

Hoang Pham (Editor)

**Handbook of
Reliability
Engineering**



Springer

Contents

PART I. System Reliability and Optimization

1 Multi-state k -out-of- n Systems

<i>Ming J. Zuo, Jinsheng Huang and Way Kuo</i>	3
1.1 Introduction	3
1.2 Relevant Concepts in Binary Reliability Theory	3
1.3 Binary k -out-of- n Models	4
1.3.1 The k -out-of- n :G System with Independently and Identically Distributed Components	5
1.3.2 Reliability Evaluation Using Minimal Path or Cut Sets	5
1.3.3 Recursive Algorithms	6
1.3.4 Equivalence Between a k -out-of- n :G System and an $(n - k + 1)$ -out-of- n :F system	6
1.3.5 The Dual Relationship Between the k -out-of- n G and F Systems	7
1.4 Relevant Concepts in Multi-state Reliability Theory	8
1.5 A Simple Multi-state k -out-of- n :G Model	10
1.6 A Generalized Multi-state k -out-of- n :G System Model	11
1.7 Properties of Generalized Multi-state k -out-of- n :G Systems	13
1.8 Equivalence and Duality in Generalized Multi-state k -out-of- n Systems	15

2 Reliability of Systems with Multiple Failure Modes

<i>Hoang Pham</i>	19
2.1 Introduction	19
2.2 The Series System	20
2.3 The Parallel System	21
2.3.1 Cost Optimization	21
2.4 The Parallel-Series System	22
2.4.1 The Profit Maximization Problem	23
2.4.2 Optimization Problem	24
2.5 The Series-Parallel System	25
2.5.1 Maximizing the Average System Profit	26
2.5.2 Consideration of Type I Design Error	27
2.6 The k -out-of- n Systems	27
2.6.1 Minimizing the Average System Cost	29
2.7 Fault-tolerant Systems	32
2.7.1 Reliability Evaluation	33

2.7.2	Redundancy Optimization	34
2.8	Weighted Systems with Three Failure Modes	34
3	Reliabilities of Consecutive-k Systems	
	<i>Jen-Chun Chang and Frank K. Hwang</i>	37
3.1	Introduction	37
3.1.1	Background	37
3.1.2	Notation	38
3.2	Computation of Reliability	39
3.2.1	The Recursive Equation Approach	39
3.2.2	The Markov Chain Approach	40
3.2.3	Asymptotic Analysis	41
3.3	Invariant Consecutive Systems	41
3.3.1	Invariant Consecutive-2 Systems	41
3.3.2	Invariant Consecutive- k Systems	42
3.3.3	Invariant Consecutive- k G System	43
3.4	Component Importance and the Component Replacement Problem	43
3.4.1	The Birnbaum Importance	44
3.4.2	Partial Birnbaum Importance	45
3.4.3	The Optimal Component Replacement	45
3.5	The Weighted-consecutive- k -out-of- n System	47
3.5.1	The Linear Weighted-consecutive- k -out-of- n System	47
3.5.2	The Circular Weighted-consecutive- k -out-of- n System	47
3.6	Window Systems	48
3.6.1	The f -within-consecutive- k -out-of- n System	49
3.6.2	The 2-within-consecutive- k -out-of- n System	51
3.6.3	The b -fold-window System	52
3.7	Network Systems	53
3.7.1	The Linear Consecutive-2 Network System	53
3.7.2	The Linear Consecutive- k Network System	54
3.7.3	The Linear Consecutive- k Flow Network System	55
3.8	Conclusion	57
4	Multi-state System Reliability Analysis and Optimization	
	<i>G. Levitin and A. Lisnianski</i>	61
4.1	Introduction	61
4.1.1	Notation	63
4.2	Multi-state System Reliability Measures	63
4.3	Multi-state System Reliability Indices Evaluation Based on the Universal Generating Function	64
4.4	Determination of μ -function of Complex Multi-state System Using Composition Operators	67
4.5	Importance and Sensitivity Analysis of Multi-state Systems	68
4.6	Multi-state System Structure Optimization Problems	72
4.6.1	Optimization Technique	73
4.6.1.1	Genetic Algorithm	73

4.6.1.2	Solution Representation and Decoding Procedure	75
4.6.2	Structure Optimization of Series-Parallel System with Capacity-based Performance Measure	75
4.6.2.1	Problem Formulation	75
4.6.2.2	Solution Quality Evaluation	76
4.6.3	Structure Optimization of Multi-state System with Two Failure Modes	77
4.6.3.1	Problem Formulation	77
4.6.3.2	Solution Quality Evaluation	80
4.6.4	Structure Optimization for Multi-state System with Fixed Resource Requirements and Unreliable Sources	83
4.6.4.1	Problem Formulation	83
4.6.4.2	Solution Quality Evaluation	84
4.6.4.3	The Output Performance Distribution of a System Containing Identical Elements in the Main Producing Subsystem	85
4.6.4.4	The Output Performance Distribution of a System Containing Different Elements in the Main Producing Subsystem	85
4.6.5	Other Problems of Multi-state System Optimization	87
5 Combinatorial Reliability Optimization		
	<i>C. S. Sung, Y. K. Cho and S. H. Song</i>	91
5.1	Introduction	91
5.2	Combinatorial Reliability Optimization Problems of Series Structure	95
5.2.1	Optimal Solution Approaches	95
5.2.1.1	Partial Enumeration Method	95
5.2.1.2	Branch-and-bound Method	96
5.2.1.3	Dynamic Programming	98
5.2.2	Heuristic Solution Approach	99
5.3	Combinatorial Reliability Optimization Problems of a Non-series Structure	102
5.3.1	Mixed Series-Parallel System Optimization Problems	102
5.3.2	General System Optimization Problems	106
5.4	Combinatorial Reliability Optimization Problems with Multiple-choice Constraints	107
5.4.1	One-dimensional Problems	108
5.4.2	Multi-dimensional Problems	111
5.5	Summary	113
PART II. Statistical Reliability Theory		
6 Modeling the Observed Failure Rate		
	<i>M. S. Finkelstein</i>	117
6.1	Introduction	117
6.2	Survival in the Plane	118

6.2.1	One-dimensional Case	118
6.2.2	Fixed Obstacles	119
6.2.3	Failure Rate Process	121
6.2.4	Moving Obstacles	122
6.3	Multiple Availability	124
6.3.1	Statement of the Problem	124
6.3.2	Ordinary Multiple Availability	125
6.3.3	Accuracy of a Fast Repair Approximation	126
6.3.4	Two Non-serviced Demands in a Row	127
6.3.5	Not More than N Non-serviced Demands	129
6.3.6	Time Redundancy	130
6.4	Modeling the Mixture Failure Rate	132
6.4.1	Definitions and Conditional Characteristics	132
6.4.2	Additive Model	133
6.4.3	Multiplicative Model	133
6.4.4	Some Examples	135
6.4.5	Inverse Problem	136
7	Concepts of Stochastic Dependence in Reliability Analysis	
	<i>C. D. Lai and M. Xie</i>	141
7.1	Introduction	141
7.2	Important Conditions Describing Positive Dependence	142
7.2.1	Six Basic Conditions	143
7.2.2	The Relative Stringency of the Conditions	143
7.2.3	Positive Quadrant Dependent in Expectation	144
7.2.4	Associated Random Variables	144
7.2.5	Positively Correlated Distributions	145
7.2.6	Summary of Interrelationships	145
7.3	Positive Quadrant Dependent Concept	145
7.3.1	Constructions of Positive Quadrant Dependent Bivariate Distributions	146
7.3.2	Applications of Positive Quadrant Dependence Concept to Reliability	146
7.3.3	Effect of Positive Dependence on the Mean Lifetime of a Parallel System	146
7.3.4	Inequality Without Any Aging Assumption	147
7.4	Families of Bivariate Distributions that are Positive Quadrant Dependent	147
7.4.1	Positive Quadrant Dependent Bivariate Distributions with Simple Structures	148
7.4.2	Positive Quadrant Dependent Bivariate Distributions with More Complicated Structures	149
7.4.3	Positive Quadrant Dependent Bivariate Uniform Distributions	150
	7.4.3.1 Generalized Farlie-Gumbel-Morgenstern Family of Copulas	151
7.5	Some Related Issues on Positive Dependence	152

7.5.1	Examples of Bivariate Positive Dependence Stronger than Positive Quadrant Dependent Condition	152
7.5.2	Examples of Negative Quadrant Dependence	153
7.6	Positive Dependence Orderings	153
7.7	Concluding Remarks	154
8 Statistical Reliability Change-point Estimation Models		
	<i>Ming Zhao</i>	157
8.1	Introduction	157
8.2	Assumptions in Reliability Change-point Models	158
8.3	Some Specific Change-point Models	159
8.3.1	Jelinski-Moranda De-eutrophication Model with a Change Point	159
8.3.1.1	Model Review	159
8.3.1.2	Model with One Change Point	159
8.3.2	Weibull Change-point Model	160
8.3.3	Littlewood Model with One Change Point	160
8.4	Maximum Likelihood Estimation	160
8.5	Application	161
8.6	Summary	162
9 Concepts and Applications of Stochastic Aging in Reliability		
	<i>C. D. Lai and M. Xie</i>	165
9.1	Introduction	165
9.2	Basic Concepts for Univariate Reliability Classes	167
9.2.1	Some Acronyms and the Notions of Aging	167
9.2.2	Definitions of Reliability Classes	167
9.2.3	Interrelationships	169
9.3	Properties of the Basic Concepts	169
9.3.1	Properties of Increasing and Decreasing Failure Rates	169
9.3.2	Property of Increasing Failure Rate on Average	169
9.3.3	Properties of NBU, NBUC, and NBUE	169
9.4	Distributions with Bathtub-shaped Failure Rates	169
9.5	Life Classes Characterized by the Mean Residual Lifetime	170
9.6	Some Further Classes of Aging	171
9.7	Partial Ordering of Life Distributions	171
9.7.1	Relative Aging	172
9.7.2	Applications of Partial Orderings	172
9.8	Bivariate Reliability Classes	173
9.9	Tests of Stochastic Aging	173
9.9.1	A General Sketch of Tests	174
9.9.2	Summary of Tests of Aging in Univariate Case	177
9.9.3	Summary of Tests of Bivariate Aging	177
9.10	Concluding Remarks on Aging	177

10 Class of NBU- t_0 Life Distribution

<i>Dong Ho Park</i>	181
10.1 Introduction	181
10.2 Characterization of NBU- t_0 Class	182
10.2.1 Boundary Members of NBU- t_0 and NWU- t_0	182
10.2.2 Preservation of NBU- t_0 and NWU- t_0 Properties under Reliability Operations	184
10.3 Estimation of NBU- t_0 Life Distribution	186
10.3.1 Reneau-Samaniego Estimator	186
10.3.2 Chang-Rao Estimator	188
10.3.2.1 Positively Biased Estimator	188
10.3.2.2 Geometric Mean Estimator	188
10.4 Tests for NBU- t_0 Life Distribution	189
10.4.1 Tests for NBU- t_0 Alternatives Using Complete Data	189
10.4.1.1 Hollander-Park-Proschan Test	190
10.4.1.2 Ebrahimi-Habibullah Test	192
10.4.1.3 Ahmad Test	193
10.4.2 Tests for NBU- t_0 Alternatives Using Incomplete Data	195

PART III. Software Reliability**11 Software Reliability Models: A Selective Survey and New Directions**

<i>Siddhartha R. Dalal</i>	201
11.1 Introduction	201
11.2 Static Models	203
11.2.1 Phase-based Model: Gaffney and Davis	203
11.2.2 Predictive Development Life Cycle Model: Dalal and Ho	203
11.3 Dynamic Models: Reliability Growth Models for Testing and Operational Use	205
11.3.1 A General Class of Models	205
11.3.2 Assumptions Underlying the Reliability Growth Models	206
11.3.3 Caution in Using Reliability Growth Models	207
11.4 Reliability Growth Modeling with Covariates	207
11.5 When to Stop Testing Software	208
11.6 Challenges and Conclusions	209

12 Software Reliability Modeling

<i>James Ledoux</i>	213
12.1 Introduction	213
12.2 Basic Concepts of Stochastic Modeling	214
12.2.1 Metrics with Regard to the First Failure	214
12.2.2 Stochastic Process of Times of Failure	215
12.3 Black-box Software Reliability Models	215
12.3.1 Self-exciting Point Processes	216
12.3.1.1 Counting Statistics for a Self-exciting Point Process	218

12.3.1.2	Likelihood Function for a Self-exciting Point Process	218
12.3.1.3	Reliability and Mean Time to Failure Functions . . .	218
12.3.2	Classification of Software Reliability Models	219
12.3.2.1	0-Memory Self-exciting Point Process	219
12.3.2.2	Non-homogeneous Poisson Process Model: $\lambda(t; \mathcal{H}_t, \mathcal{F}_0) = f(t; \mathcal{F}_0)$ and is Deterministic	220
12.3.2.3	1-Memory Self-exciting Point Process with $\lambda(t; \mathcal{H}_t, \mathcal{F}_0) = f(N(t), t - T_{N(t)}, \mathcal{F}_0)$	221
12.3.2.4	$m \geq 2$ -Memory	221
12.4	White-box Modeling	222
12.5	Calibration of Model	223
12.5.1	Frequentist Procedures	223
12.5.2	Bayesian Procedure	225
12.6	Current Issues	225
12.6.1	Black-box Modeling	225
12.6.1.1	Imperfect Debugging	225
12.6.1.2	Early Prediction of Software Reliability	226
12.6.1.3	Environmental Factors	227
12.6.1.4	Conclusion	228
12.6.2	White-box Modeling	229
12.6.3	Statistical Issues	230
13 Software Availability Theory and Its Applications		
	<i>Koichi Tokuno and Shigeru Yamada</i>	235
13.1	Introduction	235
13.2	Basic Model and Software Availability Measures	236
13.3	Modified Models	239
13.3.1	Model with Two Types of Failure	239
13.3.2	Model with Two Types of Restoration	240
13.4	Applied Models	241
13.4.1	Model with Computation Performance	241
13.4.2	Model for Hardware-Software System	242
13.5	Concluding Remarks	243
14 Software Rejuvenation: Modeling and Applications		
	<i>Tadashi Dohi, Katerina Goševa-Popstojanova, Kalyanaraman Vaidyanathan, Kishor S. Trivedi and Shunji Osaki</i>	245
14.1	Introduction	245
14.2	Modeling-based Estimation	246
14.2.1	Examples in Telecommunication Billing Applications	247
14.2.2	Examples in a Transaction-based Software System	251
14.2.3	Examples in a Cluster System	255
14.3	Measurement-based Estimation	257
14.3.1	Time-based Estimation	258
14.3.2	Time and Workload-based Estimation	260
14.4	Conclusion and Future Work	262

15 Software Reliability Management: Techniques and Applications	
<i>Mitsuhiro Kimura and Shigeru Yamada</i>	265
15.1 Introduction	265
15.2 Death Process Model for Software Testing Management	266
15.2.1 Model Description	267
15.2.1.1 Mean Number of Remaining Software Faults/Testing Cases	268
15.2.1.2 Mean Time to Extinction	268
15.2.2 Estimation Method of Unknown Parameters	268
15.2.2.1 Case of $0 < \alpha \leq 1$	268
15.2.2.2 Case of $\alpha = 0$	269
15.2.3 Software Testing Progress Evaluation	269
15.2.4 Numerical Illustrations	270
15.2.5 Concluding Remarks	271
15.3 Estimation Method of Imperfect Debugging Probability	271
15.3.1 Hidden-Markov modeling for software reliability growth phenomenon	271
15.3.2 Estimation Method of Unknown Parameters	272
15.3.3 Numerical Illustrations	273
15.3.4 Concluding Remarks	274
15.4 Continuous State Space Model for Large-scale Software	274
15.4.1 Model Description	275
15.4.2 Nonlinear Characteristics of Software Debugging Speed	277
15.4.3 Estimation Method of Unknown Parameters	277
15.4.4 Software Reliability Assessment Measures	279
15.4.4.1 Expected Number of Remaining Faults and Its Variance	279
15.4.4.2 Cumulative and Instantaneous Mean Time Between Failures	279
15.4.5 Concluding Remarks	280
15.5 Development of a Software Reliability Management Tool	280
15.5.1 Definition of the Specification Requirement	280
15.5.2 Object-oriented Design	281
15.5.3 Examples of Reliability Estimation and Discussion	282
16 Recent Studies in Software Reliability Engineering	
<i>Hoang Pham</i>	285
16.1 Introduction	285
16.1.1 Software Reliability Concepts	285
16.1.2 Software Life Cycle	288
16.2 Software Reliability Modeling	288
16.2.1 A Generalized Non-homogeneous Poisson Process Model	289
16.2.2 Application 1: The Real-time Control System	289
16.3 Generalized Models with Environmental Factors	289
16.3.1 Parameters Estimation	292
16.3.2 Application 2: The Real-time Monitor Systems	292

16.4	Cost Modeling	295
16.4.1	Generalized Risk-Cost Models	295
16.5	Recent Studies with Considerations of Random Field Environments	296
16.5.1	A Reliability Model	297
16.5.2	A Cost Model	297
16.6	Further Reading	300

PART IV. Maintenance Theory and Testing

17 Warranty and Maintenance

<i>D. N. P. Murthy and N. Jack</i>		305
17.1	Introduction	305
17.2	Product Warranties: An Overview	306
17.2.1	Role and Concept	306
17.2.2	Product Categories	306
17.2.3	Warranty Policies	306
17.2.3.1	Warranties Policies for Standard Products Sold Individually	306
17.2.3.2	Warranty Policies for Standard Products Sold in Lots	307
17.2.3.3	Warranty Policies for Specialized Products	307
17.2.3.4	Extended Warranties	307
17.2.3.5	Warranties for Used Products	308
17.2.4	Issues in Product Warranty	308
17.2.4.1	Warranty Cost Analysis	308
17.2.4.2	Warranty Servicing	309
17.2.5	Review of Warranty Literature	309
17.3	Maintenance: An Overview	309
17.3.1	Corrective Maintenance	309
17.3.2	Preventive Maintenance	310
17.3.3	Review of Maintenance Literature	310
17.4	Warranty and Corrective Maintenance	311
17.5	Warranty and Preventive Maintenance	312
17.6	Extended Warranties and Service Contracts	313
17.7	Conclusions and Topics for Future Research	314

18 Mechanical Reliability and Maintenance Models

<i>Gianpaolo Pulcini</i>		317
18.1	Introduction	317
18.2	Stochastic Point Processes	318
18.3	Perfect Maintenance	320
18.4	Minimal Repair	321
18.4.1	No Trend with Operating Time	323
18.4.2	Monotonic Trend with Operating Time	323
18.4.2.1	The Power Law Process	324
18.4.2.2	The Log-Linear Process	325
18.4.2.3	Bounded Intensity Processes	326

18.4.3	Bathtub-type Intensity	327
18.4.3.1	Numerical Example	328
18.4.4	Non-homogeneous Poisson Process Incorporating Covariate Information	329
18.5	Imperfect or Worse Repair	330
18.5.1	Proportional Age Reduction Models	330
18.5.2	Inhomogeneous Gamma Processes	331
18.5.3	Lawless-Thiagarajah Models	333
18.5.4	Proportional Intensity Variation Model	334
18.6	Complex Maintenance Policy	335
18.6.1	Sequence of Perfect and Minimal Repairs Without Preventive Maintenance	336
18.6.2	Minimal Repairs Interspersed with Perfect Preventive Maintenance	338
18.6.3	Imperfect Repairs Interspersed with Perfect Preventive Maintenance	339
18.6.4	Minimal Repairs Interspersed with Imperfect Preventive Maintenance	340
18.6.4.1	Numerical Example	341
18.6.5	Corrective Repairs Interspersed with Preventive Maintenance Without Restrictive Assumptions	342
18.7	Reliability Growth	343
18.7.1	Continuous Models	344
18.7.2	Discrete Models	345
19 Preventive Maintenance Models: Replacement, Repair, Ordering, and Inspection		
	<i>Tadashi Dohi, Naoto Kaio and Shunji Osaki</i>	349
19.1	Introduction	349
19.2	Block Replacement Models	350
19.2.1	Model I	350
19.2.2	Model II	352
19.2.3	Model III	352
19.3	Age Replacement Models	354
19.3.1	Basic Age Replacement Model	354
19.4	Ordering Models	356
19.4.1	Continuous-time Model	357
19.4.2	Discrete-time Model	358
19.4.3	Combined Model with Minimal Repairs	359
19.5	Inspection Models	361
19.5.1	Nearly Optimal Inspection Policy by Kaio and Osaki (K&O Policy)	362
19.5.2	Nearly Optimal Inspection Policy by Munford and Shahani (M&S Policy)	363
19.5.3	Nearly Optimal Inspection Policy by Nakagawa and Yasui (N&Y Policy)	363
19.6	Concluding Remarks	363

20 Maintenance and Optimum Policy

<i>Toshio Nakagawa</i>	367
20.1 Introduction	367
20.2 Replacement Policies	368
20.2.1 Age Replacement	368
20.2.2 Block Replacement	370
20.2.2.1 No Replacement at Failure	370
20.2.2.2 Replacement with Two Variables	371
20.2.3 Periodic Replacement	371
20.2.3.1 Modified Models with Two Variables	372
20.2.3.2 Replacement at N Variables	373
20.2.4 Other Replacement Models	373
20.2.4.1 Replacements with Discounting	373
20.2.4.2 Discrete Replacement Models	374
20.2.4.3 Replacements with Two Types of Unit	375
20.2.4.4 Replacement of a Shock Model	376
20.2.5 Remarks	377
20.3 Preventive Maintenance Policies	378
20.3.1 One-unit System	378
20.3.1.1 Interval Reliability	379
20.3.2 Two-unit System	380
20.3.3 Imperfect Preventive Maintenance	381
20.3.3.1 Imperfect with Probability	383
20.3.3.2 Reduced Age	383
20.3.4 Modified Preventive Maintenance	384
20.4 Inspection Policies	385
20.4.1 Standard Inspection	386
20.4.2 Inspection with Preventive Maintenance	387
20.4.3 Inspection of a Storage System	388

21 Optimal Imperfect Maintenance Models

<i>Hongzhou Wang and Hoang Pham</i>	397
21.1 Introduction	397
21.2 Treatment Methods for Imperfect Maintenance	399
21.2.1 Treatment Method 1	399
21.2.2 Treatment Method 2	400
21.2.3 Treatment Method 3	401
21.2.4 Treatment Method 4	402
21.2.5 Treatment Method 5	403
21.2.6 Treatment Method 6	403
21.2.7 Treatment Method 7	403
21.2.8 Other Methods	404
21.3 Some Results on Imperfect Maintenance	404
21.3.1 A Quasi-renewal Process and Imperfect Maintenance	404
21.3.1.1 Imperfect Maintenance Model A	405
21.3.1.2 Imperfect Maintenance Model B	405

21.3.1.3	Imperfect Maintenance Model C	405
21.3.1.4	Imperfect Maintenance Model D	407
21.3.1.5	Imperfect Maintenance Model E	408
21.3.2	Optimal Imperfect Maintenance of k -out-of- n Systems	409
21.4	Future Research on Imperfect Maintenance	411
21.A	Appendix	412
21.A.1	Acronyms and Definitions	412
21.A.2	Exercises	412
22	Accelerated Life Testing	
	<i>Elsayed A. Elsayed</i>	415
22.1	Introduction	415
22.2	Design of Accelerated Life Testing Plans	416
22.2.1	Stress Loadings	416
22.2.2	Types of Stress	416
22.3	Accelerated Life Testing Models	417
22.3.1	Parametric Statistics-based Models	418
22.3.2	Acceleration Model for the Exponential Model	419
22.3.3	Acceleration Model for the Weibull Model	420
22.3.4	The Arrhenius Model	422
22.3.5	Non-parametric Accelerated Life Testing Models: Cox's Model	424
22.4	Extensions of the Proportional Hazards Model	426
23	Accelerated Test Models with the Birnbaum-Saunders Distribution	
	<i>W. Jason Owen and William J. Padgett</i>	429
23.1	Introduction	429
23.1.1	Accelerated Testing	430
23.1.2	The Birnbaum-Saunders Distribution	431
23.2	Accelerated Birnbaum-Saunders Models	431
23.2.1	The Power-law Accelerated Birnbaum-Saunders Model	432
23.2.2	Cumulative Damage Models	432
23.2.2.1	Additive Damage Models	433
23.2.2.2	Multiplicative Damage Models	434
23.3	Inference Procedures with Accelerated Life Models	435
23.4	Estimation from Experimental Data	437
23.4.1	Fatigue Failure Data	437
23.4.2	Micro-Composite Strength Data	437
24	Multiple-steps Step-stress Accelerated Life Test	
	<i>Loon-Ching Tang</i>	441
24.1	Introduction	441
24.2	Cumulative Exposure Models	443
24.3	Planning a Step-stress Accelerated Life Test	445
24.3.1	Planning a Simple Step-stress Accelerated Life Test	446
24.3.1.1	The Likelihood Function	446
24.3.1.2	Setting a Target Accelerating Factor	447

24.3.1.3	Maximum Likelihood Estimator and Asymptotic Variance	447
24.3.1.4	Nonlinear Programming for Joint Optimality in Hold Time and Low Stress	447
24.3.2	Multiple-steps Step-stress Accelerated Life Test Plans	448
24.4	Data Analysis in the Step-stress Accelerated Life Test	450
24.4.1	Multiply Censored, Continuously Monitored Step-stress Accelerated Life Test	450
24.4.1.1	Parameter Estimation for Weibull Distribution	451
24.4.2	Read-out Data	451
24.5	Implementation in Microsoft Excel TM	453
24.6	Conclusion	454

25 Step-stress Accelerated Life Testing

	<i>Chengjie Xiong</i>	457
25.1	Introduction	457
25.2	Step-stress Life Testing with Constant Stress-change Times	457
25.2.1	Cumulative Exposure Model	457
25.2.2	Estimation with Exponential Data	459
25.2.3	Estimation with Other Distributions	462
25.2.4	Optimum Test Plan	463
25.3	Step-stress Life Testing with Random Stress-change Times	463
25.3.1	Marginal Distribution of Lifetime	463
25.3.2	Estimation	467
25.3.3	Optimum Test Plan	467
25.4	Bibliographical Notes	468

PART V. Practices and Emerging Applications

26 Statistical Methods for Reliability Data Analysis

	<i>Michael J. Phillips</i>	475
26.1	Introduction	475
26.2	Nature of Reliability Data	475
26.3	Probability and Random Variables	478
26.4	Principles of Statistical Methods	479
26.5	Censored Data	480
26.6	Weibull Regression Model	483
26.7	Accelerated Failure-time Model	485
26.8	Proportional Hazards Model	486
26.9	Residual Plots for the Proportional Hazards Model	489
26.10	Non-proportional Hazards Models	490
26.11	Selecting the Model and the Variables	491
26.12	Discussion	491

27 The Application of Capture–Recapture Methods in Reliability Studies	
<i>Paul S. F. Yip, Yan Wang and Anne Chao</i>	493
27.1 Introduction	493
27.2 Formulation of the Problem	495
27.2.1 Homogeneous Model with Recapture	496
27.2.2 A Seeded Fault Approach Without Recapture	498
27.2.3 Heterogeneous Model	499
27.2.3.1 Non-parametric Case: $\lambda_i(t) = \gamma_i \alpha_i$	499
27.2.3.2 Parametric Case: $\lambda_i(t) = \gamma_i$	501
27.3 A Sequential Procedure	504
27.4 Real Examples	504
27.5 Simulation Studies	505
27.6 Discussion	508
28 Reliability of Electric Power Systems: An Overview	
<i>Roy Billinton and Ronald N. Allan</i>	511
28.1 Introduction	511
28.2 System Reliability Performance	512
28.3 System Reliability Prediction	515
28.3.1 System Analysis	515
28.3.2 Predictive Assessment at HLI	516
28.3.3 Predictive Assessment at HLII	518
28.3.4 Distribution System Reliability Assessment	519
28.3.5 Predictive Assessment at HLIII	520
28.4 System Reliability Data	521
28.4.1 Canadian Electricity Association Database	522
28.4.2 Canadian Electricity Association Equipment Reliability Information System Database for HLI Evaluation	523
28.4.3 Canadian Electricity Association Equipment Reliability Information System Database for HLII Evaluation	523
28.4.4 Canadian Electricity Association Equipment Reliability Information System Database for HLIII Evaluation	524
28.5 System Reliability Worth	525
28.6 Guide to Further Study	527
29 Human and Medical Device Reliability	
<i>B. S. Dhillon</i>	529
29.1 Introduction	529
29.2 Human and Medical Device Reliability Terms and Definitions	529
29.3 Human Stress—Performance Effectiveness, Human Error Types, and Causes of Human Error	530
29.4 Human Reliability Analysis Methods	531
29.4.1 Probability Tree Method	531
29.4.2 Fault Tree Method	532
29.4.3 Markov Method	534

29.5	Human Unreliability Data Sources	535
29.6	Medical Device Reliability Related Facts and Figures	535
29.7	Medical Device Recalls and Equipment Classification	536
29.8	Human Error in Medical Devices	537
29.9	Tools for Medical Device Reliability Assurance	537
	29.9.1 General Method	538
	29.9.2 Failure Modes and Effect Analysis	538
	29.9.3 Fault Tree Method	538
	29.9.4 Markov Method	538
29.10	Data Sources for Performing Medical Device Reliability Studies	539
29.11	Guidelines for Reliability Engineers with Respect to Medical Devices	539
30 Probabilistic Risk Assessment		
	<i>Robert A. Bari</i>	543
30.1	Introduction	543
30.2	Historical Comments	544
30.3	Probabilistic Risk Assessment Methodology	546
30.4	Engineering Risk Versus Environmental Risk	549
30.5	Risk Measures and Public Impact	550
30.6	Transition to Risk-informed Regulation	553
30.7	Some Successful Probabilistic Risk Assessment Applications	553
30.8	Comments on Uncertainty	554
30.9	Deterministic, Probabilistic, Prescriptive, Performance-based	554
30.10	Outlook	555
31 Total Dependability Management		
	<i>Per Anders Akersten and Bengt Klefsjö</i>	559
31.1	Introduction	559
31.2	Background	559
31.3	Total Dependability Management	560
31.4	Management System Components	561
31.5	Conclusions	564
32 Total Quality for Software Engineering Management		
	<i>G. Albeanu and Fl. Popentiu Vladicescu</i>	567
32.1	Introduction	567
	32.1.1 The Meaning of Software Quality	567
	32.1.2 Approaches in Software Quality Assurance	569
32.2	The Practice of Software Engineering	571
	32.2.1 Software Lifecycle	571
	32.2.2 Software Development Process	574
	32.2.3 Software Measurements	575
32.3	Software Quality Models	577
	32.3.1 Measuring Aspects of Quality	577
	32.3.2 Software Reliability Engineering	577
	32.3.3 Effort and Cost Models	579

32.4	Total Quality Management for Software Engineering	580
32.4.1	Deming's Theory	580
32.4.2	Continuous Improvement	581
32.5	Conclusions	582
33 Software Fault Tolerance		
	<i>Xiaolin Teng and Hoang Pham</i>	585
33.1	Introduction	585
33.2	Software Fault-tolerant Methodologies	586
33.2.1	N -version Programming	586
33.2.2	Recovery Block	586
33.2.3	Other Fault-tolerance Techniques	587
33.3	N -version Programming Modeling	588
33.3.1	Basic Analysis	588
33.3.1.1	Data-domain Modeling	588
33.3.1.2	Time-domain Modeling	589
33.3.2	Reliability in the Presence of Failure Correlation	590
33.3.3	Reliability Analysis and Modeling	591
33.4	Generalized Non-homogeneous Poisson Process Model Formulation	594
33.5	Non-homogeneous Poisson Process Reliability Model for N -version Programming Systems	595
33.5.1	Model Assumptions	597
33.5.2	Model Formulations	599
33.5.2.1	Mean Value Functions	599
33.5.2.2	Common Failures	600
33.5.2.3	Concurrent Independent Failures	601
33.5.3	N -version Programming System Reliability	601
33.5.4	Parameter Estimation	602
33.6	N -version programming-Software Reliability Growth	602
33.6.1	Applications of N -version Programming-Software Reliability Growth Models	602
33.6.1.1	Testing Data	602
33.7	Conclusion	610
34 Markovian Dependability/Performability Modeling of Fault-tolerant Systems		
	<i>Juan A. Carrasco</i>	613
34.1	Introduction	613
34.2	Measures	615
34.2.1	Expected Steady-state Reward Rate	617
34.2.2	Expected Cumulative Reward Till Exit of a Subset of States	618
34.2.3	Expected Cumulative Reward During Stay in a Subset of States	618
34.2.4	Expected Transient Reward Rate	619
34.2.5	Expected Averaged Reward Rate	619
34.2.6	Cumulative Reward Distribution Till Exit of a Subset of States	619
34.2.7	Cumulative Reward Distribution During Stay in a Subset of States	620

34.2.8	Cumulative Reward Distribution	621
34.2.9	Extended Reward Structures	621
34.3	Model Specification	622
34.4	Model Solution	625
34.5	The Largeness Problem	630
34.6	A Case Study	632
34.7	Conclusions	640
35	Random-request Availability	
	<i>Kang W. Lee</i>	643
35.1	Introduction	643
35.2	System Description and Definition	644
35.3	Mathematical Expression for the Random-request Availability	645
35.3.1	Notation	645
35.3.2	Mathematical Assumptions	645
35.3.3	Mathematical Expressions	645
35.4	Numerical Examples	647
35.5	Simulation Results	647
35.6	Approximation	651
35.7	Concluding Remarks	652
Index	653