

TABLE OF CONTENTS

About the Companion Website	xvii
Preface	xix
Acknowledgments	xxiii
1 Concepts of Simulation Modeling	1
1.1 Overview, 1	
1.2 System Modeling, 2	
1.2.1 System Concept, 2	
1.2.2 Modeling Concept, 4	
1.2.3 Types of Models, 5	
1.3 Simulation Modeling, 11	
1.3.1 Simulation Defined, 11	
1.3.2 Simulation Taxonomy, 12	
1.4 The Role of Simulation, 15	
1.4.1 Simulation Justified, 15	
1.4.2 Simulation Applications, 16	
1.4.3 Simulation Precautions, 17	
1.5 Simulation Methodology, 20	
1.5.1 Identify Problem/Opportunity, 20	
1.5.2 Develop Solution/Improvement Alternatives, 21	
1.5.3 Evaluate Solution Alternatives, 21	
1.5.4 Select the Best Alternative, 22	
1.5.5 Implement the Selected Alternative, 22	

- 1.6 Steps in a Simulation Study, 22
 - 1.6.1 Problem Formulation, 23
 - 1.6.2 Setting Study Objectives, 23
 - 1.6.3 Conceptual Modeling, 25
 - 1.6.4 Data Collection, 26
 - 1.6.5 Model Building, 27
 - 1.6.6 Model Verification, 30
 - 1.6.7 Model Validation, 30
 - 1.6.8 Model Analysis, 31
 - 1.6.9 Study Documentation, 32
- 1.7 Simulation Software, 34
 - 1.7.1 WITNESS® Simulation Software, 35
- 1.8 Summary, 36
 - Questions and Exercises, 37
 - Bibliography, 38

2 World-Views of Simulation

41

- 2.1 Overview, 41
- 2.2 System Modeling with DES, 42
 - 2.2.1 System Structure, 42
 - 2.2.2 System Layout, 43
 - 2.2.3 System Data, 43
 - 2.2.4 System Logic, 44
 - 2.2.5 System Statistics, 45
- 2.3 Elements of Discrete Event Simulation (DES), 45
 - 2.3.1 System Entities (EN), 45
 - 2.3.2 System State (S), 46
 - 2.3.3 State Variables (VR), 46
 - 2.3.4 System Events (E), 47
 - 2.3.5 System Activities (A), 48
 - 2.3.6 System Resources (R), 48
 - 2.3.7 System Delay (D), 50
 - 2.3.8 System Logic (L), 50
- 2.4 DES Functionality, 51
 - 2.4.1 Discrete-Event Mechanism, 52
 - 2.4.2 Time-Advancement Mechanism, 54
 - 2.4.3 Random Sampling Mechanism, 55
 - 2.4.4 Statistical Accumulation Mechanism, 58
 - 2.4.5 Animation Mechanism, 59
- 2.5 Example of DES Mechanisms, 60
- 2.6 Monte Carlo Simulation (MCS), 65
- 2.7 Continuous Simulation, 68
 - 2.7.1 WITNESS® for Continuous Simulation, 69
 - 2.7.2 Hybrid Simulation, 69

- 2.8 WITNESS® World-views of Simulation, 70
 - 2.8.1 Attribute, 72
 - 2.8.2 Buffer, 72
 - 2.8.3 Carrier, 72
 - 2.8.4 Conveyor, 73
 - 2.8.5 Fluid, 73
 - 2.8.6 Labor, 74
 - 2.8.7 Machine, 74
 - 2.8.8 Part, 75
 - 2.8.9 Path, 75
 - 2.8.10 Pipe, 75
 - 2.8.11 Processor, 75
 - 2.8.12 Sections, 75
 - 2.8.13 Station, 76
 - 2.8.14 Tank, 76
 - 2.8.15 Track, 76
 - 2.8.16 Vehicle, 76
- 2.9 Summary, 77
 - Questions and Exercises, 78
 - Bibliography, 80

3 WITNESS® Environment

83

- 3.1 Overview, 83
- 3.2 The WITNESS® Environment, 83
- 3.3 Menus, 85
 - 3.3.1 General Menu Operation, 86
- 3.4 Tool Bars, 86
 - 3.4.1 Standard Tool Bar, 86
 - 3.4.2 Views Toolbar, 87
 - 3.4.3 Element Tool Bar, 89
 - 3.4.4 Model Tool Bar, 92
 - 3.4.5 Assistant Toolbar, 92
 - 3.4.6 Run Toolbar, 93
 - 3.4.7 Reporting Toolbar, 95
 - 3.4.8 Display Edit Toolbar, 96
 - 3.4.9 Creating a New Toolbar, 99
- 3.5 Dialog Boxes and Property Sheets, 100
 - 3.5.1 Entry/Field Types, 100
- 3.6 Windows, 102
- 3.7 Layers, 103
- 3.8 The WITNESS® Editor, 103
 - 3.8.1 Editor Features, 103
 - 3.8.2 Manipulating a Window, 105

3.9	Window Operations, 105	
3.9.1	Windows Options, 105	
3.9.2	The Interact Box, 106	
3.9.3	The Clock (Time), 107	
3.9.4	The Analog Clock, 107	
3.9.5	Copying, Cutting, and Pasting, 107	
3.9.6	Copy and Cut Element's Display or Detail Features, 108	
3.10	The Help Facility, 108	
3.11	The Basic Elements, 109	
	Questions and Exercises, 109	
	Bibliography, 110	
4	Basic WITNESS® Modeling Techniques	111
4.1	Overview, 111	
4.2	Step-by-Step Model Building, 111	
4.3	Modeling a Simple Manufacturing Process, 112	
4.3.1	Define: Specifying Elements of the Manufacturing Process Simulation Model, 114	
4.3.2	Detail: Adding Specifications for Elements to the Model, 114	
4.3.3	Display: Modifying the Appearance of Elements in the Layout Window, 118	
4.4	Modeling a Service Process, 126	
4.4.1	Service Model Example, 126	
4.5	WITNESS® Code, 141	
4.6	An Extended Example, 141	
	Questions and Exercises, 143	
	Bibliography, 146	
5	Modeling Material Handling Systems	149
5.1	Overview, 149	
5.2	Material Handling Systems, 149	
5.3	Material Handling Systems in WITNESS®, 150	
5.4	Modeling Conveyors, 152	
5.5	Modeling Paths for Labor and Parts Transit, 156	
5.6	Modeling Vehicles and Tracks, 161	
5.7	Modeling Power-&-Free Systems, 167	
	Questions and Exercises, 176	
	Bibliography, 176	
6	Basic Probability and Statistics for Simulation	179
6.1	Overview, 179	
6.2	Random Variables (RVs), 179	
6.2.1	Examples of Discrete Random Variables, 180	
6.2.2	Examples of Continuous Random Variables, 181	

6.3	Point Estimation, 182	
6.4	Confidence Intervals for the Population Mean, 182	
6.5	Confidence Intervals for the Population Variance and Standard Deviation, 184	
6.6	Sample Size Determination when Estimating Population Mean, 185	
6.7	Theoretical Probability Distributions, 186	
6.7.1	The Uniform Distribution, 187	
6.7.2	The Normal Distribution, 187	
6.7.3	The Exponential Distribution, 190	
6.7.4	The Erlang Distribution, 190	
6.7.5	The Gamma Distribution, 192	
6.7.6	The Weibull Distribution, 193	
6.7.7	Triangular Distribution, 193	
	Questions and Exercises, 197	
	Bibliography, 198	
7	Simulation Input Modeling	199
7.1	Overview, 199	
7.2	Determining Data Requirements, 200	
7.3	Methods of Data Collection, 202	
7.4	Representing Collected Data, 211	
7.5	Validating Collected Data, 213	
7.5.1	Filtering the Data from Outliers and Wrong Measures, 215	
7.5.2	Testing the Data for Independence, 215	
7.5.3	Testing if Data are Identically Distributed, 218	
7.6	Fitting Probability Distributions to Collected Data, 219	
7.6.1	Using Empirical Distributions, 225	
7.7	WITNESS® Input Modeling, 226	
7.7.1	WITNESS® RNG, 227	
7.7.2	Incorporating Collected Data in WITNESS®, 229	
7.7.3	Using Databases with WITNESS®, 233	
7.8	Practical Aspects of Input Modeling, 234	
7.8.1	Example of Input Modeling: Auto Service Center, 236	
7.8.2	Example of Input Modeling: ER Simulation, 243	
7.9	Summary, 249	
	Questions and Exercises, 249	
	Bibliography, 252	
8	Simulation Output Analysis	253
8.1	Overview, 253	
8.2	Terminating Versus Steady-State Simulation, 254	
8.2.1	Terminating Simulation, 254	
8.2.2	Steady-State Simulation, 257	

8.3	Determining Simulation Run Controls, 259	
8.3.1	Determining Warm-Up Period, 260	
8.3.2	Determining Simulation Run Length, 263	
8.3.3	Determining the Number of Simulation Runs, 266	
8.4	Variability in Simulation Outputs, 267	
8.4.1	Variance Reduction Techniques, 269	
8.5	Simulation Output Analysis, 270	
8.5.1	Statistical Analysis of Simulation Outputs, 272	
8.5.2	Experimental Design, 285	
8.6	Example: Output Analyses of a Clinic Simulation, 291	
8.7	WITNESS® Modules for Simulation Output Analysis, 296	
8.7.1	WITNESS® Outputs and Charts, 296	
8.7.2	WITNESS® Costing, 297	
8.7.3	WITNESS® Scenario Manager, 299	
8.7.4	WITNESS® Documentor, 299	
8.7.5	WITNESS® Optimizer, 300	
8.8	Summary, 300	
	Questions and Exercises, 301	
	Bibliography, 303	
9	Model Verification and Validation Techniques	305
9.1	Overview, 305	
9.2	Model Verification Techniques, 306	
9.2.1	Verifying Model Inputs, 308	
9.2.2	Verifying Model Logic, 309	
9.2.3	Verifying Model Outputs, 314	
9.3	Model Validation Techniques, 314	
9.3.1	Validating Model Inputs, 316	
9.3.2	Validating Model Behavior, 318	
9.3.3	Validating Model Outputs, 319	
9.4	Verifying WITNESS® Models, 320	
9.5	Summary, 330	
	Question and Exercise, 330	
	Bibliography, 332	
10	Simulation Project Management	331
10.1	Overview, 331	
10.2	Define the Problem, 332	
10.2.1	Define the Objectives of the Study, 332	
10.2.2	List the Specific Issues to Be Addressed, 334	
10.2.3	Determine the Boundary or Domain of the Study, 334	
10.2.4	Determine the Level of Detail or Proper Abstraction Level, 334	

- 10.2.5 Determine if a Simulation Model is Actually Needed. 335
- 10.2.6 Estimate the Required Resources Needed to Do the Study. 335
- 10.2.7 Perform a Cost-Benefit Analysis. 335
- 10.2.8 Create a Planning Chart of the Proposed Project. 336
- 10.2.9 Write a Formal Proposal. 336
- 10.3 Design the Study. 337
 - 10.3.1 Estimate the Life Cycle of the Model. 338
 - 10.3.2 List Broad Assumptions. 338
 - 10.3.3 Estimate the Number of Models Required. 338
 - 10.3.4 Determine the Animation Requirements. 338
 - 10.3.5 Select the Tool. 339
 - 10.3.6 Determine the Level of Data Available and What Data is Needed. 339
 - 10.3.7 Determine the Human Requirements and Skill Levels. 339
 - 10.3.8 Determine the Audience (Levels of Management). 340
 - 10.3.9 Identify the Deliverables. 340
 - 10.3.10 Determine the Priority of the Study in Relationship to Other Studies. 340
 - 10.3.11 Set Milestone Dates. 341
 - 10.3.12 Write the Project Functional Specifications. 341
- 10.4 Design the Conceptual Model. 341
 - 10.4.1 Decide on Continuous, Discrete, or Combined Modeling. 342
 - 10.4.2 Determine the Elements that Drive the System. 342
 - 10.4.3 Determine the Entities that Should Represent the System Elements. 343
 - 10.4.4 Determine the Level of Detail Needed to Describe the System Components. 343
 - 10.4.5 Determine the Graphics Requirements of the Model. 343
 - 10.4.6 Identify the Areas That Utilize Special Control Logic. 344
 - 10.4.7 Determine How to Collect Statistics in the Model and Communicate Results to the Customer. 344
- 10.5 Formulate Inputs, Assumptions, and Process Definition. 344
 - 10.5.1 Specify the Operating Philosophy of the System. 345
 - 10.5.2 Describe the Physical Constraints of the System. 345
 - 10.5.3 Describe the Creation and Termination of Dynamic Elements. 345
 - 10.5.4 Describe the Process in Detail. 345
 - 10.5.5 Obtain the Operation Specifications. 346
 - 10.5.6 Obtain the Material Handling Specifications. 346
 - 10.5.7 List All the Assumptions. 346

- 10.5.8 Analyze the Input Data, 346
- 10.5.9 Specify the Runtime Parameters, 347
- 10.5.10 Write the Detailed Project Functional Specifications, 347
- 10.5.11 Validate the Conceptual Model, 347
- 10.6 Build, Verify, and Validate the Model, 348
- 10.7 Experiment with the Model, 348
- 10.8 Documentation and Presentation, 349
 - 10.8.1 Project Book, 350
 - 10.8.2 Documentation of Model Input, Code, and Output, 350
 - 10.8.3 Project Functional Specifications, 350
 - 10.8.4 User Manual, 350
 - 10.8.5 Maintenance Manual, 351
 - 10.8.6 Discussion and Explanation of Model Results, 351
 - 10.8.7 Recommendations for Further Areas of Study, 351
 - 10.8.8 Final Project Report and Presentation, 351
- 10.9 Define the Model Life Cycle, 352
 - 10.9.1 Construct User-Friendly Model Input and Output Interfaces, 353
 - 10.9.2 Determine Model and Training Responsibility, 353
 - 10.9.3 Establish Data Integrity and Collection Procedures, 354
 - 10.9.4 Perform Field Data Validation Tests, 354
- 10.10 Summary, 354
 - Bibliography, 354

11 Manufacturing Simulation Case Studies

357

- 11.1 Overview, 357
- 11.2 Hybrid Simulation of Titanium Manufacturing Process, 358
 - 11.2.1 Model Description, 358
 - 11.2.2 Model Assumptions, 360
 - 11.2.3 Process Logic, 360
 - 11.2.4 Start-up Conditions and Model Run Length, 361
 - 11.2.5 Model Input Data, 361
 - 11.2.6 Model Outputs, 363
 - 11.2.7 The WITNESS® Model, 363
 - 11.2.8 Model Verification and Validation, 366
 - 11.2.9 Model Experiments, 367
 - 11.2.10 Project Results and Conclusions, 371
- 11.3 Paint Capacity Study of an Aviation Company, 373
 - 11.3.1 Paint Shop Layout, 373
 - 11.3.2 Study Assumptions, 373
 - 11.3.3 Data Collection, 375
 - 11.3.4 The WITNESS® Model, 375
 - 11.3.5 Study Results, 375
 - 11.3.6 Throughput Improvement Opportunities, 375

- 11.4 Simulation of a Seamless Pipe Facility, 376
 - 11.4.1 Study Objectives Include, 377
 - 11.4.2 System Description, 379
 - 11.4.3 Input Parameters, 379
 - 11.4.4 Schedule Data, 381
 - 11.4.5 The WITNESS® Model, 381
 - 11.4.6 Base Model–Worst-Case Schedule, 381
 - 11.4.7 Results Summary, 387
 - 11.4.8 Observations Summary, 389
 - 11.4.9 Conclusions, 393
- 11.5 Summary, 393
 - Bibliography, 393

12 Service Simulation Case Studies

395

- 12.1 Overview, 395
- 12.2 Elements of Service Systems, 396
 - 12.2.1 System Entities, 396
 - 12.2.2 Service Providers, 396
 - 12.2.3 Customer Service, 397
 - 12.2.4 Staff and Human Resources, 397
 - 12.2.5 Facility Layout and Physical Structure, 397
 - 12.2.6 Operating Policies, 398
- 12.3 Characteristics of Service Systems, 398
- 12.4 Modeling Service Systems, 399
 - 12.4.1 Modeling Considerations, 399
 - 12.4.2 Model Elements, 401
 - 12.4.3 Model Control Factors, 401
 - 12.4.4 Model Performance Measures, 402
- 12.5 Applications of Service System Simulation, 402
 - 12.5.1 Examples of Service Systems Simulation, 403
- 12.6 Case Studies on Service Systems Simulation, 404
 - 12.6.1 Car Wash, 404
 - 12.6.2 Harbor Traffic Simulation, 406
 - 12.6.3 Bank Simulation Example, 409
 - 12.6.4 Clinic Simulation Example, 411
 - 12.6.5 Public Service Office Simulation, 417
- 12.7 Summary, 423
 - Bibliography, 423

13 Simulation-Based Optimization Methods

425

- 13.1 Overview, 425
- 13.2 Optimization Approaches in Simulation Studies, 426
- 13.3 Simulation-Based Optimization, 427
- 13.4 WITNESS® Experimenter, 429

13.4.1	Comparison of Multiple Alternatives with WITNESS® Experimenter, 429	
13.4.2	More Advanced Use of the Experimenter, 435	
13.5	Optimization within the WITNESS® Experimenter, 440	
13.5.1	Productivity-Cost Tradeoffs Explored with the Experimenter, 444	
13.6	Summary, 447	
	Questions and Exercises, 447	
	Bibliography, 448	
14	Simulation for Lean Systems	449
14.1	Overview, 449	
14.2	Basics of Lean Systems, 450	
14.2.1	Lean Principles, 450	
14.2.2	Lean Techniques, 453	
14.2.3	Value Stream Mapping, 454	
14.3	Simulation-Based Lean Systems, 457	
14.3.1	Lean Simulation Example, 459	
14.4	Lean Using WITNESS®, 477	
14.5	Summary, 485	
	Question and Exercises, 485	
	Bibliography, 487	
15	Simulation for Six Sigma	489
15.1	Overview, 489	
15.2	Six Sigma Quality, 490	
15.2.1	Six Sigma Capability, 493	
15.2.2	Determining Process Sigma Rating, 494	
15.3	Six Sigma Methods, 496	
15.3.1	DMAIC Process, 497	
15.3.2	Design for Six Sigma (DFSS), 499	
15.4	WITNESS® for Six Sigma, 501	
15.4.1	Sigma Ratings in WITNESS®, 504	
15.5	Simulation-Based Six Sigma, 520	
15.5.1	Simulation-Based DMAIC, 520	
15.5.2	Simulation-Based DFSS, 526	
15.5.3	Lean Six Sigma (LSS), 537	
15.6	Summary, 545	
	Questions and Exercises, 546	
	Bibliography, 547	
	Appendix	549
	Index	553