	207
	Algorithm H-L	208
5.4.5	Best FES Manager	209
5.5	Broadening the Class of Delay Models	211
	Capacitated Travel	211
	Uncapacitated Travel	212
5.5.1	Variable Transit Times	212
5.5.2	Varying Number of Tasks per Job	214
5.6	Lessons Learned	216
5.7	Exercises	216
5.8	References	217
6	Output Analysis	218
6.1	Warm-Up Interval	220
6.1.1	Multiple Initial States	227
6.1.2	How Many Warm-Up Analyses?	228
6.1.3	Steps for Estimating the Length of the Warm-up Interval	228
6.2	Assessing the Accuracy of the Sample Average	232
6.3	Formalisms	233
6.4	Independent Replications	235

	Recursive Computation	238
	6.4.1 Allowing t to Grow	238
	Brownian Motion	238
	Assumption of Weak Approximation	239
6.5	Strictly Stationary Stochastic Processes	241
6.6	Batch-Means Method	246
	6.6.1 LABATCH.2 Tableaus	248
	6.6.2 Systematic Variance Error	248
	6.6.3 Interim Review	253
	6.6.4 FNB Rule	253
	6.6.5 Arena's Automatic Use of the Batch-Means Method	254
	6.6.6 SQRT Rule	256
	6.6.7 LBATCH and ABATCH Rules	256
	LBATCH Rule	257
	ABATCH Rule	259
	6.6.8 Testing H_0	260
	6.6.9 Assessing the Adequacy of the Warm-Up Interval	264
6.7	LABATCH.2	265
	6.7.1 Two Modalities	267
	6.7.2 Interacting with the Analysis	268
	6.7.3 Implementation	270
	6.7.4 User-Specified l_1 and b_1	270
	6.7.5 Coding	271
6.8	Airline Reservation Problem	271
6.9	Batch Means in Arena	273
6.10	Prebatching	278
6.11	Ratio Estimation	278
6.12	Lessons Learned	283
6.13	Exercises	284
6.14	References	292
7	Making Sense of Output and Increasing Efficiency	294
	7.1 Simultaneous Confidence Statements	297
	7.2 Comparing Two Means	300
	7.3 Rationale for Degrees of Freedom	303
	7.4 Ratio Analysis	305
	7.5 Comparison of Means on Two Sample Paths	306
	7.6 Multiple Comparisons	306
	7.6.1 Library Photocopying	307
	Scenario	307
	Natural Ordering	308
7.7	Common Pseudorandom Numbers Revisited	312

7.7.1	How Scenarios Affect Correlation	313
7.7.2	Multiple Comparisons	315
7.8	Optimal Sample-Path Lengths	315
7.9	Unequal Sampling Costs	316
7.10	Errors in Optimality	319
7.11	opt and Multiple Replications	320
7.12	Lessons Learned	321
7.13	Exercises	322
7.14	References	324
8	Sampling from Probability Distributions	326
8.1	Inverse Transform Method	329
	Algorithm ITM	329
8.1.1	Continuous Distributions	330
	Algorithm BISECTION	330
	Algorithm N-R	330
8.1.2	Restricted Sampling	332
8.1.3	Discrete Distributions	332
	Algorithm DI	333
	Algorithm ITR	333
	Accumulated Round-off Error	334
8.2	Cutpoint Method	334
	Algorithm CM	336
	Algorithm CMSET	337
8.2.1	Restricted Sampling	337
8.3	Composition Method	338
	Algorithm COMPM	338
	Algorithm RWTE	340
8.4	Alias Method	341
	Algorithm ALIAS	342
	Algorithm ALSET	343
8.4.1	Setting Up the Tables	343
8.5	Acceptance-Rejection Method	345
	Algorithm AR	347
	Version 1	349
	Version 2	349
8.5.1	Squeeze Method	349
	Algorithm ARS	350
8.5.2	Theory and Practice	352
8.6	Ratio-of-Uniforms Method	352
	Algorithm ROU	354
8.7	Exact-Approximation Method	358

	Algorithm EAM	359
	Algorithm CA	360
8.8	Algorithms for Selected Distributions	360
8.9	Exponential Distribution	361
	Algorithm EA	362
	8.9.1 Weibull Distribution	362
	8.9.2 Inverse Weibull Distribution	363
8.10	Normal Distribution	364
	Algorithm NA	365
8.11	Lognormal Distribution	366
8.12	Cauchy Distribution	366
8.13	Gamma Distribution	367
	$\alpha \leq 1$	368
	Algorithm GS*	369
	$\alpha > 1$	369
	Algorithm GKM1	373
	Algorithm GKM2	373
	Algorithm GKM3	374
	8.13.1 Inverted Gamma Distribution	374
8.14	Beta Distribution	375
	$\max(\alpha, \beta) < 1$	375
	Algorithm AW	376
	$\min(\alpha, \beta) > 1$	377
	Algorithm BB*	378
	8.14.1 Beta-Prime Distribution	378
8.15	Revisiting the Ratio-of-Uniforms Method	379
8.16	Poisson Distribution	380
	Algorithm PRUA*	383
8.17	Binomial Distribution	384
	Algorithm BER	385
	Algorithm BRUA*	386
8.18	Hypergeometric Distribution	387
	Algorithm HYP	388
	Algorithm HRUA*	390
8.19	Geometric Distribution	390
	Algorithm GEO	391
8.20	Negative Binomial Distribution	391
	Algorithm NEGBIN	392
8.21	Multinomial Distribution	392
	Algorithm MULTN	394
8.22	Bernoulli Trials	394

Algorithm SKIP	394
8.23 Lessons Learned	395
8.24 Exercises	395
Hands-On-Exercises	407
8.25 References	410
9 Pseudorandom Number Generation	416
9.1 Linear Congruential Generators	418
9.1.1 Period	419
9.1.2 Prime Modulus	420
9.1.3 Multiplicative Inverse	420
9.1.4 Finding Primitive Roots	421
9.2 Modulus 2^{β}	422
9.2.1 Mixed Congruential Generators	425
9.3 Implementation and Portability	426
9.4 How Random Are Pseudorandom Numbers?	427
9.5 Choosing Among Multipliers	433
9.5.1 Number of Parallel Hyperplanes	435
9.5.2 Should the Simulationist Be Concerned About a Theoretically Poor Multiplier?	436
Algorithm H-N	438
9.5.3 Dangerous Multipliers	439
9.6 Multiple Replications	441
9.7 Combined Generators	442
9.7.1 Multiple Pseudorandom Number Streams	445
9.7.2 Cost of Improved Quality	446
9.8 Lessons Learned	446
9.9 Exercises	448
9.10 References	450
10 Preparing the Input	452
10.1 Arrival Processes	454
10.2 Empirical and Fitted Distributions	456
10.3 Empirical D.F. Approach	457
10.3.1 Sampling Properties	459
10.3.2 Assessing the Approximation	460
10.3.3 Sampling from $\{F_n(x)\}$	461
10.3.4 The Quantile Method	462
10.4 Characterizations from Theory	464
10.4.1 An Exponential Limit	464
10.4.2 Heavy Traffic	465
10.5 Expert Opinion	466

10.6	Choosing a Distribution	467
10.6.1	Exponential Tails	468
10.6.2	Sub- and Hyperexponential Tails	468
10.6.3	Lognormal Distribution	468
10.6.4	Inverted Gamma and Inverse Weibull Distributions	469
10.7	Support	470
10.8	Maximum Likelihood Estimation	472
10.8.1	Beta Distribution	479
10.8.2	Generalized Beta Distribution	481
10.8.3	Beta-Prime Distribution	481
10.8.4	Inverted Gamma and Inverse Weibull M.L.E.s	481
10.9	Adequacy of Fit	482
10.10	Attributes and Fitting Distributions	483
10.10.1	Attributes Affect Decision Flow	483
10.10.2	Attributes Do Not Affect Decision Flow	485
10.11	Dependent Historical Data	485
10.11.1	Time Dependence	486
10.11.2	Local Dependence	486
10.12	Library Photocopying (Section 1.4 Example)	488
10.12.1	Interarrival Times	489
10.12.2	Likelihood Ratio Test	494
10.12.3	Off-Peak Hours	494
10.12.4	Number of Pages	495
10.12.5	Photocopying Time	497
10.12.6	Relationship with Standard Linear Regression	501
10.13	Waste Generation (Section 1.5 Example)	502
	Algorithm WASTE	505
10.14	Nonhomogeneous Poisson Processes	506
	Algorithm NHPP	508
10.14.1	Clearing Books	508
	Algorithm CLEAR	510
10.15	Lessons Learned	513
10.16	References	514
Appendix	More on the Batch-Means Method	516
A.1	FNB Rule (Section 6.6.4)	517
A.2	SQRT Rule (Section 6.6.5)	520
A.3	Choosing t , l_1 , and b_1 (Section 6.6.6)	522
Author Index		525
Subject Index		529