Contents

1 Introduction 1
1.1 The Need for System Software Reliability 1
1.2 Software-related Problems 3
1.3 Software Reliability Engineering 5
1.4 Future Problems in the Twenty-first Century 5
1.5 Further Reading 6
1.6 Problems 7

2 System Reliability Concepts 9
2.1 Reliability Measures 10
2.2 Common Distribution Functions 16
2.3 A Generalized Systemability Function 32
2.3.1 Systemability Definition 33
2.3.2 Systemability Calculations 33
2.4 System Reliability with Multiple Failure Modes 41
2.4.1 Reliability Calculations 42
2.4.2 An Application of Systems with Multiple Failure Modes 48
2.5 Markov Processes 50
2.6 Counting Processes 62
2.6.1 Poisson Processes 63
2.6.2 Renewal Processes 64
2.6.3 Quasi-renewal Processes 66
2.6.4 Non-homogeneous Poisson Processes 69
2.7 Further Reading 71
2.8 Problems 71

3 Theory of Estimation 77
3.1 Point Estimation 77
3.2 Maximum Likelihood Estimation Method 79
3.3 Maximum Likelihood Estimation with Censored Data 86
3.3.1 Parameter Estimate with Multiple-censored Data 86

3.3.2 Confidence Intervals of Estimates 88
3.3.3 Applications 89
3.4 Statistical Change-point Estimation Methods 91
3.4.1 Application: A Software Model with a Change Point 95
3.5 Goodness of Fit Techniques 96
3.5.1 Chi-squared Test 96
3.5.2 Kolmogorov-Smirnov *d* Test 98
3.6 Least Squared Estimation 98
3.7 Interval Estimation 100
3.7.1 Confidence Intervals for the Normal Parameters 100
3.7.2 Confidence Intervals for the Exponential Parameters 102
3.7.3 Confidence Intervals for the Binomial Parameters 104
3.7.4 Confidence Intervals for the Poisson Parameters 106
3.8 Non-parametric Tolerance Limits 106
3.9 Sequential Sampling 107
3.10 Bayesian Methods 113
3.11 Further Reading 118
3.12 Problems 119

4 Software Development Lifecycle and Data Analysis 121
4.1 Introduction 121
4.2 Software *vs* Hardware Reliability 122
4.3 Software Reliability and Testing Concepts 124
4.4 Software Lifecycle 127
4.5 Software Development Process and its Applications 132
4.5.1 Analytic Hierarchy Process 133
4.5.2 Evaluation of Software Development Process 133
4.6 Software Verification and Validation 134
4.7 Data Analysis 135
4.8 Failure Data Sets 136
4.9 Further Reading 150
4.10 Problems 150

5 Software Reliability Modeling 153
5.1 Introduction 153
5.2 Halstead's Software Metric 154
5.3 McCabe's Cyclomatic Complexity Metric 157
5.4 Error Seeding Models 159
5.5 Failure Rate Models 164
5.6 Curve Fitting Models 169
5.7 Reliability Growth Models 171
5.8 Markov Structure Models 172
5.9 Time Series Models 174
5.10 Non-homogeneous Poisson Process Models 175
5.11 Further Reading 176
5.12 Problems 176

6 Imperfect-debugging Models 179
6.1 Introduction 179
6.2 Parameter Estimation 180
6.3 Model Selection 181
6.4 NHPP Exponential Models 183
6.5 NHPP S-shaped Models 188
6.6 NHPP Imperfect Debugging Models 192
6.7 NHPP Imperfect Debugging S-shaped Models 194
6.7.1 A Generalized Imperfect-debugging Fault-detection Model 195
6.8 Applications 203
6.9 Imperfect Debugging *vs* Perfect Debugging 211
6.10 Mean Time Between Failures for NHPP 213
6.11 Further Reading 216
6.12 Problems 216

7 Testing Coverage and Removal Models 219
7.1 Introduction 219
7.2 Testing Coverage Models 219
7.3 Testing Coverage and Imperfect Debugging 222
7.4 Fault Removal Efficiency Model 224
7.5 Model Implementations 231
7.6 Imperfect Debugging Model with Multiple Failure Types 247
7.6.1 A Constant Fault Detection Rate 248
7.6.2 Fault Detection Time-dependent Rate 251
7.7 Further Reading 255
7.8 Problems 256

8 Software Reliability Models with Environmental Factors 257
8.1 Introduction 257
8.2 Data Analysis 257
8.2.1 Survey Analysis 258
8.2.2 Statistical Methods 261
8.3 Exploratory Analysis of Environmental Factors 263
8.4 Further Exploratory Analysis 266
8.5 A Generalized Model with Environmental Factors 272
8.6 Environmental Parameter Estimation 275
8.7 Enhanced Proportional Hazard Jelinski-Moranda (EPJM) Model 276
8.8 Applications 279
8.9 Further Reading 292
8.10 Problems 292

9 Calibrating Software Reliability Models 293
9.1 Introduction 293
9.2 Calibration Factor Approach 294
9.3 Model Application 295
9.4 Calibrating Models with Random Field Environments 296
9.4.1 A Generalized Random Field Environmental Model 298

9.4.2 RFE Reliability Models 301
9.4.3 Applications 303
9.5 Further Reading 313
9.6 Problems 313

10 Optimal Release Policies 315
10.1 Introduction 315
10.2 A Software Cost Model with Risk Factor 316
10.3 Cost Model with Testing Coverage 319
10.4 A Generalized Software Cost Model 323
10.5 Cost Model with Multiple Failure Errors 326
10.6 Gain Model with Random Field Environments 332
10.6.1 Model Formulation 334
10.6.2 Applications 338
10.7 Other Cost Models 342
10.8 Further Reading 343
10.9 Problems 343

11 Complex Fault-tolerant System Reliability Modeling 347
11.1 Introduction 347
11.2 Basic Fault-tolerant Software Techniques 348
11.2.1 Recovery Block Scheme 349
11.2.2 N-version Programming 350
11.3 Other Advanced Techniques 352
11.3.1 Self-checking Duplex Scheme 352
11.3.2 Hybrid Fault-tolerant Scheme 353
11.3.3 Reduction of Common-cause Failures 355
11.4 Triple-version Programming Model with Common Failures 357
11.4.1 Modeling Assumptions 360
11.4.2 TVP Reliability Function 364
11.4.3 Numerical Example 366
11.5 Complex-system Reliability Modeling 375
11.5.1 System Considerations 375
11.5.2 Reliability Modeling 377
11.6 Application Example 383
11.7 Further Reading 385
11.8 Problems 386

Appendix 1: Distribution Tables 389

Appendix 2: Laplace Transform 395

Appendix 3: Survey of Factors that Affect Software Reliability 399

References 407

Glossary 423

Solutions to Selected Problems 429

Index 437