

Mohamed Ben-Daya • Salih O. Duffuaa
Abdul Raouf • Jezdimir Knezevic • Daoud Ait-Kadi
Editors

Handbook of Maintenance Management and Engineering

Contents

List of Contributors	xxv
-----------------------------------	------------

Part I – Maintenance Organization

1 Maintenance Organization	3
---	----------

Ahmed E. Haroun and Salih O. Duffuaa

1.1 Introduction.....	3
1.2 Maintenance Organization Objectives and Responsibility	5
1.3 Determinants of a Maintenance Organization.....	6
1.3.1 Maintenance Capacity Planning	6
1.3.2 Centralization vs Decentralization.....	7
1.3.2 In-house vs Outsourcing	7
1.4 Design of the Maintenance Organization.....	8
1.4.1 Current Criteria for Organizational Change.....	8
1.4.2 Criteria to Assess Organizational Effectiveness	9
1.5 Basic Types of Organizational Models	9
1.6 Material and Spare Parts Management	10
1.7 Establishment of Authority and Reporting	13
1.8 Quality of Leadership and Supervision.....	13
1.9 Incentives	13
1.10 Education and Training.....	14
1.11 Management and Labor Relations	14
1.12 Summary	15
References.....	15

2 Maintenance Productivity and Performance Measurement.....	17
--	-----------

Aditya Parida and Uday Kumar

2.1 Introduction.....	17
2.2 Performance Measurement and Maintenance Productivity.....	19
2.3 Maintenance Performance	21
2.4 Measurement of Maintenance Productivity	23

2.4.1 Maintenance Performance Indicator (MPI).....	24
2.4.2 MPM Issues	24
2.4.3 MPM System	27
2.5 MPI Standards and MPIs as in Use in Different Industries	31
2.5.1 Nuclear Industry.....	32
2.5.2 Maintenance Indicators by EFNMS.....	33
2.5.3 SMRP Metrics.....	34
2.5.4 Oil and Gas Industry	35
2.5.5 Railway Industry	36
2.5.6 Process Industry	36
2.5.7 Utility Industry.....	37
2.5.8 Auto-industry Related MPIs for the CEO.....	38
2.6 Concluding Remarks.....	39
References.....	39

Part II – Methods and Tools in Maintenance

3 Failure Statistics	45
<i>Mohamed Ben-Daya</i>	
3.1 Introduction.....	45
3.2 Introduction to Probability	45
3.2.1 Sample Spaces and Events.....	45
3.2.2 Definition of Probability	46
3.2.3 Probability Rules.....	46
3.2.4 Conditional Probabilities.....	47
3.2.5 Random Variables.....	48
3.3 Probability Distributions.....	49
3.4 Reliability and Failure Rate Functions.....	51
3.4.1 Introduction.....	51
3.4.2 Reliability Function	52
3.4.3 Failure Rate Function.....	52
3.4.4 Mean Time Between Failure (MTBF)	53
3.5 Commonly Used Distributions.....	54
3.5.1 The Binomial Distribution	54
3.5.2 The Poisson Distribution.....	55
3.5.3 The Normal Distribution.....	56
3.5.4 The Lognormal Distribution	58
3.5.5 The Exponential Distribution.....	60
3.5.6 The Weibull Distribution	61
3.6 Failure Statistics.....	63
3.6.1 Types of Data.....	63
3.6.2 Parameter Estimation	64
References.....	73
4 Failure Mode and Effect Analysis.....	75
<i>Mohamed Ben-Daya</i>	
4.1 Introduction.....	75

4.2 FMEA Defined	76
4.3 FMEA Process	78
4.4 FMEA Applications	83
4.5 Related Tools	83
4.5.1 Root Cause Analysis	83
4.5.2 Pareto Chart	87
4.5.3 Cause and Effect Diagram	87
References.....	90

Part III – Maintenance Control Systems

5 Maintenance Control.....93

Salih O. Duffuaa and Ahmed E. Haroun

5.1 Introduction.....	93
5.2 The Maintenance Control Function	95
5.3 The Control Process.....	96
5.4 Functional Structure of Maintenance Control.....	97
5.5 Work Order System	99
5.5.1 Basic Documentation for Work Order System	99
5.5.2 Work Order System Flow	105
5.6 Tools Necessary for Effective Maintenance Control System	107
5.6.1 Work Control	108
5.6.2 Cost Control	109
5.6.3 Quality Control	109
5.6.4 Plant Condition Control	109
5.7 Effective Programs for Improving Maintenance Control.....	110
5.7.1 Emergency Maintenance.....	110
5.7.2 Reliability Improvement	110
5.7.3 Total Productive Maintenance	111
5.7.4 Computerized Maintenance Management and Information Technology	111
5.8 Summary	112
References.....	112

6 Guidelines for Budgeting and Costing Planned Maintenance Services 115

Mohamed Ali Mirghani

6.1 Introduction.....	115
6.2 An Overview of Budgeting and Costing Systems.....	116
6.2.1 Budgeting Systems.....	116
6.2.2 Costing Systems.....	117
6.3 Proposed Budgetary System	118
6.3.1 Planned Maintenance Operating Budget.....	118
6.3.2 Financial Budget	119
6.3.3 The Budget Cycle	120
6.3.4 Top Management Support.....	120
6.3.5 Budget Performance Reports	122
6.4 Planned Maintenance Job Costing	123

6.4.1 Standard Cost Elements of a Planned Maintenance Job	123
6.4.2 Actual Cost Elements of a Planned Maintenance Job	128
6.4.3 Total Cost of a Planned Maintenance Job	129
6.4.4 Planned Maintenance Job Cost Variances	129
6.4.5 Significant Cost Variances	130
6.5 Summary and Conclusions	131
References	132
7 Simulation Based Approaches for Maintenance Strategies Optimization..	133
<i>Fouad Riane, Olivier Roux, Olivier Basile, and Pierre Dehombreux</i>	
7.1 Introduction	133
7.2 Reliability Models Estimation	134
7.2.1 Regression and ML Methods	134
7.2.2 Uncertainty Affecting Reliability Model	136
7.3 Maintenance Performance	138
7.3.1 Availability Model	138
7.3.2 Costs Model	139
7.4 Simulation Based Maintenance Framework	141
7.4.1 Toward a Unified Framework	141
7.4.2 Maintenance Strategies	142
7.4.3 Uncertainty Affecting Maintenance Performances	146
7.5 A Case Study	148
7.6 Conclusion	152
References	152
Part IV – Maintenance Planning and Scheduling	
8 Maintenance Forecasting and Capacity Planning	157
<i>Hesham K. Alfares and Salih O. Duffuaa</i>	
8.1 Introduction	157
8.2 Forecasting Basics	158
8.3 Qualitative Forecasting Techniques	159
8.3.1 The Delphi Method	160
8.4 Quantitative Forecasting Techniques	161
8.4.1 Simple Moving Averages	161
8.4.2 Weighted Moving Average	162
8.4.3 Regression Analysis	163
8.4.4 Exponential Smoothing	165
8.4.5 Seasonal Forecasting	167
8.4.6 Box-Jenkins Time Series Models	171
8.5 Error Analysis	172
8.6 Forecasting Maintenance Workload	173
8.7 Maintenance Capacity Planning	175
8.8 Deterministic Approaches for Capacity Planning	176
8.8.1 Modified Transportation Tableau Method	176
8.8.2 Mathematical Programming Methods	179
8.9 Stochastic Techniques for Capacity Planning	182

8.9.1 Queuing Models.....	182
8.9.2 Stochastic Simulation.....	186
8.10 Summary.....	188
References.....	189
9 Integrated Spare Parts Management.....	191
<i>Claver Diallo, Daoud Aït-Kadi, and Anis Chelbi</i>	
9.1 Introduction.....	191
9.2 Spare Parts Identification and Classification	192
9.3 Determination of the Required Quantity of Spare Parts.....	193
9.3.1 Recommendations.....	193
9.3.2 Reliability and Availability Based Procedures.....	193
9.3.3 Forecasting Procedure.....	198
9.3.4 Simulation.....	200
9.4 Inventory Control Policies	201
9.4.1 Model with Known and Constant Demand and Lead-time (EOQ Model).....	202
9.4.2 Model with Constant Demand and Perishable Items	202
9.4.3 Model with Random Demand and Lead-time	203
9.5 Joint Maintenance and Provisioning Strategies	204
9.5.1 Joint Replacement and Ordering Policy for a Spare Unit (One Unit Provisioning).....	205
9.5.2 Joint Replacement and Multiple Spare Parts Ordering Policy (Batch Provisioning).....	207
9.6 Inventory and Maintenance Policies for Reconditioned Spare Parts	209
9.6.1 Age of Recovered Parts to be Used for Replacement Actions.....	209
9.6.2 Review of Inventory Control Policies with Random Returns	213
9.7 Collaborative Management of Spare Parts.....	213
9.7.1 Access to Documentation and Knowledge Bases	213
9.7.2 Lead-time Reduction.....	214
9.7.3 Virtually Centralized Spare Parts Stock (Inventory Pooling)	214
9.7.4 Joint Replenishment of Spare Parts.....	216
9.8 Conclusion	218
References.....	218
10 Turnaround Maintenance.....	223
<i>Salih Duffuwa and Mohamed Ben-Daya</i>	
10.1 Introduction.....	223
10.2 Turnaround Initiation	225
10.3 Work Scope.....	226
10.4 Long Lead Time Resources	227
10.5 Contractors.....	228
10.6 TAM Planning	228
10.7 TAM Organization.....	229
10.8 Site Logistics.....	230
10.9 TAM Budget.....	230
10.10 Quality and Safety Plans.....	231

10.10.1 Quality Plan	231
10.10.2 Safety Plan	231
10.11 TAM Communication Procedures	232
10.12 TAM Execution	233
10.13 TAM Closing and Final Report	233
10.14 Conclusion	234
References.....	235
11 Maintenance Planning and Scheduling	237
<i>Umar M. Al-Turki</i>	
11.1 Introduction.....	237
11.2 Strategic Planning in Maintenance.....	240
11.3 Medium Range Planning.....	244
11.4 Short Range Planning	247
11.5 Maintenance Scheduling.....	247
11.5.1 Elements of Sound Scheduling	249
11.5.2 Maintenance Job Priority System.....	249
11.6 Scheduling Techniques	250
11.6.1 Gantt Charts and Scheduling Theory	250
11.6.2 Project Scheduling	253
11.6.3 Critical Path Method	256
11.6.4 Program Evaluation Review Techniques (PERT).....	258
11.7 Scheduling Using Computers.....	260
11.8 Summary.....	260
References.....	261
12 Models for Production and Maintenance Planning in Stochastic Manufacturing Systems	263
<i>E.K. Boukas</i>	
12.1 Introduction.....	263
12.2 Problem Statement and Preliminary Results.....	264
12.3 Dynamic Programming Approach	274
12.4 Linear Programming Approach	280
12.5 Conclusion	295
References.....	296
Part V – Maintenance Strategies	
13 Inspection Strategies for Randomly Failing Systems	303
<i>Anis Chelbi and Daoud Ait-Kadi</i>	
13.1 Introduction.....	303
13.1.1 Notation	304
13.2 Basic Inspection Model.....	305
13.2.1 Problem Definition.....	305
13.2.2 Working Assumptions and Mathematical Model.....	306
13.3 Extensions of the Basic Model.....	308
13.3.1 Inspection Models for Single Component Systems	308

13.4 Inspection Models for Multi-component Systems	318
13.4.1 Failure Tree Method Based Strategies	318
13.4.2 Cases of Cold and Hot Stand-by Systems with Known and Partially Known Lifetime Distributions.....	319
13.4.3 Case of Systems with Components Failure Dependency	320
13.5 Conditional Maintenance Models	321
13.5.1 Conditional Maintenance Models for Single Component Systems..	321
13.5.2 Conditional Maintenance Models for Multi-Component Systems...	329
13.6 Conclusion	331
References.....	332
 14 System Health Monitoring and Prognostics – A Review of Current Paradigms and Practices.....	 337
<i>Ranganath Kothamasu, Samuel H. Huang, William H. VerDuin</i>	
14.1 Maintenance Strategies: Motivations for Health Monitoring.....	337
14.2 Health Monitoring Paradigms.....	340
14.3 Health Monitoring Tools and Techniques.....	343
14.3.1 Reliability-based Maintenance.....	343
14.3.2 Model-based Approach to FDI.....	344
14.3.3 Signal-based FDI	346
14.3.4 Statistical FDI/Maintenance.....	347
14.4 Case Studies in System Monitoring and Control	347
14.5 Organizations and Standards.....	352
14.6 Summary and Research Directions	356
References.....	357
 15 Applied Maintenance Models.....	 363
<i>K. Ito and T. Nakagawa</i>	
15.1 Introduction.....	363
15.2 Missile Maintenance	365
15.2.1 Expected Cost	366
15.2.2 Optimal Inspection Policies	367
15.2.3 Numerical Illustrations.....	370
15.3 Phased Array Radar Maintenance.....	373
15.3.1 Cyclic Maintenance	374
15.3.2 Delayed Maintenance.....	377
15.3.3 Numerical Illustrations.....	379
15.4 Self-diagnosis for FADEC	380
15.4.1 Double Module System.....	381
15.4.2 Triple Module System.....	384
15.4.3 N Module System.....	386
15.4.4 Numerical Illustrations.....	386
15.5 Co-generation System Maintenance	387
15.5.1 Model and Assumptions.....	388
15.5.2 Analysis	389
15.5.3 Optimal Policy	390
15.5.4 Numerical Illustration	391
References.....	392

16 Reliability Centered Maintenance	397
<i>Atiq Waliullah Siddiqui and Mohamed Ben-Daya</i>	
16.1 Introduction.....	397
16.2 RCM Philosophy.....	400
16.2.1 RCM Principles and Key Features.....	400
16.2.2 RCM Goals and Benefits	401
16.2.3 System, System Boundary, Interfaces and Interactions	401
16.3 Failure and its Nature.....	404
16.4 RCM Methodology	405
16.4.1 Selecting Systems Selection and Collecting Information	405
16.4.2 System Boundary Definition.....	407
16.4.3 System Description and Functional Block Diagram	407
16.4.4 System Functions and Functional Failure.....	410
16.4.5 Failure Mode and Effective Analysis (FEMA)	410
16.4.6 Logic or Decision Tree Analysis (LTA)	411
16.4.7 Task Selection.....	411
16.5 RCM Implementation	411
16.5.1 Organizational Factors	412
16.5.2 RCM Teams.....	413
16.5.3 Scheduling Consideration and Training.....	413
16.6 Conclusion	414
References.....	414
 17 Total Productive Maintenance	 417
<i>P.S. Ahuja</i>	
17.1 Introduction to TPM	417
17.2 Evolution Towards TPM.....	420
17.3 Need of TPM	422
17.4 Basic Elements of TPM	424
17.5 Roadmap for TPM Implementation	429
17.6 An Ideal TPM Methodology	435
17.6.1 Introduction Phase (Phase I)	435
17.6.2 TPM Initiatives Implementation Phase (Phase II)	445
17.6.3 Standardization Phase (Phase III)	451
17.7 Barriers in TPM Implementation	453
17.8 Success Factors for Effective TPM Implementation.....	456
17.9 Summary	458
References.....	458
 18 Warranty and Maintenance	 461
<i>D.N.P. Murthy and N. Jack</i>	
18.1 Introduction.....	461
18.2 Maintenance Modelling	462
18.2.1 Reliability.....	462
18.2.2 Types of Maintenance	462
18.2.3 Failure Modelling.....	462

18.3 Warranties.....	465
18.3.1 Base Warranties	465
18.3.2 Classification of Base Warranties.....	466
18.3.3 Warranty Servicing Cost Analysis.....	466
18.3.4 Extended Warranties.....	467
18.4 Link Between Warranty and Maintenance.....	467
18.4.1 Taxonomy for Classification.....	467
18.4.2 Warranty Servicing Involving Only CM.....	468
18.4.3 Warranty Servicing Involving Both CM and PM	469
18.5 Maintenance Logistics for Warranty Servicing	470
18.5.1 Strategic Issues.....	471
18.5.2 Tactical and Operational Issues	472
18.6 Outsourcing of Maintenance for Warranty Servicing	474
18.6.1 Agency Theory.....	474
18.7 Conclusions and Topics for Future Research.....	476
References.....	476

19 Delay Time Modeling for Optimized Inspection Intervals of Production Plant..... 479

Wenbin Wang

19.1 Introduction.....	479
19.2 The DT Concept and Modeling Characteristics	480
19.3 The DT Models for Complex Plant.....	483
19.3.1 The Down Time/Cost Model	483
19.3.2 Modeling $E[N_f((i-1)T, iT)]$ and $E[N_s(iT)]$ Under the Assumption of Perfect Inspections.....	484
19.3.3 Modeling $E[N_f((i-1)T, iT)]$ and $E[N_s(iT)]$ Under the Assumption of Imperfect Inspections	485
19.4 Delay Time Model Parameters Estimation	487
19.4.1 Introduction.....	487
19.4.2 Complex System – Parameter Estimation.....	488
19.5 A Case Example.....	493
19.6 Other Developments in DT Modeling and Future Research Directions	496
References.....	497

20 Integrated E-maintenance and Intelligent Maintenance Systems..... 499

Jayantha P. Liyanage, Jay Lee, Christos Emmanouilidis, and Jun Ni

20.1 Introduction.....	499
20.2 Condition-based Maintenance Technology and the State of Development.....	501
20.3 Integrated E-maintenance Solutions and Current Status	503
20.4 Technical Framework for E-maintenance.....	507
20.5 Watchdog Agent-based Intelligent Maintenance Systems	511
20.5.1 R ² M-PHM Platform	511
20.5.2 System Architecture.....	512

20.5.3 Toolbox for Multi-sensor Performance Assessment and Prognostics.....	514
20.5.4 Maintenance Decision Support System	518
20.6 Technology Integration for Advanced E-maintenance	520
20.6.1 Generic ICT Interface	520
20.6.2 Generic Interface Requirements for Watchdog Agents.....	525
20.6.3 Systems-user Interface Needs	528
20.7 Some Industrial Applications.....	528
20.7.1 E-maintenance Solutions for Complex Industrial Assets.....	528
20.7.2 Watchdog Technology for Product Life-cycle Design and Management.....	532
20.7.3 Watchdog Technology to Trouble-shoot Bearing Degradation	533
20.8 Challenges of E-maintenance Application Solutions.....	536
20.9 Conclusion	538
References.....	539

Part VI – Maintainability and System Effectiveness

21 Maintainability and System Effectiveness.....	547
<i>J. Knezevic</i>	
21.1 Introduction.....	547
21.2 The Concept of Maintainability	550
21.2.1 Maintainability Impact on System Effectiveness.....	552
21.2.2 Maintainability Impact on Safety	555
21.2.3 Undesirable Maintainability Practices	558
21.2.4 Desirable Maintainability Practices	559
21.3 Maintainability Analysis.....	561
21.3.1 Measures of Maintainability	565
21.3.2 Maintenance Labour-hour Factors	568
21.3.3 Maintenance Frequency Factors	569
21.3.4 Maintenance Cost Factors.....	570
21.3.5 Related Maintenance Factors	570
21.4 Empirical Data and Maintainability Measures.....	571
21.4.1 Possible Approaches to Analysis of Existing Data	571
21.4.2 Parametric Approach to Maintainability Data	572
21.4.3 Distribution Approach to Maintainability Data	572
21.4.4 Distribution Approach.....	575
21.5 Maintainability Engineering Predictions.....	576
21.5.1 Introduction.....	577
21.5.2 Concept of the Maintainability Block Diagram	577
21.5.3 Derivation of the Expression for the Maintainability Function.....	580
21.5.4 Maintainability Characteristics for Different Design Options	585
21.6 Maintainability Engineering Management.....	592
21.6.1 Role of the Maintainability Engineering Management Function	593
21.6.2 MEMF Opportunities.....	594
21.6.3 MEMF Obstacles	594
21.6.4 Design Methods for Attaining Maintainability	596

21.6.5 Maintainability Engineering Management – Lessons Learned	603
21.7 Concluding Remarks.....	607
References.....	610

Part VII – Maintenance Safety, Environment and Human Error

22 Safety and Maintenance..... 613

Liliane Pintelon and Peter N. Muchiri

22.1 Setting the Scene.....	613
22.2 Definitions	615
22.2.1 Maintenance.....	615
22.2.2 Safety	616
22.2.3 Hazard.....	616
22.2.4 Stimuli.....	616
22.2.5 Accident	616
22.3 The Maintenance Link to Safety	617
22.3.1 The Role of Maintenance	617
22.3.2 Safety During Maintenance	620
22.3.3 Maintenance for Safety	622
22.3.4 Human Errors in Maintenance	625
22.3.5 Accident Causation Theories vs Maintenance	626
22.4 Maintenance Policies and Concepts vs Safety	629
22.4.1 Definitions	630
22.4.2 Maintenance Actions.....	630
22.4.3 Maintenance Policies	631
22.4.4 Maintenance Concepts	633
22.5 Maintenance Safety and Accident Prevention	636
22.5.1 Methods of Accidents and Hazards Avoidance in Maintenance	637
22.5.2 Analytical Approach	637
22.5.3 The Engineering Approach	638
22.5.4 Safety Culture	641
22.5.5 Safety Legislations.....	642
22.6 Safety Measurement.....	643
References.....	646

23 Maintenance Quality and Environmental Performance Improvement: An Integrated Approach..... 649

Abdul Raouf

23.1 Introduction.....	649
23.2 Maintenance Quality	650
23.2.1 Improving Maintenance Quality	650
23.2.2 Benchmarking and Quality	651
23.2.3 Maintenance Audit.....	655
23.2.4 Improving Maintenance Quality Based on Stakeholder Feedback ..	656
23.3 Lean Manufacturing – Maintenance Quality Relationship	656
23.3.1 Basic Environmental Measure	656
23.4 Integrated Approach.....	660

23.5 Conclusion	663
References.....	663
24 Industrial Asset Maintenance and Sustainability Performance: Economical, Environmental, and Societal Implications.....	665
<i>Jayantha P. Liyanage, Fazleena Badurdeen, R.M. Chandima Ratnayake</i>	
24.1 Introduction.....	665
24.2 Industrial Activities and Sustainability Trends	666
24.3 Sustainability Performance in Perspective.....	668
24.4 Sustainability Performance Framework: From Business to Asset	671
24.5 Defining Maintenance Custodianship Within an Asset's Sustainability Performance	676
24.6 Generic Maintenance Impact Management Process	683
24.7 Adapting an Effective Asset Maintenance Practice for Sustainability.....	686
24.8 Conclusion	689
References.....	689
25 Human Reliability and Error in Maintenance.....	695
<i>B.S. Dhillon</i>	
25.1 Introduction.....	695
25.2 Terms and Definitions.....	695
25.3 Human Reliability and Error in Maintenance-Related Facts, Figures, and Examples	696
25.4 Occupational Stressors, Human Performance Effectiveness, and Human Performance Reliability Function	697
25.5 Human Error Occurrence Ways, Consequences, and Classifications, and Maintenance Error in System Life Cycle	700
25.6 Reasons for the Occurrence of Human Error in Maintenance and Top Human Problems in Maintenance	701
25.7 Mathematical Models for Performing Maintenance Error Analysis in Engineering Systems.....	702
25.7.1 Model I.....	703
25.7.2 Model II	705
25.8 Useful Guidelines to Reduce the Occurrence of Human Error in Maintenance.....	707
References.....	709
26 Human Error in Maintenance – A Design Perspective	711
<i>Clive Nicholas</i>	
26.1 Introduction.....	711
26.2 Human Error in Aircraft Maintenance	712
26.3 Significance of Maintenance Error	713
26.4 Design Impact	717
26.5 Analysis Required for Design Solutions	718
26.5.1 Maintenance Tasks.....	721
26.5.2 Maintenance Errors.....	722
26.5.3 Causal Factors.....	724

26.6 Design Strategies and Principles.....	726
26.6.1 Appreciate the Maintainer's Perspective of the Aircraft.....	729
26.6.2 Design for the Aircraft Maintenance Environment.....	729
26.6.3 Protect the Aircraft and Protect the Maintainer.....	731
26.6.4 Avoid Complexity of Maintenance Tasks.....	732
26.6.5 Enable Adequate Maintenance Access	732
26.6.6 Positively Standardise and Positively Differentiate	733
26.6.7 Build Error Detection into the Maintenance Process	734
26.7 Conclusion	734
References.....	735
Index.....	737