

PART I**STUDY CHAPTERS****1 Introduction to Simulation 3**

- 1.1 Introduction 3
- 1.2 What Is Simulation? 5
- 1.3 Why Simulate? 6
- 1.4 Doing Simulation 8
- 1.5 Use of Simulation 10
- 1.6 When Simulation Is Appropriate 11
- 1.7 Qualifications for Doing Simulation 13
- 1.8 Conducting a Simulation Study 14
 - 1.8.1 Defining the Objective 15
 - 1.8.2 Planning the Study 18
- 1.9 Economic Justification of Simulation 18
- 1.10 Sources of Information on Simulation 22
- 1.11 How to Use This Book 22
- 1.12 Summary 23
- 1.13 Review Questions 24
- 1.14 Case Studies 25
- References 30

2 System Dynamics 33

- 2.1 Introduction 33
- 2.2 System Definition 34
- 2.3 System Elements 35
 - 2.3.1 Entities 36
 - 2.3.2 Activities 36
 - 2.3.3 Resources 36
 - 2.3.4 Controls 37
- 2.4 System Complexity 37
 - 2.4.1 Interdependencies 38
 - 2.4.2 Variability 39
- 2.5 System Performance Metrics 41
- 2.6 System Variables 43
 - 2.6.1 Decision Variables 43
 - 2.6.2 Response Variables 44
 - 2.6.3 State Variables 44
- 2.7 System Optimization 44

- 2.8 The Systems Approach 46
 - 2.8.1 Identifying Problems and Opportunities 47
 - 2.8.2 Developing Alternative Solutions 47
 - 2.8.3 Evaluating the Solutions 48
 - 2.8.4 Selecting and Implementing the Best Solution 48
- 2.9 Systems Analysis Techniques 48
 - 2.9.1 Hand Calculations 50
 - 2.9.2 Spreadsheets 50
 - 2.9.3 Operations Research Techniques 51
 - 2.9.4 Special Computerized Tools 54
- 2.10 Summary 55
- 2.11 Review Questions 55
- References 56

3 Simulation Basics 57

- 3.1 Introduction 57
- 3.2 Types of Simulation 57
 - 3.2.1 Static versus Dynamic Simulation 58
 - 3.2.2 Stochastic versus Deterministic Simulation 58
 - 3.2.3 Discrete-Event versus Continuous Simulation 59
- 3.3 Random Behavior 61
- 3.4 Simulating Random Behavior 63
 - 3.4.1 Generating Random Numbers 63
 - 3.4.2 Generating Random Variates 68
 - 3.4.3 Generating Random Variates from Common Continuous Distributions 71
 - 3.4.4 Generating Random Variates from Common Discrete Distributions 73

3.5	Simple Spreadsheet Simulation	74	4.8	Summary	112
3.5.1	Simulating Random Variates	75	4.9	Review Questions	113
3.5.2	Simulating Dynamic, Stochastic Systems	79		References	114
3.5.3	Simulation Replications and Output Analysis	82	5	Data Collection and Analysis	115
3.6	Summary	83	5.1	Introduction	115
3.7	Review Questions	83	5.2	Guidelines for Data Gathering	116
	References	85	5.3	Determining Data Requirements	118
4	Discrete-Event Simulation	87	5.3.1	Structural Data	118
4.1	Introduction	87	5.3.2	Operational Data	118
4.2	How Discrete-Event Simulation Works	88	5.3.3	Numerical Data	119
4.3	A Manual Discrete-Event Simulation Example	89	5.3.4	Use of a Questionnaire	119
4.3.1	Simulation Model Assumptions	91	5.4	Identifying Data Sources	120
4.3.2	Setting Up the Simulation	91	5.5	Collecting the Data	121
4.3.3	Running the Simulation	94	5.5.1	Defining the Entity Flow	121
4.3.4	Calculating Results	99	5.5.2	Developing a Description of Operation	122
4.3.5	Issues	102	5.5.3	Defining Incidental Details and Refining Data Values	123
4.4	Commercial Simulation Software	102	5.6	Making Assumptions	124
4.4.1	Modeling Interface Module	102	5.7	Statistical Analysis of Numerical Data	125
4.4.2	Model Processor	103	5.7.1	Tests for Independence	127
4.4.3	Simulation Interface Module	103	5.7.2	Tests for Identically Distributed Data	132
4.4.4	Simulation Processor	104	5.8	Distribution Fitting	134
4.4.5	Animation Processor	104	5.8.1	Frequency Distributions	135
4.4.6	Output Processor	105	5.8.2	Theoretical Distributions	138
4.4.7	Output Interface Module	105	5.8.3	Fitting Theoretical Distributions to Data	142
4.5	Simulation Using ProModel	106	5.9	Selecting a Distribution in the Absence of Data	148
4.5.1	Building a Model	106	5.9.1	Most Likely or Mean Value	149
4.5.2	Running the Simulation	106	5.9.2	Minimum and Maximum Values	149
4.5.3	Output Analysis	107	5.9.3	Minimum, Most Likely, and Maximum Values	149
4.6	Languages versus Simulators	109			
4.7	Future of Simulation	111			

5.10	Bounded versus Boundless Distributions	151
5.11	Modeling Discrete Probabilities Using Continuous Distributions	151
5.12	Data Documentation and Approval	152
5.12.1	Data Documentation Example	152
5.13	Summary	155
5.14	Review Questions	155
5.15	Case Study	158
	References	159

6 Model Building 161

6.1	Introduction	161
6.2	Converting a Conceptual Model to a Simulation Model	162
6.2.1	Modeling Paradigms	162
6.2.2	Model Definition	164
6.3	Structural Elements	165
6.3.1	Entities	165
6.3.2	Locations	167
6.3.3	Resources	169
6.3.4	Paths	171
6.4	Operational Elements	171
6.4.1	Routings	171
6.4.2	Entity Operations	172
6.4.3	Entity Arrivals	175
6.4.4	Entity and Resource Movement	177
6.4.5	Accessing Locations and Resources	178
6.4.6	Resource Scheduling	180
6.4.7	Downtimes and Repairs	181
6.4.8	Use of Programming Logic	185
6.5	Miscellaneous Modeling Issues	187
6.5.1	Modeling Rare Occurrences	187
6.5.2	Large-Scale Modeling	188
6.5.3	Cost Modeling	189
6.6	Summary	190
6.7	Review Questions	190
	References	192

7 Model Verification and Validation 193

7.1	Introduction	193
7.2	Importance of Model Verification and Validation	194
7.2.1	Reasons for Neglect	194
7.2.2	Practices That Facilitate Verification and Validation	195
7.3	Model Verification	196
7.3.1	Preventive Measures	197
7.3.2	Establishing a Standard for Comparison	198
7.3.3	Verification Techniques	198
7.4	Model Validation	202
7.4.1	Determining Model Validity	203
7.4.2	Maintaining Validation	205
7.4.3	Validation Examples	205
7.5	Summary	209
7.6	Review Questions	210
	References	210

8 Simulation Output Analysis 211

8.1	Introduction	211
8.2	Statistical Analysis of Simulation Output	212
8.2.1	Simulation Replications	213
8.2.2	Performance Estimation	214
8.2.3	Number of Replications (Sample Size)	218
8.2.4	Real-World Experiments versus Simulation Experiments	221
8.3	Statistical Issues with Simulation Output	222
8.4	Terminating and Nonterminating Simulations	225
8.4.1	Terminating Simulations	226

8.4.2	Nonterminating Simulations	226	More Than Two Alternative Systems	258	
8.5	Experimenting with Terminating Simulations	227	9.4.3	Factorial Design and Optimization	264
8.5.1	Selecting the Initial Model State	228	9.5	Variance Reduction Techniques	265
8.5.2	Selecting a Terminating Event to Control Run Length	228	9.5.1	Common Random Numbers	266
8.5.3	Determining the Number of Replications	228	9.5.2	Example Use of Common Random Numbers	268
8.6	Experimenting with Nonterminating Simulations	229	9.5.3	Why Common Random Numbers Work	270
8.6.1	Determining the Warm-up Period	229	9.6	Summary	271
8.6.2	Obtaining Sample Observations	234	9.7	Review Questions	271
8.6.3	Determining Run Length	239	References	272	
8.7	Summary	240			
8.8	Review Questions	241			
	References	242			

9 Comparing Systems 243

9.1	Introduction	243
9.2	Hypothesis Testing	244
9.3	Comparing Two Alternative System Designs	247
9.3.1	Welch Confidence Interval for Comparing Two Systems	248
9.3.2	Paired- <i>t</i> Confidence Interval for Comparing Two Systems	250
9.3.3	Welch versus the Paired- <i>t</i> Confidence Interval	252
9.4	Comparing More Than Two Alternative System Designs	253
9.4.1	The Bonferroni Approach for Comparing More Than Two Alternative Systems	253
9.4.2	Advanced Statistical Models for Comparing	

10 Simulation Optimization 273

10.1	Introduction	273
10.2	In Search of the Optimum	275
10.3	Combining Direct Search Techniques with Simulation	276
10.4	Evolutionary Algorithms	277
10.4.1	Combining Evolutionary Algorithms with Simulation	278
10.4.2	Illustration of an Evolutionary Algorithm's Search of a Response Surface	279
10.5	Strategic and Tactical Issues of Simulation Optimization	281
10.5.1	Operational Efficiency	281
10.5.2	Statistical Efficiency	282
10.5.3	General Optimization Procedure	282
10.6	Formulating an Example Optimization Problem	284
10.6.1	Problem Description	284
10.6.2	Demonstration of the General Optimization Procedure	286
10.7	Real-World Simulation Optimization Project	289
10.7.1	Problem Description	289

10.7.2	Simulation Model and Performance Measure	290	11.7	Summary	320
10.7.3	Toyota Solution Technique	291	11.8	Review Questions	320
10.7.4	Simulation Optimization Technique	292		References	320
10.7.5	Comparison of Results	292			
10.8	Summary	294	12	Modeling Material Handling Systems	323
10.9	Review Questions	294			
	References	295	12.1	Introduction	323
11	Modeling Manufacturing Systems	299	12.2	Material Handling Principles	323
11.1	Introduction	299	12.3	Material Handling Classification	324
11.2	Characteristics of Manufacturing Systems	300	12.4	Conveyors	325
11.3	Manufacturing Terminology	301	12.4.1	Conveyor Types	325
11.4	Use of Simulation in Manufacturing	303	12.4.2	Operational Characteristics	327
11.5	Applications of Simulation in Manufacturing	304	12.4.3	Modeling Conveyor Systems	328
	11.5.1 Methods Analysis	305	12.4.4	Modeling Single-Section Conveyors	329
	11.5.2 Plant Layout	306	12.4.5	Modeling Conveyor Networks	330
	11.5.3 Batch Sizing	308	12.5	Industrial Vehicles	330
	11.5.4 Production Control	309	12.5.1	Modeling Industrial Vehicles	331
	11.5.5 Inventory Control	312	12.6	Automated Storage/Retrieval Systems	331
	11.5.6 Supply Chain Management	313	12.6.1	Configuring an AS/RS	332
	11.5.7 Production Scheduling	314	12.6.2	Modeling AS/RSS	334
	11.5.8 Real-Time Control	315	12.7	Carousels	335
	11.5.9 Emulation	315	12.7.1	Carousel Configurations	335
11.6	Manufacturing Modeling Techniques	316	12.7.2	Modeling Carousels	335
	11.6.1 Modeling Machine Setup	316	12.8	Automatic Guided Vehicle Systems	336
	11.6.2 Modeling Machine Load and Unload Time	316	12.8.1	Designing an AGVS	337
	11.6.3 Modeling Rework and Scrap	317	12.8.2	Controlling an AGVS	338
	11.6.4 Modeling Transfer Machines	317	12.8.3	Modeling an AGVS	339
	11.6.5 Continuous Process Systems	319	12.9	Cranes and Hoists	340
			12.9.1	Crane Management	340
			12.9.2	Modeling Bridge Cranes	340
			12.10	Robots	341
			12.10.1	Robot Control	341
			12.10.2	Modeling Robots	342

- 12.11 Summary 343
- 12.12 Review Questions 343
- References 344

13 Modeling Service Systems 345

- 13.1 Introduction 345
- 13.2 Characteristics of Service Systems 346
- 13.3 Performance Measures 347
- 13.4 Use of Simulation in Service Systems 348
- 13.5 Applications of Simulation in Service Industries 350
 - 13.5.1 Process Design 350
 - 13.5.2 Method Selection 350
 - 13.5.3 System Layout 351
 - 13.5.4 Staff Planning 351
 - 13.5.5 Flow Control 352
- 13.6 Types of Service Systems 352
 - 13.6.1 Service Factory 352
 - 13.6.2 Pure Service Shop 353
 - 13.6.3 Retail Service Store 353
 - 13.6.4 Professional Service 354
 - 13.6.5 Telephonic Service 354
 - 13.6.6 Delivery Service 355
 - 13.6.7 Transportation Service 355
- 13.7 Simulation Example: A Help Desk Operation 355
 - 13.7.1 Background 356
 - 13.7.2 Model Description 356
 - 13.7.3 Results 359
- 13.8 Summary 360
- 13.9 Review Questions 360
- References 360

PART II

LABS

1 Introduction to ProModel 365

- L1.1 ProModel Opening Screen 366
- L1.2 ProModel Menu Bar 366
- L1.3 ProModel Tool Bars 367

- L1.4 Run-Time Menus and Controls 368
- L1.5 Simulation in Decision Making 369
 - L1.5.1 California Cellular 370
 - L1.5.2 ATM System 373
- L1.6 Exercises 376

2 Building Your First Model 379

- L2.1 Building Your First Simulation Model 379
- L2.2 Building the Bank of USA ATM Model 387
- L2.3 Locations, Entities, Processing, and Arrivals 392
- L2.4 Add Location 396
- L2.5 Effect of Variability on Model Performance 397
- L2.6 Blocking 398
- L2.7 Effect of Traffic Intensity on System Performance 401
- L2.8 Exercises 402

3 ProModel's Output Viewer 405

- L3.1 The Output Viewer 405
- L3.2 Report Tables 407
- L3.3 Column Charts 408
- L3.4 Utilization Charts 409
- L3.5 State Charts 409
- L3.6 Time-Series Charts 412
- L3.7 Dynamic Plots 413
- L3.8 Exercises 415

4 Basic Modeling Concepts 419

- L4.1 Multiple Locations, Multiple Entity Types 419
- L4.2 Multiple Parallel Identical Locations 421
- L4.3 Resources 425
- L4.4 Routing Rules 426
- L4.5 Variables 429
- L4.6 Uncertainty in Routing—Track Defects and Rework 432

L4.7	Batching Multiple Entities of Similar Type	434	L6.2	Cycle Time	479
L4.7.1	Temporary Batching	434	L6.3	Sorting, Inspecting a Sample, and Rework	480
L4.7.2	Permanent Batching	436	L6.4	Preventive Maintenance and Machine Breakdowns	483
L4.8	Attaching One or More Entities to Another Entity	438	L6.4.1	Downtime Using MTBF and MTTR Data	484
L4.8.1	Permanent Attachment	438	L6.4.2	Downtime Using MTTF and MTTR Data	484
L4.8.2	Temporary Attachment	439	L6.5	Shift Working Schedule	488
L4.9	Accumulation of Entities	443	L6.6	Job Shop	491
L4.10	Splitting of One Entity into Multiple Entities	444	L6.7	Modeling Priorities	492
L4.11	Decision Statements	445	L6.7.1	Selecting among Upstream Processes	493
L4.11.1	IF-THEN-ELSE Statement	445	L6.8	Modeling a Pull System	494
L4.11.2	WHILE...DO Loop	447	L6.8.1	Pull Based on Downstream Demand	495
L4.11.3	DO...WHILE Loop	449	L6.8.2	Kanban System	497
L4.11.4	DO...UNTIL Statement	449	L6.9	Tracking Cost	499
L4.11.5	GOTO Statement	451	L6.10	Importing a Background	502
L4.11.6	WAIT UNTIL Statement	452	L6.11	Defining and Displaying Views	503
L4.12	Periodic System Shutdown	453	L6.12	Creating a Model Package	506
L4.13	Exercises	456	L6.13	Exercises	508
5	Fitting Statistical Distributions to Input Data	465	7	Model Verification and Validation	517
L5.1	An Introduction to Stat::Fit	465	L7.1	Verification of an Inspection and Rework Model	517
L5.2	An Example Problem	467	L7.2	Verification by Tracing the Simulation Model	519
L5.3	Auto::Fit Input Data	470	L7.3	Debugging the Simulation Model	520
L5.4	Exercises	472	L7.3.1	Debugging ProModel Logic	522
6	Intermediate Model Building	475	L7.3.2	Basic Debugger Options	523
L6.1	Attributes	475	L7.3.3	Advanced Debugger Options	524
L6.1.1	Using Attributes to Track Customer Types	476	L7.4	Exercises	525
L6.1.2	Using Attributes and Local Variables	478			

8 Simulation Output Analysis 527	L10.2.2 Multiterm Objective Functions 583
L8.1 Terminating versus Nonterminating Simulations 527	L10.2.3 Target Range Objective Functions 586
L8.2 Terminating Simulation 528	L10.3 Conclusions 588
L8.2.1 Starting and Terminating Conditions (Run Length) 529	L10.4 Exercises 590
L8.2.2 Replications 530	
L8.2.3 Required Number of Replications 534	
L8.2.4 Simulation Output Assumptions 534	
L8.3 Nonterminating Simulation 536	11 Modeling Manufacturing Systems 595
L8.3.1 Warm-up Time and Run Length 538	L11.1 Macros and Run-time Interface 595
L8.3.2 Replications or Batch Intervals 543	L11.2 Generating Scenarios 599
L8.3.3 Required Batch Interval Length 545	L11.3 External Files 600
L8.4 Exercises 547	L11.4 Arrays 604
9 Comparing Alternative Systems 549	L11.5 Subroutines 607
L9.1 Overview of Statistical Methods 549	L11.6 Random Number Streams 611
L9.2 Three Alternative Systems 550	L11.7 Merging a Submodel 611
L9.3 Common Random Numbers 553	L11.8 Exercises 614
L9.4 Bonferroni Approach with Paired- <i>t</i> Confidence Intervals 554	
L9.5 Analysis of Designed Experiments 557	12 Material Handling Concepts 617
L9.5.1 Full Factorial Design Simulation Experiment 558	L12.1 Conveyors 617
L9.5.2 Fraction Factorial Experiment 561	L12.1.1 Single Conveyor 618
L9.6 Exercises 563	L12.1.2 Multiple Conveyors 618
10 Simulation Optimization with SimRunner 569	L12.1.3 Recirculating Conveyor 620
L10.1 Introduction to SimRunner 569	L12.2 Resources, Path Networks, and Interfaces 621
L10.2 SimRunner Projects 572	L12.2.1 Resource as Material Handler 622
L10.2.1 Single Term Objective Functions 574	L12.2.2 Resource as Machine Operator and Material Handler 625
	L12.3 Crane Systems 626
	L12.4 Exercises 628
	Reference 637
13 Modeling Service Systems 639	
	L13.1 Balking of Customers 639
	L13.2 Table Functions 641
	L13.3 Arrival Cycles 643
	L13.4 User Distribution 646

L13.5	Modeling a University Cafeteria	647
L13.6	Modeling a Call Center—Outsource2US	651
L13.7	Modeling a Triage—Los Angeles County Hospital	654
L13.8	Modeling an Office (DMV)	657
L13.9	Exercises	662

Appendix A	Continuous and Discrete Distributions in ProModel	669
-------------------	---	-----

Appendix B	Critical Values for Student's t Distribution and Standard Normal Distribution	674
-------------------	---	-----

Appendix C	F Distribution for $\alpha = 0.05$	675
-------------------	--------------------------------------	-----

Appendix D	Critical Values for Chi-Square Distribution	676
-------------------	---	-----

Index	677
--------------	-----