

Simulation with Arena

Fourth Edition

W. David Kelton

Professor

*Department of Quantitative Analysis and Operations Management
University of Cincinnati*

Randall P. Sadowski

Product Manager

*Application Programs
Rockwell Automation*

David T. Sturrock

Product Manager

*Simulation
Rockwell Automation*

• HOCHSCHULE
• LIECHTENSTEIN
Bibliothek



Higher Education

Boston Burr Ridge, IL Dubuque, IA New York San Francisco St. Louis
Bangkok Bogota Caracas Kuala Lumpur Lisbon London Madrid Mexico City
Milan Montreal New Delhi Santiago Seoul Singapore Sydney Taipei Toronto

Contents

Chapter 1:	What Is Simulation?	1
1.1	Modeling	1
1.1.1	What's Being Modeled?	2
1.1.2	How About Just Playing with the System?	3
1.1.3	Sometimes You Can't (or Shouldn't) Play with the System	3
1.1.4	Physical Models	4
1.1.5	Logical (or Mathematical) Models	4
1.1.6	What Do You Do with a Logical Model?	4
1.2	Computer Simulation	5
1.2.1	Popularity and Advantages	5
1.2.2	The Bad News	6
1.2.3	Different Kinds of Simulations	7
1.3	How Simulations Get Done	8
1.3.1	By Hand	8
1.3.2	Programming in General-Purpose Languages	9
1.3.3	Simulation Languages	10
1.3.4	High-Level Simulators	10
1.3.5	Where Arena Fits In	10
1.4	When Simulations Are Used	12
1.4.1	The Early Years	12
1.4.2	The Formative Years	12
1.4.3	The Recent Past	13
1.4.4	The Present	13
1.4.5	The Future	13
Chapter 2:	Fundamental Simulation Concepts	15
2.1	An Example	15
2.1.1	The System	15
2.1.2	Goals of the Study	17
2.2	Analysis Options	18
2.2.1	Educated Guessing	18
2.2.2	Queueing Theory	19
2.2.3	Mechanistic Simulation	20
2.3	Pieces of a Simulation Model	20
2.3.1	Entities	20
2.3.2	Attributes	21
2.3.3	(Global) Variables	21
2.3.4	Resources	22
2.3.5	Queues	22

	2.3.6	Statistical Accumulators.....	23
	2.3.7	Events.....	23
	2.3.8	Simulation Clock.....	24
	2.3.9	Starting and Stopping.....	24
2.4		Event-Driven Hand Simulation.....	25
	2.4.1	Outline of the Action.....	25
	2.4.2	Keeping Track of Things.....	26
	2.4.3	Carrying It Out.....	28
	2.4.4	Finishing Up.....	32
2.5		Event- and Process-Oriented Simulation.....	32
2.6		Randomness in Simulation.....	34
	2.6.1	Random Input, Random Output.....	34
	2.6.2	Replicating the Example.....	35
	2.6.3	Comparing Alternatives.....	36
2.7		Simulating with Spreadsheets.....	38
	2.7.1	A Newsvendor Problem.....	38
	2.7.2	A Single-Server Queue.....	43
	2.7.3	Extensions and Limitations.....	47
2.8		Overview of a Simulation Study.....	47
2.9		Exercises.....	48
Chapter 3: A Guided Tour Through Arena.....			53
3.1		Starting Up.....	53
3.2		Exploring the Arena Window.....	55
	3.2.1	Opening a Model.....	55
	3.2.2	Basic Interaction and Pieces of the Arena Window.....	56
	3.2.3	Panning, Zooming, Viewing, and Aligning in the Flowchart View.....	58
	3.2.4	Modules.....	60
	3.2.5	Internal Model Documentation.....	61
3.3		Browsing Through an Existing Model: Model 3-1.....	62
	3.3.1	The Create Flowchart Module.....	62
	3.3.2	The Entity Data Module.....	63
	3.3.3	The Process Flowchart Module.....	64
	3.3.4	The Resource Data Module.....	66
	3.3.5	The Queue Data Module.....	67
	3.3.6	Animating Resources and Queues.....	67
	3.3.7	The Dispose Flowchart Module.....	68
	3.3.8	Connecting Flowchart Modules.....	68
	3.3.9	Dynamic Plots.....	69
	3.3.10	Dressing Things Up.....	71
	3.3.11	Setting the Run Conditions.....	72
	3.3.12	Running It.....	73
	3.3.13	Viewing the Reports.....	74

3.4	Building Model 3-1 Yourself.....	79
3.4.1	New Model Window and Basic Process Panel.....	80
3.4.2	Place and Connect the Flowchart Modules.....	81
3.4.3	The Create Flowchart Module.....	81
3.4.4	Displays.....	82
3.4.5	The Entity Data Module.....	83
3.4.6	The Process Flowchart Module.....	83
3.4.7	The Resource and Queue Data Modules.....	84
3.4.8	Resource Animation.....	84
3.4.9	The Dispose Flowchart Module.....	85
3.4.10	Dynamic Plots.....	85
3.4.11	Window Dressing.....	88
3.4.12	The Run > Setup Dialog Boxes.....	89
3.4.13	Establishing Named Views.....	89
3.5	Case Study: Specialized Serial Processing vs. Generalized Parallel Processing.....	89
3.5.1	Model 3-2: Serial Processing - Specialized Separated Work.....	90
3.5.2	Model 3-3: Parallel Processing - Generalized Integrated Work.....	92
3.5.3	Models 3-4 and 3-5: The Effect of Task-Time Variability.....	95
3.6	More on Menus, Toolbars, Drawing, and Printing.....	97
3.6.1	Menus.....	97
3.6.2	Toolbars.....	102
3.6.3	Drawing.....	105
3.6.4	Printing.....	107
3.7	Help!.....	107
3.8	More on Running Models.....	108
3.9	Summary and Forecast.....	109
3.10	Exercises.....	110
 Chapter 4: Modeling Basic Operations and Inputs.....		 115
4.1	Model 4-1: An Electronic Assembly and Test System.....	115
4.1.1	Developing a Modeling Approach.....	116
4.1.2	Building the Model.....	117
4.1.3	Running the Model.....	128
4.1.4	Viewing the Results.....	130
4.2	Model 4-2: The Enhanced Electronic Assembly and Test System.....	132
4.2.1	Expanding Resource Representation: Schedules and States.....	133
4.2.2	Resource Schedules.....	134
4.2.3	Resource Failures.....	138
4.2.4	Frequencies.....	140
4.2.5	Results of Model 4-2.....	143
4.3	Model 4-3: Enhancing the Animation.....	147
4.3.1	Changing Animation Queues.....	148
4.3.2	Changing Entity Pictures.....	150

4.3.3	Adding Resource Pictures.....	152
4.3.4	Adding Variables and Plots.....	154
4.4	Model 4-4: The Electronic Assembly and Test System with Part Transfers	156
4.4.1	Some New Arena Concepts: Stations and Transfers.....	156
4.4.2	Adding the Route Logic.....	158
4.4.3	Altering the Animation.....	161
4.5	Finding and Fixing Errors.....	164
4.6	Input Analysis: Specifying Model Parameters and Distributions.....	172
4.6.1	Deterministic vs. Random Inputs.....	173
4.6.2	Collecting Data.....	174
4.6.3	Using Data.....	175
4.6.4	Fitting Input Distributions via the Input Analyzer.....	176
4.6.5	No Data?.....	183
4.6.6	Nonstationary Arrival Processes.....	186
4.6.7	Multivariate and Correlated Input Data.....	187
4.7	Summary and Forecast.....	187
4.8	Exercises.....	188
 Chapter 5: Modeling Detailed Operations.....		195
5.1	Model 5-1: A Simple Call Center System.....	196
5.2	New Modeling Issues.....	197
5.2.1	Customer Rejections and Balking.....	197
5.2.2	Three-Way Decisions.....	198
5.2.3	Variables and Expressions.....	198
5.2.4	Storages.....	199
5.2.5	Terminating or Steady-State.....	199
5.3	Modeling Approach.....	200
5.4	Building the Model.....	202
5.4.1	Create Arrivals and Direct to Service.....	202
5.4.2	Arrival Cutoff Logic.....	208
5.4.3	Technical Support Calls.....	210
5.4.4	Sales Calls.....	213
5.4.5	Order-Status Calls.....	214
5.4.6	System Exit and Run Setup.....	220
5.4.7	Animation.....	222
5.5	Model 5-2; The Enhanced Call Center System	225
5.5.1	The New Problem Description.....	225
5.5.2	New Concepts.....	227
5.5.3	Defining the Data.....	229
5.5.4	Modifying the Model.....	233
5.6	Model 5-3: The Enhanced Call Center with More Output Performance Measures.....	238
5.7	Model 5-4: An (s, S) Inventory Simulation.....	244
5.7.1	System Description.....	244
5.7.2	Simulation Model.....	246

5.8	Summary and Forecast.....	258
5.9	Exercises.....	258
Chapter 6:	Statistical Analysis of Output from Terminating Simulations.....	265
6.1	Time Frame of Simulations.....	266
6.2	Strategy for Data Collection and Analysis.....	266
6.3	Confidence Intervals for Terminating Systems.....	268
6.4	Comparing Two Scenarios.....	273
6.5	Evaluating Many Scenarios with the Process Analyzer (PAN).....	277
6.6	Searching for an Optimal Scenario with OptQuest.....	282
6.7	Summary and Forecast.....	287
6.8	Exercises.....	288
Chapter 7:	Intermediate Modeling and Steady-State Statistical Analysis.....	293
7.1	Model 7-1: A Small Manufacturing System.....	293
7.1.1	New Arena Concepts.....	294
7.1.2	The Modeling Approach.....	296
7.1.3	The Data Modules.....	297
7.1.4	The Logic Modules.....	299
7.1.5	Animation.....	306
7.1.6	Verification.....	308
7.2	Statistical Analysis of Output from Steady-State Simulations.....	312
7.2.1	Warm-Up and Run Length.....	312
7.2.2	Truncated Replications.....	316
7.2.3	Batching in a Single Run.....	317
7.2.4	What To Do?.....	320
7.2.5	Other Methods and Goals for Steady-State Statistical Analysis.....	321
7.3	Summary and Forecast.....	321
7.4	Exercises.....	321
Chapter 8:	Entity Transfer.....	327
8.1	Types of Entity Transfers.....	327
8.2	Model 8-1; The Small Manufacturing System with Resource-Constrained Transfers.....	329
8.3	The Small Manufacturing System with Transporters.....	333
8.3.1	Model 8-2: The Modified Model 8-1 for Transporters.....	334
8.3.2	Model 8-3: Refining the Animation for Transporters.....	341
8.4	Conveyors.....	347
8.4.1	Model 8-4: The Small Manufacturing System with Nonaccumulating Conveyors.....	350
8.4.2	Model 8-5: The Small Manufacturing System with Accumulating Conveyors.....	355

8.5	Summary and Forecast.....	356
8.6	Exercises.....	356
Chapter 9: A Sampler of Further Modeling Issues and Techniques.....		359
9.1	Modeling Conveyors Using the Advanced Transfer Panel.....	359
9.1.1	Model 9-1.: Finite Buffers at Stations.....	360
9.1.2	Model 9-2: Parts Stay on Conveyor During Processing.....	364
9.2	More on Transporters.....	365
9.3	Entity Reneging.....	366
9.3.1	Entity Balking and Reneging.....	366
9.3.2	Model 9-3: A Service Model with Balking and Reneging	367
9.4	Holding and Batching Entities.....	375
9.4.1	Modeling Options.....	375
9.4.2	Model 9-4: A Batching Process Example.....	376
9.5	Overlapping Resources.....	382
9.5.1	System Description.....	382
9.5.2	Model 9-5: A Tightly Coupled Production System	384
9.5.3	Model 9-6: Adding Part-Status Statistics.....	390
9.6	A Few Miscellaneous Modeling Issues.....	393
9.6.1	Guided Transporters.....	394
9.6.2	Parallel Queues.....	394
9.6.3	Decision Logic.....	395
9.7	Exercises.....	396
Chapter 10: Arena Integration and Customization.....		403
10.1	Model 10-1: Reading and Writing Data Files.....	403
10.1.1	Model 10-2: Reading Entity Arrivals from a Text File.....	405
10.1.2	Model 10-3 and Model 10-4: Reading and Writing Access and Excel. Fjles	409
10.1.3	Advanced Reading and Writing.....	416
10.2	VBA in Arena.....	420
10.2.1	Overview of ActiveX Automation and VBA.....	420
10.2.2	Built-in Arena VBA Events.....	422
10.2.3	" Arena's Object Model.....	425
10.2.4	Arena's Macro Recorder.....	428
10.3	Model 10-5: Presenting Arrival Choices to the User.....	431
10.3.1	Modifying the Creation Logic.....	432
10.3.2	Designing the VBA UserForm.....	434
10.3.3	Displaying the Form and Setting Model Data.....	435
10.4	Model 10-6: Recording and Charting Model Results in Microsoft Excel.....	442
10.4.1	Setting Up Excel at the Beginning of the Run.....	443
10.4.2	Storing Individual Call Data Using the VBA Module.....	446
10.4.3	Charting the Results and Cleaning Up at the End of the Run.....	448

10.5	Creating Modules Using the Arena Professional Edition: Template 10-1.....	449
10.5.1	The Create from File Module.....	450
10.5.2	The Template Source File: Template 10-01-.tpl.....	451
10.5.3	The Panel Icon and User View.....	451
10.5.4	The Module Logic and Operands.....	452
10.5.5	Uses of Templates.....	456
10.6	Real-time Integration.....	457
10.7	Summary and Forecast.....	462
10.8	Exercises.....	462

Chapter 11: Continuous and Combined Discrete/Continuous Models.....465

11.1	Modeling Simple Discrete/Continuous Systems.....	466
11.1.1	Model 11-1: A Simple Continuous System.....	466-
11.1.2	Model 11-2: Interfacing Continuous and Discrete Logic.....	469
11.2	A Coal-Loading Operation.....	473
11.2.1	System Description.....	474
11.2.2	Modeling Approach.....	475
11.2.3	Model 11-3: Coal Loading with Continuous Approach.....	477
11.2.4	Model 11-4: Coal Loading with Flow Process.....	487
11.3	Continuous State-Change Systems.....	491
11.3.1	Model 11-5: A Soaking-Pit Furnace.....	491
11.3.2	Modeling Continuously Changing Rates.....	492
11.3.3	Arena's Approach for Solving Differential Equations.....	493
11.3.4	Building the Model.....	494
11.3.5	Defining the Differential Equations Using VBA.....	498
11.4	Summary and Forecast.....	500
11.5	Exercises.....	501

Chapter 12: Further Statistical Issues.....505

12.1	Random-Number Generation.....	505
12.2	Generating Random Variates.....	511
12.2.1	Discrete.....	511
12.2.2	Continuous.....	513
12.3	Nonstationary Poisson Processes.....	515
12.4	Variance Reduction.....	516
12.4.1	Common Random Numbers.....	517
12.4.2	Other Methods.....	523
12.5	Sequential Sampling.....	524
12.5.1	Terminating Models.....	525
12.5.2	Steady-State Models.....	529
12.6	Designing and Executing Simulation Experiments.....	531
12.7	Exercises.....	532

Chapter 13: Conducting Simulation Studies.....	535
13.1 A Successful Simulation Study.....	535
13.2 Problem Formulation.....	538
13.3 Solution Methodology.....	539
13.4 System and Simulation Specification.....	540
13.5 Model Formulation and Construction.....	544
13.6 Verification and Validation.....	546
13.7 Experimentation and Analysis.....	549
13.8 Presenting and Preserving the Results.....	550
13.9 Disseminating the Model.....	551
Appendix A: A Functional Specification for <i>The Washington Post</i>	553
A.I Introduction.....	553
A.1.1 Document Organization.....	553
A.1.2 Simulation Objectives.....	553
A.1.3 Purpose of the Functional Specification.....	554
- A.1.4 Use of the Model.....	554
A.1.5 Hardware and Software Requirements.....	555
A.2 System Description and Modeling Approach.....	555
A.2.1 Model Timeline.....	555
A.2.2 Presses.....	555
A.2.3 Product Types.....	557
A.2.4 Press Packaging Lines.....	557
A.2.5 Tray System.....	557
A.2.6 Truck Arrivals.....	558
A.2.7 Docks.....	559
A.2.8 Palletizers.....	559
A.2.9 Manual Insertion Process.....	560
A.3 Animation.....	561
A.4 Summary of Input and Output.....	561
A.4.1 Model Input.....	561
A.4.2 Model Output.....	562
A.5 Project Deliverables.....	564
A.5.1 Simulation Model Documentation.....	564
A.5.2 User's Manual.....	564
A.5.3 Model Validation.....	564
A.5.4 Animation.....	564
A.6 Acceptance.....	564
Appendix B: IIE/RA Contest Problems.....	567

Appendix C: A Refresher on Probability and Statistics.....	569
C.1 Probability Basics.....	569
C.2 Random Variables.....	571
C.2.1 Basics.....	571
C.2.2 Discrete.....	572
C.2.3 Continuous.....	574
C.2.4 Joint Distributions, Covariance, Correlation, and Independence.....	576
C.3 Sampling and Sampling Distributions.....	579
C.4 Point Estimation.....	581
C.5 Confidence Intervals.....	581
C.6 Hypothesis Tests.....	583
C.7 Exercises.....	585
Appendix D: Arena's Probability Distributions.....	587
Arena's Probability Distributions.....	587
Beta.....	589
Continuous.....	590
Discrete.....	592
Erlang.....	593
Exponential.....	594
Gamma.....	595
Johnson.....	596
Lognormal.....	597
Normal.....	598
Poisson.....	599
Triangular.....	600
Uniform.....	601
Weibull.....	602
Appendix E: Academic Software Installation Instructions.....	603
E.1 Authorization to Copy Software.....	603
E.2 Installing the Arena Software.....	603
E.3 System-Requirements.....	604
References.....	605
Index.....	609