SIMULATION
A STATISTICAL PERSPECTIVE

JACK KLEIJNEN
AND
WILLEM VAN GROENENDAAL

WILEY
Publishers Since 1807

Contents

Preface ix

CHAPTER 1 Introduction 1
1.1 Some examples 1
1.2 Some definitions 11
Appendix 12
References 13

CHAPTER 2 Random Numbers 15
2.1 Introduction 15
2.2 Techniques for generating random numbers 17
2.2.1 The ten-sided die 17
2.2.2 Throwing a coin 17
2.2.3 Other physical devices 17
2.2.4 Tables 18
2.2.5 Pseudorandom numbers 18
2.3 Pseudorandom numbers 18
2.3.1 Midsquare method 18
2.3.2 Congruential method 19
2.3.3 Additive congruential method 21
2.3.4 Tausworthe generators 21
2.3.5 Shuffling generators 22
2.4 Tests for pseudorandom numbers 22
2.4.1 Frequency test 22
2.4.2 Test on pairs of pseudorandom numbers 24
2.4.3 Correlation test 25
2.4.4 Run tests 26
2.4.5 Gap test 27
2.4.6 Poker test 27
2.5 Practical computer subroutines 28
References 30

CHAPTER 3 Sampling from Non-uniform Distributions 33
3.1 Table look-up for discrete distributions 34
3.1.1 Geometric distribution 36
3.2 Simulating the statistical process 37
3.2.1 Hypergeometric distribution 38
3.3 Inverse transformation 38

3.3.1 Exponential distribution 39
3.3.2 Uniform distribution 39
3.4 Distributions related to the exponential distribution 40
3.4.1 Gamma, Erlang, chi-square, and beta distributions 40
3.4.2 Poisson distribution 41
3.5 Normal distribution 43
3.5.1 Central limit theorem 43
3.5.2 Box–Muller method 44
3.6 Rejection method 46
3.6.1 Normal distribution 47
3.7 Distributions related to the normal distribution 47
3.7.1 Lognormal distribution 47
3.7.2 Chi-square distribution 47
3.7.3 Student's *t* distribution 48
3.7.4 *F* distribution 49
3.8 Multivariate distributions 49
3.8.1 Multivariate normal distribution 50
3.9 Time series 52
3.9.1 Linear autocorrelation function 52
3.9.2 Exponential autocorrelation function 53
3.10 Epilogue 54
Appendix: NAG routines 54
References 55

CHAPTER 4 Economic and Corporate Models 57
4.1 Macro-economic models 58
4.1.1 Klein's model 58
4.1.2 Simultaneous equations 59
4.1.3 Noise 60
4.2 Meso-economic models 64
4.2.1 Cobweb models 66
4.3 Micro-economic models 68
4.4 Micro-simulation 69
4.4.1 Typology of micro-simulation 72
4.5 Corporate models 73
4.5.1 Example: Anheuser–Busch model 74
4.6 Risk analysis 75
4.7 System dynamics 78
References 91

CHAPTER 5 Operations Research Models 93
5.1 Fixed versus variable time increments 94
5.2 Inventory models 95
5.3 Queuing models 100
5.3.1 Single server 101
5.3.2 Parallel servers 106
5.3.3 Repairmen model 107

5.3.4 Servers in sequence ... 110
5.3.5 Practical queuing simulations ... 113
5.4 Miscellaneous models, including combined continuous/discrete-event models ... 114
5.4.1 Case study: The Europe Container Terminus (ECT) in Rotterdam harbour ... 115
Appendix: Analytic solution of M/M/*n* models ... 116
References ... 117

CHAPTER 6 Simulation Software ... 119
6.1 Simulation package for parallel servers ... 119
6.1.1 System components and organization ... 119
6.1.2 System states ... 121
6.1.3 Synchronization of server and transaction states ... 123
6.1.4 Resulting simulation package ... 124
6.1.5 Data structures ... 126
6.2 Simulation software: a survey ... 127
6.2.1 Discrete-event simulation ... 127
6.2.2 System dynamics models ... 130
6.2.3 Economic and corporate models ... 131
6.2.4 Conclusions ... 132
References ... 132

CHAPTER 7 Statistical Applications ... 135
7.1 Regression models ... 136
7.2 Ordinary least squares (OLS) ... 139
7.3 Estimated weighted least squares (EWLS) ... 140
7.4 Corrected least squares (CLS) ... 141
7.5 Case study: simulation of EWLS and CLS ... 141
7.5.1 Verification of the computer program ... 143
7.5.2 Asymptotic covariances in EWLS ... 145
7.5.3 Relative efficiency of EWLS and CLS ... 145
7.5.4 Confidence intervals in EWLS and CLS ... 145
References ... 146

CHAPTER 8 Regression Metamodels ... 147
8.1 The metamodel concept ... 149
8.2 Simulation data for regression analysis ... 151
8.3 Least squares estimation ... 153
8.4 Validation of metamodels ... 154
8.4.1 Cross-validation ... 156
8.4.2 Rao's lack-of-fit test ... 158
8.5 Use of metamodels ... 158
8.5.1 Detailed example of metamodelling: M/M/*s* ... 159
8.6 Higher-order metamodels: interactions and quadratic effects ... 160
8.6.1 Case study: FMS example ... 162

8.7 Epilogue 164
References 164

CHAPTER 9 Design of Experiments 167
9.1 Classical experimental designs 169
9.1.1 One factor at a time designs 171
9.1.2 Full factorial designs 172
9.1.3 Incomplete factorial designs 175
9.1.4 Comments: replications and scaling effects 177
9.2 Screening 179
9.3 Optimization: response surface methodology 181
9.3.1 Case study: production planning 183
References 185

CHAPTER 10 Tactical Aspects 187
10.1 Terminating models 188
10.2 Non-terminating, steady-state models 190
10.2.1 Nearly independent subruns: batching 192
10.2.2 Renewal analysis 193
10.3 Proportions and quantiles 195
10.4 Variance reduction techniques 197
10.4.1 Common random numbers 197
10.4.2 Antithetic variables 198
10.4.3 Control variates or regression sampling 200
10.5 Jackknifing 201
References 203

CHAPTER 11 Verification and Validation 205
11.1 Verification 205
11.2 Validation 207
11.3 Case study: mine hunting by sonar 212
11.3.1 Conceptual model of mine hunting 213
11.3.2 Validation of mine-hunting model 215
11.3.3 Future research in mine hunting 219
References 219

CHAPTER 12 Epilogue 221
References 221

Solutions to Exercises 223

Author index 231

Subject index 235