

Contents

DEDICATION	v
PREFACE	xv
ACKNOWLEDGMENTS	xix
CHAPTER 1: RELIABILITY AND SIX SIGMA-INTRODUCTION	
1.1 INTRODUCTION	1
1.2 WHAT IS SIX SIGMA?	3
1.3 WHAT IS NEW IN SIX SIGMA?	6
1.4 QUALITY AND SIX SIGMA LEVEL	8
1.5 RELIABILITY AND SIX SIGMA	9
CHAPTER 2: RELIABILITY AND SIX SIGMA: PROBABILISTIC MODELS	
2.1 INTRODUCTION	11
2.2 PROBABILITY TERMINOLOGY	12
2.3 ELEMENTARY THEORY OF PROBABILITY	14
2.3.1 AXIOMS OF PROBABILITY	14
2.3.2 RULES OF PROBABILITY	15
2.3.3 JOINT EVENT	16
2.3.4 CONDITIONAL PROBABILITY	16
2.4 PROBABILITY DISTRIBUTION	17

2.5	RANDOM VARIABLE	18
2.5.1	TYPES OF RANDOM VARIABLES	20
2.6	THE PROBABILITY DISTRIBUTION OF A RANDOM VARIABLE	20
2.6.1	FUNCTIONAL METHOD	21
2.6.2	PARAMETRIC METHOD	25
2.6.2.1	<i>Measures of central tendency</i>	26
2.6.2.2	<i>Measures of dispersion</i>	27
2.6.2.3	<i>Variability</i>	29
2.7	DISCRETE PROBABILITY DISTRIBUTIONS	29
2.7.1	BERNOULLI TRIALS	30
2.7.2	BINOMIAL DISTRIBUTION	31
2.7.3	POISSON DISTRIBUTION	33
2.8	CONTINUOUS PROBABILITY DISTRIBUTIONS	35
2.8.1	EXPONENTIAL DISTRIBUTION	36
2.8.1.1	<i>Memory less property</i>	37
2.8.2	NORMAL DISTRIBUTION	38
2.8.2.1	<i>Central limit theorem</i>	42
2.8.3	LOGNORMAL DISTRIBUTION	43
2.8.4	WEIBULL DISTRIBUTION	44
2.9	STOCHASTIC PROCESSES	46
2.10	MARKOV PROCESSES	47
2.11	NON-HOMOGENEOUS POISSON PROCESS	51
2.12	RENEWAL PROCESS	52
2.12.1	RENEWAL FUNCTION	53
2.12.2	ELEMENTARY RENEWAL THEOREM	55

CHAPTER 3: RELIABILITY AND SIX SIGMA MEASURES

3.1	INTRODUCTION	57
3.2	SIX SIGMA MEASURES	57
3.3	YIELD	58
3.4	DEFECTS PER MILLION OPPORTUNITIES (DPMO)	59
3.5	SIGMA QUALITY LEVEL	60
3.5.1	CONVERSION OF YIELD TO SIGMA LEVEL	60
3.5.2	CONVERSION OF DPMO TO SIGMA LEVEL	62
3.6	RELIABILITY MEASURES	63
3.7	FAILURE FUNCTION	65
3.7.1	FAILURE FUNCTION OF SYSTEMS UNDER MULTIPLE FAILURE MECHANISMS	70
3.8	RELIABILITY FUNCTION	72

3.8.1	RELIABILITY FUNCTION OF ITEMS UNDER MULTIPLE FAILURE MECHANISMS	76
3.8.2	RELIABILITY FUNCTION AND SIX SIGMA	77
3.8.3	MISSION RELIABILITY	78
3.9	HAZARD FUNCTION (INSTANTANEOUS FAILURE RATE)	80
3.9.1	CUMULATIVE HAZARD FUNCTION	84
3.9.2	FAILURE RATE	88
3.10	MEAN TIME TO FAILURE	89
3.10.1	MTTF AND SIGMA LEVEL	91
3.10.2	MEAN RESIDUAL LIFE	93
3.11	MEAN (OPERATING) TIME BETWEEN FAILURE	95
3.12	MAINTENANCE FREE OPERATING PERIOD (MFOP)	98
3.12.1	MAINTENANCE FREE OPERATING PERIOD SURVIVABILITY	99
3.13	CASE STUDY: ENGINEER TANK ENGINE (ARMOURED VEHICLE ENGINE)	101

CHAPTER 4: SYSTEM RELIABILITY

4.1	INTRODUCTION	105
4.2	RELIABILITY PREDICTION	106
4.2.1	DUTY CYCLE	107
4.2.2	CYCLIC EXCHANGE RATE	107
4.3	RELIABILITY BLOCK DIAGRAM	108
4.4	SERIES SYSTEM	109
4.4.1	MEAN TIME TO FAILURE OF A SERIES CONFIGURATION	113
4.4.2	SIGMA LEVEL AND $MTTF_s$	114
4.4.3	HAZARD RATE (FUNCTION) OF A SERIES SYSTEM	117
4.5	LIFE EXCHANGE RATE MATRIX	118
4.6	CONDITIONAL PROBABILITIES OF SURVIVAL	120
4.7	PARALLEL SYSTEMS	122
4.7.1	MEAN TIME TO FAILURE OF A PARALLEL CONFIGURATION	126
4.7.2	HAZARD FUNCTION FOR A PARALLEL CONFIGURATION	128
4.8	SERIES-PARALLEL COMBINATION CONFIGURATION	129
4.9	K-OUT-OF-N SYSTEMS	131
4.9.1	MEAN TIME TO FAILURE FOR A K-OUT-OF-N SYSTEM	132
4.10	STANDBY REDUNDANCY	133
4.10.1	COLD STANDBY SYSTEM WITH PERFECT SWITCHING	134
4.10.2	COLD STANDBY SYSTEM WITH IMPERFECT SWITCHING	136
4.10.3	HOT STANDBY SYSTEM	136
4.11	GRACEFUL DEGRADATION	137
4.12	CASE STUDY – A SONAR SYSTEM	138

CHAPTER 5: DESIGN FOR RELIABILITY AND SIX SIGMA

5.1	INTRODUCTION	143
5.2	QUALITY FUNCTION DEPLOYMENT	144
5.2.1	BUILDING HOUSE OF QUALITY MATRIX	145
5.3	RELIABILITY ALLOCATION	152
5.3.1	MATHEMATICAL FORMULATION	152
5.3.2	EQUAL APPORTIONMENT TECHNIQUE	153
5.3.3	MINIMUM EFFORT ALGORITHM	154
5.3.4	APPORTIONMENT FOR NEW UNITS	156
5.3.5	RELIABILITY ALLOCATION FACTORS	159
5.3.5.1	<i>Complexity factor</i>	159
5.3.5.2	<i>Cost</i>	159
5.3.5.3	<i>State of the Art</i>	160
5.3.5.4	<i>Redundancy factor</i>	160
5.3.5.5	<i>Maintainability factor</i>	161
5.3.5.6	<i>Duty ratio factor</i>	161
5.3.6	RELIABILITY ALLOCATION FORMULA	161
5.4	ACCELERATED TESTING	165
5.4.1	ENVIRONMENTAL STRESS SCREENING (ESS)	166
5.4.2	ESS IN THE INFANT MORTALITY PERIOD	166
5.4.3	BURN-IN	167
5.4.4	ESS TESTS	168
5.4.5	QUANTITATIVE ACCELERATED LIFE TESTS	171
5.4.5.1	<i>Usage rate acceleration</i>	171
5.4.5.2	<i>Overstress acceleration</i>	171
5.4.6	HIGHLY ACCELERATED LIFE TESTING (HALT)	173
5.5	SAFETY AND HAZARD ANALYSIS	174
5.5.1	FAULT TREE ANALYSIS (FTA)	174
5.5.1.1	<i>Construction of FTA</i>	175
5.6	FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS	181
5.6.1	FAILURE MODE EFFECTS ANALYSIS (FMEA)	182
5.6.2	CRITICALITY ANALYSIS	183
5.6.3	RISK ANALYSIS THROUGH FMEA	185
5.6.4	FUNCTIONAL FMEA AND HARDWARE FMEA	187
5.6.5	ADVANTAGES OF FMECA	188
5.6.6	FMECA AND FTA IN DESIGN	188
5.7	HAZARD ANALYSIS	188
5.7.1	HAZARD ANALYSIS METHODOLOGY	189
5.8	FAILURE REPORTING ANALYSIS AND CORRECTIVE ACTION SYSTEM (FRACAS)	192

5.9	CASE STUDY – AIRCRAFT EMERGENCY STOPPING SYSTEM	194
5.9.1	FUNCTIONAL FMEA	195
5.9.2	HARDWARE FMEA	196

CHAPTER 6: IN-SERVICE RELIABILITY

6.1	INTRODUCTION	207
6.2	DEFINITION OF INSERVICE RELIABILITY	209
6.3	INSERVICE RELIABILITY DATA	211
6.4	INSERVICE MTBF	217
6.5	PARTS LIFE TRACKING	223
6.6	SAFETY CRITICAL PARTS	226
6.7	USAGE MONITORING	228
6.8	TIME TO FAILURE ANALYSIS	233
6.9	ESTIMATING MTTF FROM THE TEST SAMPLE	234
6.10	AGGREGATED CUMULATIVE HAZARD (ACH)	236
6.11	PROGNOSTICS	237
6.12	RELEVANT CONDITION PARAMETERS RCP	238
6.13	RELEVANT CONDITION INDICATORS RCI	243
6.14	CASE STUDY: AIRCRAFT ENGINE COMPONENTS	244
6.14.1	THE DATA	245
6.14.2	ANALYSIS OF FAILURES GENERATING UNSCHEDULED MAINTENANCE	247
6.14.3	NO FAULT FOUND (NFF)	249

CHAPTER 7: RELIABILITY AND SIX SIGMA ESTIMATION

7.1	INTRODUCTION	253
7.2	RELIABILITY ESTIMATION AND FAILURE DATA	254
7.3	ESTIMATION OF PARAMETERS: EMPIRICAL APPROACH	255
7.3.1	ESTIMATION OF PARAMETERS: COMPLETE UNGROUPED DATA	255
7.3.2	CONFIDENCE INTERVAL	256
7.3.3	ANALYSIS OF GROUPED DATA	260
7.3.4	ANALYSIS OF CENSORED DATA	263
7.4	REGRESSION	264
7.4.1	CORRELATION CO-EFFICIENT	267
7.4.2	LINEAR REGRESSION FOR EXPONENTIAL DISTRIBUTION	267
7.4.3	LINEAR REGRESSION FOR WEIBULL DISTRIBUTION	269
7.4.4	LINEAR REGRESSION FOR NORMAL DISTRIBUTION	271
7.5	MAXIMUM LIKELIHOOD ESTIMATION (MLE)	272
7.5.1	COMPLETE AND UNCENSORED DATA	273

7.5.2	MAXIMUM LIKELIHOOD ESTIMATOR OF EXPONENTIAL DISTRIBUTION	274
7.5.3	MAXIMUM LIKELIHOOD ESTIMATOR FOR WEIBULL DISTRIBUTION	276
7.5.4	MAXIMUM LIKELIHOOD ESTIMATOR FOR NORMAL DISTRIBUTION	279
7.6	CASE STUDY: ENGINEER TANK	281

CHAPTER 8: SOFTWARE RELIABILITY

8.1	INTRODUCTION	289
8.2	SOFTWARE RELIABILITY METRICS	291
8.2.1	REQUIREMENT RELIABILITY METRICS	291
8.2.2	DESIGN AND CODE RELIABILITY METRICS	292
8.2.3	TESTING RELIABILITY METRICS	293
8.3	SOFTWARE RELIABILITY MODELS	293
8.4	SOFTWARE RELIABILITY PREDICTION MODELS	295
8.4.1	IN-HOUSE HISTORICAL DATA COLLECTION MODEL	295
8.4.2	MUSA'S EXECUTION TIME MODEL	295
8.4.3	PUTNAM'S MODEL	297
8.5	SOFTWARE RELIABILITY ESTIMATION MODEL	299
8.5.1	EXPONENTIAL MODEL	299
8.5.2	GENERALIZED EXPONENTIAL MODEL	300
8.5.3	GOEL-OKUMOTO MODEL	301
8.5.4	JELINSKI-MORANDA MODEL	302
8.6	SOFTWARE TESTING	303
8.7	SOFTWARE RISK ANALYSIS USING FMEA	305
8.8	FAULT TOLERANT SOFTWARE	307
8.8.1	RECOVERY BLOCKS	307
8.8.2	N-VERSION PROGRAMMING	309
8.9	CASE STUDY: ARIANE 5	309

CHAPTER 9: AVAILABILITY AND SIX SIGMA

9.1	INTRODUCTION	313
9.2	POINT AVAILABILITY	314
9.2.1	MARKOV MODEL FOR POINT AVAILABILITY	314
9.2.2	AVERAGE AVAILABILITY	317
9.2.3	INHERENT AVAILABILITY	317
9.2.4	AVAILABILITY, DPMO AND SIGMA LEVEL	318
9.2.5	SYSTEM AVAILABILITY	320

9.3	ACHIEVED AVAILABILITY	323
9.4	OPERATIONAL AVAILABILITY	325

CHAPTER 10: RELIABILITY AND SIX SIGMA MANAGEMENT

10.1	INTRODUCTION	329
10.2	RELIABILITY MANAGEMENT	330
10.2.1	RELIABILITY DEMONSTRATION	330
10.2.1.1	<i>Two-Sided Reliability Demonstration Test</i>	331
10.2.1.2	<i>Demonstration of constant failure rate or MTBF</i>	333
10.2.2	RELIABILITY GROWTH PROGRAM	334
10.2.2.1	<i>Duane Model</i>	335
10.3	LIFE CYCLE COST AND TOTAL COST OF OWNERSHIP	338
10.4	TOTAL COST OF OWNERSHIP MODEL	339
10.4.1	MATHEMATICAL MODELS FOR ESTIMATION OF TOTAL COST OF OWNERSHIP	340
10.4.1.1	<i>Estimation of operating cost</i>	340
10.4.1.2	<i>Estimation of Maintenance Cost</i>	342
10.4.1.3	<i>Estimation of logistic support cost</i>	343
10.4.1.4	<i>Total cost of ownership</i>	343
10.5	TOTAL COST OF OWNERSHIP – CASE STUDY ON FREIGHT CARS ON AN ASIAN RAILWAY SYSTEM	344
10.5.1	RELIABILITY AND MAINTAINABILITY OF FREIGHT CAR	344
10.5.2	OPERATIONAL AVAILABILITY OF FREIGHT CAR	346
10.5.3	OPERATING COST OF FREIGHT CAR	346
10.5.4	MAINTENANCE COST FOR FREIGHT CAR	347
10.5.5	LOGISTIC SUPPORT COST	348
10.5.6	TOTAL COST OF OWNERSHIP OF FREIGHT CAR	348
10.6	IMPACT OF SIGMA LEVEL ON TOTAL COST OF OWNERSHIP	349
10.7	SIX SIGMA PROJECT MANAGEMENT	350
10.7.1	ANALYTIC HIERARCHY PROCESS (AHP) FOR SIX SIGMA PROJECT SELECTION	351
10.8	DMAIC CYCLE	355
10.8.1	DEFINE PHASE	356
10.8.2	MEASURE PHASE	357
10.8.3	ANALYZE PHASE	358
10.8.4	IMPROVE PHASE	359
10.8.5	CONTROL PHASE	359
10.9	CASE STUDY: DMAIC METHODOLOGY	360
10.9.1	POWERPLUS BATTERY MANUFACTURING COMPANY	360

10.9.1.1	<i>Define stage</i>	361
10.9.1.2	<i>Measure</i>	361
10.9.1.3	<i>Analyze</i>	361
10.9.1.4	<i>Improve Stage</i>	363
10.9.1.5	<i>Control</i>	363
10.10	DESIGN FOR SIX SIGMA (DFSS)	363
10.11	SIX SIGMA BLACK BELT AND GREEN BELT	364
APPENDIX		365
REFERENCES		371
INDEX		381