

Alessandro Birolini

Reliability Engineering

Theory and Practice

Fifth edition

With 140 Figures, 60 Tables,
120 Examples, and 50 Problems

 Springer

Contents

1	Basic Concepts, Quality and Reliability Assurance of Complex Equipment & Systems . . .	1
1.1	Introduction	1
1.2	Basic Concepts	2
1.2.1	Reliability	2
1.2.2	Failure	3
1.2.3	Failure Rate	4
1.2.4	Maintenance, Maintainability	8
1.2.5	Logistic Support	8
1.2.6	Availability	9
1.2.7	Safety, Risk, and Risk Acceptance	9
1.2.8	Quality	11
1.2.9	Cost and System Effectiveness	11
1.2.10	Product Liability	15
1.2.11	Historical Development	16
1.3	Basic Tasks & Rules for Quality & Reliability Assurance of Complex Equip. & Systems .	17
1.3.1	Quality and Reliability Assurance Tasks	17
1.3.2	Basic Quality and Reliability Assurance Rules	19
1.3.3	Elements of a Quality Assurance System	21
1.3.4	Motivation and Training	24
2	Reliability Analysis During the Design Phase (Nonrepairable Items up to System Failure). . .	25
2.1	Introduction	25
2.2	Predicted Reliability of Equipment and Systems with Simple Structure	28
2.2.1	Required Function	28
2.2.2	Reliability Block Diagram	28
2.2.3	Operating Conditions at Component Level, Stress Factors	33
2.2.4	Failure Rate of Electronic Components	35
2.2.5	Reliability of One-Item Structure	39
2.2.6	Reliability of Series-Parallel Structures	41
2.2.6.1	Systems without Redundancy	41
2.2.6.2	Concept of Redundancy	42
2.2.6.3	Parallel Models	43
2.2.6.4	Series - Parallel Structures	45
2.2.6.5	Majority Redundancy	47
2.2.7	Part Count Method	51
2.3	Reliability of Systems with Complex Structure	52
2.3.1	Key Item Method	52
2.3.1.1	Bridge Structure	53
2.3.1.2	Rel. Block Diagram in which Elements Appear More than Once	54
2.3.2	Successful Path Method	55
2.3.3	State Space Method	56
2.3.4	Boolean Function Method	57
2.3.5	Parallel Models with Constant Failure Rates and Load Sharing	61

2.3.6	Elements with more than one Failure Mechanism or one Failure Mode	64
2.3.7	Basic Considerations on Fault Tolerant Structures	66
2.4	Reliability Allocation	67
2.5	Mechanical Reliability, Drift Failures	67
2.6	Failure Mode Analysis	72
2.7	Reliability Aspects in Design Reviews	77
3	Qualification Tests for Components and Assemblies	81
3.1	Basic Selection Criteria for Electronic Components	81
3.1.1	Environment	82
3.1.2	Performance Parameters	84
3.1.3	Technology	84
3.1.4	Manufacturing Quality	86
3.1.5	Long-Term Behavior of Performance Parameters	86
3.1.6	Reliability	86
3.2	Qualification Tests for Complex Electronic Components	87
3.2.1	Electrical Test of Complex ICs	88
3.2.2	Characterization of Complex ICs	90
3.2.3	Environmental and Special Tests of Complex ICs	92
3.2.4	Reliability Tests	101
3.3	Failure Modes, Failure Mechanisms, and Failure Analysis of Electronic Components .	101
3.3.1	Failure Modes of Electronic Components	101
3.3.2	Failure Mechanisms of Electronic Components	102
3.3.3	Failure Analysis of Electronic Components	102
3.3.4	Examples of VLSI Production-Related Reliability Problems	106
3.4	Qualification Tests for Electronic Assemblies	107
4	Maintainability Analysis	112
4.1	Maintenance, Maintainability	112
4.2	Maintenance Concept	115
4.2.1	Fault Recognition and Isolation	116
4.2.2	Equipment and System Partitioning	118
4.2.3	User Documentation	118
4.2.4	Training of Operating and Maintenance Personnel	119
4.2.5	User Logistic Support	119
4.3	Maintainability Aspects in Design Reviews	121
4.4	Predicted Maintainability	121
4.4.1	Calculation of $MTTR_S$	121
4.4.2	Calculation of $MTTPM_S$	125
4.5	Basic Models for Spare Parts Provisioning	125
4.5.1	Centralized Logistic Support, Nonrepairable Spare Parts	125
4.5.2	Decentralized Logistic Support, Nonrepairable Spare Parts	129
4.5.3	Repairable Spare Parts	130
4.6	Repair strategies	134
4.7	Cost Considerations	136
5	Design Guidelines for Reliability, Maintainability, and Software Quality	139
5.1	Design Guidelines for Reliability	139
5.1.1	Derating	139

5.1.2	Cooling	140
5.1.3	Moisture	142
5.1.4	Electromagnetic Compatibility, ESD Protection	143
5.1.5	Components and Assemblies	145
5.1.5.1	Component Selection	145
5.1.5.2	Component Use	145
5.1.5.3	PCB and Assembly Design	146
5.1.5.4	PCB and Assembly Manufacturing	147
5.1.5.5	Storage and Transportation	148
5.1.6	Particular Guidelines for IC Design and Manufacturing	148
5.2	Design Guidelines for Maintainability	149
5.2.1	General Guidelines	149
5.2.2	Testability	149
5.2.3	Accessibility, Exchangeability	151
5.2.4	Operation, Adjustment	152
5.3	Design Guidelines for Software Quality	152
5.3.1	Guidelines for Software Defect Prevention	155
5.3.2	Configuration Management	158
5.3.3	Guidelines for Software Testing	158
5.3.4	Software Quality Growth Models	159
6	Reliability and Availability of Repairable Systems	162
6.1	Introduction and General Assumptions	162
6.2	One-Item Structure	168
6.2.1	One-Item Structure New at Time $t = 0$	169
6.2.1.1	Reliability Function	169
6.2.1.2	Point Availability	170
6.2.1.3	Average Availability	171
6.2.1.4	Interval Reliability	172
6.2.1.5	Special Kinds of Availability	173
6.2.2	One-Item Structure New at Time $t = 0$ and with Constant Failure Rate λ	176
6.2.3	One-Item Structure with Arbitrary Initial Conditions at Time $t = 0$	176
6.2.4	Asymptotic Behavior	178
6.2.5	Steady-State Behavior	180
6.3	Systems without Redundancy	182
6.3.1	Series Structure with Constant Failure and Repair Rates	182
6.3.2	Series Structure with Constant Failure and Arbitrary Repair Rates	185
6.3.3	Series Structure with Arbitrary Failure and Repair Rates	186
6.4	1-out-of-2 Redundancy	189
6.4.1	1-out-of-2 Redundancy with Constant Failure and Repair Rates	189
6.4.2	1-out-of-2 Redundancy with Constant Failure and Arbitrary Repair Rates	197
6.4.3	1-out-of-2 Red. with Const. Failure Rate in Res. State and Arbitr. Repair Rates	200
6.5	k -out-of- n Redundancy	206
6.5.1	k -out-of- n Warm Redundancy with Constant Failure and Repair Rates	207
6.5.2	k -out-of- n Active Redundancy with Const. Failure and Arbitrary Repair Rates	210
6.6	Simple Series - Parallel Structures	213
6.7	Approximate Expressions for Large Series - Parallel Structures	219
6.7.1	Introduction	219
6.7.2	Application to a Practical Example	223

- 6.8 Systems with Complex Structure 231
 - 6.8.1 General Considerations 231
 - 6.8.2 Preventive Maintenance 233
 - 6.8.3 Imperfect Switching. 236
 - 6.8.4 Incomplete Coverage 241
 - 6.8.5 Elements with more than two States or one Failure Mode 246
 - 6.8.6 Fault Tolerant Reconfigurable Systems 248
 - 6.8.6.1 Ideal Case 248
 - 6.8.6.2 Time Censored Reconfiguration (Phased-Mission Systems) 248
 - 6.8.6.3 Failure Censored Reconfiguration 255
 - 6.8.6.4 With Reward and Frequency / Duration Aspects 259
 - 6.8.7 Systems with Common Cause Failures. 260
 - 6.8.8 General Procedure for Modeling Complex Systems. 264
- 6.9 Alternative Investigation Methods 267
 - 6.9.1 Petri Nets 267
 - 6.9.2 Dynamic Fault Trees 270
 - 6.9.3 Computer-Aided Reliability and Availability Computation 272
 - 6.9.3.1 Numerical Solution of Equations for Reliability and Availability . . . 272
 - 6.9.3.2 Monte Carlo Simulations 273
- 7 Statistical Quality Control and Reliability Tests 277**
 - 7.1 Statistical Quality Control 277
 - 7.1.1 Estimation of a Defective Probability p 278
 - 7.1.2 Simple Two-sided Sampling Plans for Demonstration of a Def. Probability p . . 280
 - 7.1.2.1 Simple Two-sided Sampling Plans 281
 - 7.1.2.2 Sequential Tests 283
 - 7.1.3 One-sided Sampling Plans for the Demonstration of a Def. Probability p . . . 284
 - 7.2 Statistical Reliability Tests 287
 - 7.2.1 Reliability & Availability Estimation & Demon. for the case of a given Mission . 287
 - 7.2.2 Availability Estimation & Demonstration for Continuous Operation (steady-state). 289
 - 7.2.2.1 Availability Estimation 289
 - 7.2.2.2 Availability Demonstration 291
 - 7.2.2.3 Further Availability Evaluation Methods for Continuous Operation . . 292
 - 7.2.3 Estimation and Demonstration of a Constant Failure Rate λ (or of $MTBF=1/\lambda$) . 294
 - 7.2.3.1 Estimation of a Constant Failure Rate λ 296
 - 7.2.3.2 Simple Two-sided Test for the Demonstration of λ 298
 - 7.2.3.3 Simple One-sided Test for the Demonstration of λ 302
 - 7.3 Statistical Maintainability Tests 303
 - 7.3.1 Estimation of an $MTTR$ 303
 - 7.3.2 Demonstration of an $MTTR$ 305
 - 7.4 Accelerated Testing 307
 - 7.5 Goodness-of-fit Tests 312
 - 7.5.1 Kolmogorov-Smirnov Test 312
 - 7.5.2 Chi-square Test 316
 - 7.6 Statistical Analysis of General Reliability Data 319
 - 7.6.1 General considerations 319
 - 7.6.2 Tests for Nonhomogeneous Poisson Processes 321
 - 7.6.3 Trend Tests 323
 - 7.6.3.1 Tests of a HPP versus a NHPP with increasing intensity 323
 - 7.6.3.2 Tests of a HPP versus a NHPP with decreasing intensity 326

7.6.3.3	Heuristic Tests to distinguish between HPP and Gen. Monotonic Trend	327
7.7	Reliability Growth	329
8	Quality & Reliability Assurance During the Production Phase (Basic Considerations)	335
8.1	Basic Activities	335
8.2	Testing and Screening of Electronic Components	336
8.2.1	Testing of Electronic Components	336
8.2.2	Screening of Electronic Components	337
8.3	Testing and Screening of Electronic Assemblies	340
8.4	Test and Screening Strategies, Economic Aspects	342
8.4.1	Basic Considerations	342
8.4.2	Quality Cost Optimization at Incoming Inspection Level	345
8.4.3	Procedure to handle first deliveries	350
 Annexes		
A1	Terms and Definitions	351
A2	Quality and Reliability Standards	365
A2.1	Introduction	365
A2.2	Requirements in the Industrial Field	366
A2.3	Requirements in the Aerospace, Defense, and Nuclear Fields	368
A3	Definition and Realization of Quality and Reliability Requirements	369
A3.1	Definition of Quality and Reliability Requirements	369
A3.2	Realization of Quality and Reliability Requirements for Complex Equip. & Systems	371
A3.3	Elements of a Quality and Reliability Assurance Program	376
A3.3.1	Project Organization, Planning, and Scheduling	376
A3.3.2	Quality and Reliability Requirements	377
A3.3.3	Reliability and Safety Analysis	377
A3.3.4	Selection and Qualification of Components, Materials & Manuf. Processes	378
A3.3.5	Configuration Management	378
A3.3.6	Quality Tests	380
A3.3.7	Quality Data Reporting System	380
A4	Checklists for Design Reviews	383
A4.1	System Design Review	383
A4.2	Preliminary Design Reviews	384
A4.3	Critical Design Review (System Level)	386
A5	Requirements for Quality Data Reporting Systems	388
A6	Basic Probability Theory	391
A6.1	Field of Events	391
A6.2	Concept of Probability	393
A6.3	Conditional Probability, Independence	396
A6.4	Fundamental Rules of Probability Theory	397
A6.4.1	Addition Theorem for Mutually Exclusive Events	397
A6.4.2	Multiplication Theorem for Two Independent Events	398
A6.4.3	Multiplication Theorem for Arbitrary Events	399

A6.4.4	Addition Theorem for Arbitrary Events	399
A6.4.5	Theorem of Total Probability	400
A6.5	Random Variables, Distribution Functions	401
A6.6	Numerical Parameters of Random Variables	406
A6.6.1	Expected Value (Mean)	406
A6.6.2	Variance	410
A6.6.3	Modal Value, Quantile, Median	412
A6.7	Multidimensional Random Variables, Conditional Distributions	412
A6.8	Numerical Parameters of Random Vectors	414
A6.8.1	Covariance Matrix, Correlation Coefficient	415
A6.8.2	Further Properties of Expected Value and Variance	416
A6.9	Distribution of the Sum of Indep. Positive Random Variables and of τ_{\min} , τ_{\max}	416
A6.10	Distribution Functions used in Reliability Analysis	419
A6.10.1	Exponential Distribution	419
A6.10.2	Weibull Distribution	420
A6.10.3	Gamma Distribution, Erlangian Distribution, and χ^2 -Distribution	422
A6.10.4	Normal Distribution	424
A6.10.5	Lognormal Distribution	425
A6.10.6	Uniform Distribution	427
A6.10.7	Binomial Distribution	427
A6.10.8	Poisson Distribution	429
A6.10.9	Geometric Distribution	431
A6.10.10	Hypergeometric Distribution	432
A6.11	Limit Theorems	432
A6.11.1	Law of Large Numbers	433
A6.11.2	Central Limit Theorem	434
A7	Basic Stochastic-Processes Theory	438
A7.1	Introduction	438
A7.2	Renewal Processes	441
A7.2.1	Renewal Function, Renewal Density	443
A7.2.2	Recurrence Times	446
A7.2.3	Asymptotic Behavior	447
A7.2.4	Stationary Renewal Processes	449
A7.2.5	Homogeneous Poisson Processes	450
A7.3	Alternating Renewal Processes	452
A7.4	Regenerative Processes	456
A7.5	Markov Processes with Finitely Many States	458
A7.5.1	Markov Chains with Finitely Many States	458
A7.5.2	Markov Processes with Finitely Many States	460
A7.5.3	State Probabilities and Stay (Sojourn) Times in a Given Class of States	469
A7.5.3.1	Method of Differential Equations	469
A7.5.3.2	Method of Integral Equations	473
A7.5.3.3	Stationary State and Asymptotic Behavior	474
A7.5.4	Frequency / Duration and Reward Aspects	476
A7.5.4.1	Frequency / Duration	476
A7.5.4.2	Reward	478
A7.5.5	Birth and Death Process	479
A7.6	Semi-Markov Processes with Finitely Many States	483
A7.7	Semi-regenerative Processes	488
A7.8	Nonregenerative Stochastic Processes	492

A7.8.1	General Considerations	492
A7.8.2	Nonhomogeneous Poisson Processes (NHPP)	493
A7.8.3	Superimposed Renewal Processes	497
A7.8.4	Cumulative Processes	498
A7.8.5	General Point Processes	500
A8	Basic Mathematical Statistics	503
A8.1	Empirical Methods	503
A8.1.1	Empirical Distribution Function	504
A8.1.2	Empirical Moments and Quantiles	506
A8.1.3	Further Applications of the Empirical Distribution Function	507
A8.2	Parameter Estimation	511
A8.2.1	Point Estimation	511
A8.2.2	Interval Estimation	516
A8.2.2.1	Estimation of an Unknown Probability p	516
A8.2.2.2	Estimation of the Param. λ for an Exp. Distribution, Fixed T	520
A8.2.2.3	Estimation of the Param. λ for an Exp. Distribution, Fixed n	521
A8.2.2.4	Availability Estimation (Erlangian Failure-Free & Repair Times)	523
A8.3	Testing Statistical Hypotheses	525
A8.3.1	Testing an Unknown Probability p	526
A8.3.1.1	Simple Two-sided Sampling Plan	527
A8.3.1.2	Sequential Test	528
A8.3.1.3	Simple One-sided Sampling Plan	529
A8.3.1.4	Availability Demonstration (Erlangian Failure-Free & Rep. Times)	531
A8.3.2	Goodness-of-fit Tests for Completely Specified $F_0(t)$	533
A8.3.3	Goodness-of-fit Tests for $F_0(t)$ with Unknown Parameters	536
A9	Tables and Charts	539
A9.1	Standard Normal Distribution	539
A9.2	χ^2 -Distribution (Chi-Square Distribution)	540
A9.3	t -Distribution (Student distribution)	541
A9.4	F Distribution (Fisher distribution)	542
A9.5	Table for the Kolmogorov-Smirnov Test	543
A9.6	Gamma Function	544
A9.7	Laplace Transform	545
A9.8	Probability Charts (Probability Plot Papers)	547
A9.8.1	Lognormal Probability Chart	547
A9.8.2	Weibull Probability Chart	548
A9.8.3	Normal Probability Chart	549
A10	Basic Technological Component's Properties	550
A11	Problems for Home-Work	554
Acronyms	560
References	561
Index	581