# Contents


**I Setting the Scene** **1**

**1 Maintenance/Asset Management** **3**
1.1 Definition . . . 3
1.2 Historical perspective . . . 5
1.2.1 What has happened? . . . 5
1.2.2 How did this change maintenance management? . . . 7
1.2.3 What exactly is expected? . . . 9
1.3 Wrapping things up . . . 10
1.3.1 Drivers and dillemmas . . . 10
1.3.2 Critical success factors for maintenance today and (the day after) tomorrow . . . 11
1.4 Selected further reading . . . 12

**2 Managerial decision framework** **15**
2.1 Vision - mission . . . 15
2.2 Strategy and maintenance . . . 16
2.2.1 Strategy . . . 16
2.2.2 Maintenance/asset management in context . . . 17
2.2.3 Maintenance strategy . . . 20
2.3 Case example: Maintenance strategy formulation . . . 24
2.4 Selected further reading . . . 31

**3 Maintenance and IT** **33**
3.1 IT as a tool for maintenance management . . . 33
3.1.1 Useful IT capabilities . . . 33
3.1.2 Management perception of IT . . . 34
3.2 CMMS-EAMS . . . 34
3.2.1 Basics . . . 34
3.2.2 Issues to consider . . . 35
3.3 Knowledge management . . . 37
3.3.1 Concepts . . . 37
3.3.2 Basic example: expert systems . . . 39
3.4 E-maintenance . . . 41
3.4.1 E-maintenance explored . . . 41
3.4.2 Case example: POM project . . . 43
3.5 Selected further reading . . . 43

**II Computational Tools 47**

**4 Failure statistics 49**
4.1 Failures explored . . . 49
4.1.1 Failure . . . 49
4.1.2 Origin of failure . . . 50
4.1.3 Beware: common mode/cause failures . . . 50
4.2 Prerequisites: Probability theory . . . 51
4.3 Distributions . . . 52
4.3.1 Types of distributions . . . 52
4.3.2 Probability density/mass function . . . 52
4.3.3 Discrete distributions . . . 53
4.3.4 Continuous distributions . . . 53
4.4 Failure functions . . . 59
4.4.1 f(t), F(t), R(t) and h(t) . . . 59
4.4.2 Numerical illustrations . . . 63
4.5 Data analysis . . . 64
4.5.1 Data fitting . . . 64
4.5.2 Statistical tests . . . 66
4.6 Case examples . . . 69
4.7 Selected further reading . . . 72

**5 RAMS 73**
5.1 RAMS: what is it about? . . . 73
5.2 Reliability prediction . . . 77
5.2.1 Measured failure data . . . 77
5.2.2 Physics-on-failure . . . 79
5.2.3 System reliability . . . 83
5.2.4 State space analysis . . . 86
5.3 Risk analysis and reliability . . . 91
5.3.1 Risk analysis . . . 91
5.3.2 Fault tree analysis (FTA) . . . 91
5.3.3 Event tree analysis (ETA) . . . 93
5.3.4 Hazard and operability study (HAZOP) . . . 93
5.3.5 Root cause analysis (RCA) . . . 94
5.3.6 Bow tie analysis . . . 96
5.3.7 Failure mode effect analysis (FMEA) . . . 96
5.4 Human reliability analysis (HRA) . . . 98
5.5 Case study illustrations . . . 100
5.5.1 RCA1 . . . 100
5.5.2 RCA2 . . . 100
5.5.3 FMEA1 . . . 101
5.5.4 FMEA2 . . . 101
5.5.5 FMEA3 . . . 102
5.6 Numerical illustrations . . . 104
5.7 Selected further reading . . . 108

**6 Data quality management** **111**
6.1 Importance of data quality . . . 111
6.1.1 Factual decision making . . . 111
6.1.2 Anecdotes . . . 111
6.1.3 Ideal world . . . 112
6.2 Data collection process . . . 113
6.2.1 Internal data . . . 113
6.2.2 External data . . . 116
6.2.3 Special topic: FRACAS . . . 116
6.3 Data visualization . . . 117
6.3.1 Visualization before statistical analysis . . . 117
6.3.2 Visualization for general management purposes . . . 118
6.4 Selected further reading . . . 119

**III Decision Support** **123**

**7 Maintenance concepts** **125**
7.1 Definitions: maintenance actions, policies and concepts . . . 125
7.2 Maintenance actions . . . 126
7.3 Maintenance policies . . . 127
7.3.1 Failure based maintenance (FBM) . . . 127
7.3.2 Use/time based maintenance (UBM/TBM) . . . 127
7.3.3 Condition based maintenance (CBM) . . . 127
7.3.4 Opportunity based maintenance (OBM) . . . 128
7.3.5 Design-out maintenance (DOM) . . . 128
7.3.6 Example . . . 129
7.4 Maintenance concepts . . . 129
7.4.1 Quick & Dirty decision charts (Q&D) . . . 129
7.4.2 Life cycle costing (LCC) - Total cost of ownership (TCO) 130
7.4.3 Total productive maintenance (TPM) . . . 137
7.4.4 Reliability centered maintenance (RCM) . . . 145
7.4.5 Customized concepts . . . 153
7.4.6 Lean maintenance . . . 155
7.4.7 Concepts in practice . . . 158
7.4.8 Extra illustration: OEE . . . 160
7.5 Selected further reading . . . 161

**8 Maintenance policy optimization** **165**
8.1 Optimization in maintenance/asset management . . . 165
8.1.1 Optimization . . . 165
8.1.2 Need for optimization models in maintenance/asset management . . . 169
8.1.3 Practical issues . . . 171
8.2 Renewal theory . . . 174
8.2.1 Basics . . . 174
8.2.2 Illustrations . . . 177
8.2.3 Case study: Policy optimization for a can line . . . 181
8.3 Simulation . . . 186
8.3.1 Simulation as alternative for mathematical programming 186

8.3.2 Simulation approach . . . 188
8.3.3 Monte Carlo simulation . . . 191
8.3.4 Case studies . . . 192
8.4 Multi-criteria decision making (MCDM) . . . 195
8.4.1 General methodology . . . 195
8.4.2 Consensus method . . . 196
8.4.3 Analytic network process (ANP) . . . 197
8.4.4 MCDM and cost-effectiveness analysis . . . 201
8.5 Selected further reading . . . 210

**9 Operational planning 213**
9.1 Operational planning defined . . . 213
9.2 Project planning . . . 213
9.2.1 PERT - CPM . . . 213
9.2.2 Example . . . 215
9.2.3 Discussion . . . 216
9.3 Maintenance scheduling . . . 218
9.3.1 Maintenance jobs . . . 218
9.3.2 Production scheduling vs maintenance scheduling . . . 219
9.3.3 Planning requirements . . . 220
9.3.4 Planning algorithms . . . 222
9.4 Selected further reading . . . 226

**IV Resources 227**

**10 MRO management 229**
10.1 Problem setting . . . 229
10.1.1 Terminology . . . 229
10.1.2 Characteristics . . . 230
10.2 Inventory decision models . . . 231
10.2.1 Logistic costs . . . 231
10.2.2 Optimization issues . . . 232
10.2.3 Traditional models for non-repairable items . . . 232
10.2.4 Newer concepts . . . 239
10.2.5 Avoiding or reducing spare inventory . . . 242
10.2.6 Repairable items . . . 243
10.3 Case studies . . . 243
10.3.1 Case study 1 . . . 244
10.3.2 Case study 2 . . . 247
10.4 Selected further reading . . . 249

**11 Personnel 251**
11.1 Organizational context . . . 251
11.2 Maintenance personnel . . . 252
11.2.1 The maintenance/asset manager . . . 252
11.2.2 Maintenance workers . . . 253
11.2.3 Safety and ergonomics . . . 255
11.3 Quantitative techniques . . . 258
11.3.1 Time and method study . . . 258

11.3.2 Queueing . . . 259
11.4 Case studies . . . 266
11.4.1 Company case . . . 266
11.4.2 Herald of Free Enterprise case . . . 267
11.5 Selected further reading . . . 269

**12 Maintenance service sector 271**
12.1 Services . . . 271
12.2 Maintenance consultants . . . 271
12.3 Maintenance service providers . . . 272
12.4 Maintenance outsourcing . . . 275
12.4.1 Levels in maintenance outsourcing . . . 275
12.4.2 Issues to consider . . . 277
12.4.3 Guidelines for outsourcing . . . 279
12.5 Cases studies . . . 280
12.5.1 Survey on facility management outsourcing . . . 280
12.5.2 Field service as after-sales support . . . 283
12.6 Selected further reading . . . 289

**V Assessment 291**

**13 Performance reporting 293**
13.1 Performance reporting defined . . . 293
13.2 Approaches . . . 296
13.2.1 Alternative approaches . . . 296
13.2.2 Indicators . . . 297
13.2.3 Performance reporting models . . . 300
13.3 System design issues . . . 303
13.4 Selected further references . . . 308

**14 Auditing - Benchmarking 311**
14.1 Auditing . . . 311
14.1.1 Auditing defined . . . 311
14.1.2 Carrying out an audit . . . 312
14.2 Audit approaches . . . 313
14.2.1 Starting point . . . 313
14.2.2 Information phase . . . 315
14.2.3 Deliverables . . . 316
14.2.4 Illustration: Marcelis procedure . . . 316
14.3 Benchmarking . . . 319
14.3.1 Benchmarking defined . . . 319
14.3.2 Benchmarking in practice . . . 320
14.4 Selected further reading . . . 322

**VI Wrap-up 325**

**15 Towards world class maintenance 327**
15.1 Introduction . . . 327

15.2 Maintenance excellence framework . . . . . 327
15.2.1 Stage 1: Starting level . . . . . 328
15.2.2 Stage 2: Basic level . . . . . 328
15.2.3 Stage 3: Advanced level . . . . . 328
15.2.4 Stage 4: Excellence level . . . . . 329
15.3 Organizing for success: JALF . . . . . 329
15.4 Selected further reading . . . . . 330

# List of Figures


1.1 Asset/maintenance management defined . . . . . 4
1.2 Historical perspective on maintenance management . . . . . 6
1.3 Evolution in maintenance policy implementation . . . . . 8

2.1 Different production layouts . . . . . 18
2.2 Solutions for unreliable machine: illustration . . . . . 19
2.3 Some generic organization charts . . . . . 20
2.4 Maintenance decision pyramid . . . . . 21
2.5 Cost iceberg in maintenance . . . . . 22
2.6 Case study: Asset management strategy design methodology . . 25
2.7 Case study: cognitive map . . . . . 27
2.8 Case study: Nework and structure of the supermatrix . . . . . 29
2.9 Case study: Example of pairwise comparison . . . . . 30

3.1 IT capabilities and maintenance applications: examples . . . . . 33
3.2 CMMS: Embedded or Best-of-Breed . . . . . 35
3.3 From data to knowledge . . . . . 38
3.4 Nonaka's knowledge spiral . . . . . 39
3.5 Expert system: example . . . . . 41
3.6 E-maintenance system components . . . . . 42
3.7 Illustrationn of an e-maintenance project . . . . . 44

4.1 Hierarchy of components in an industrial installation . . . . . 49
4.2 Triangular and uniform distribution . . . . . 59
4.3 Continuous failure distributions: Graphs . . . . . 62
4.4 Weibull plot for the example . . . . . 67
4.5 Illustration for Laplace test . . . . . 70
4.6 Illustration: Job statuses . . . . . 70

5.1 RAMS concept . . . . . 75
5.2 Uptime, downtime, TTF, TTS and TTR . . . . . 75
5.3 Bathtub curve . . . . . 76
5.4 PF-curve . . . . . 76
5.5 Load-strength diagram . . . . . 80
5.6 Physics-of-failures principle illustrated . . . . . 81
5.7 Degradation modeling principle . . . . . 82
5.8 Series and parallel component configurations . . . . . 83
5.9 Example of cut & tie set approach . . . . . 85

5.10 State transition diagram for a repairable component . . . . . 87
5.11 Example of Markov diagram . . . . . 90
5.12 Risk management illustrated . . . . . 92
5.13 FTA: example . . . . . 93
5.14 ETA: example . . . . . 94
5.15 HAZOP risk matrix . . . . . 94
5.16 Root cause mapping techniques . . . . . 96
5.17 Bow tie analysis . . . . . 96
5.18 FMEA worksheet . . . . . 98
5.19 HRA procedure . . . . . 99
5.20 Illustration case study RCA1 . . . . . 101
5.21 Illustration case study RCA2 . . . . . 101
5.22 Illustration of an FMEA sheet for a paint shop . . . . . 102
5.23 Illustration of failure modes and associated costs for wind turbine gear boxes . . . . . 102
5.24 Illustration of starting point for a FMEA study of medical ventilators . . . . . 103
5.25 Block diagram example . . . . . 104
5.26 Cut & tie set illustration . . . . . 105
5.27 System availability illustration . . . . . 105
5.28 Markov example . . . . . 107

6.1 FRACAS basics . . . . . 117
6.2 Illustration of mixed distribution . . . . . 118
6.3 Illustration of deceptive data sets . . . . . 119
6.4 Appropriate charts choice . . . . . 120
6.5 Illustration on the choice of chart types . . . . . 120

7.1 Maintenance concepts and the tactical decision level . . . . . 125
7.2 Definitions . . . . . 126
7.3 Illustration of a Q&D decision chart . . . . . 131
7.4 Basic principles of LCC . . . . . 131
7.5 Maintenance considerations during the equipment life cycle . . . 132
7.6 LCC cost breakdown . . . . . 133
7.7 Illustration of an LCC analysis . . . . . 134
7.8 Illustration: LCC modeling approach . . . . . 135
7.9 Point of view in logistics engineering . . . . . 136
7.10 Total participation within TPM . . . . . 137
7.11 TPM pillars . . . . . 138
7.12 Overall equipment effectiveness (OEE) . . . . . 139
7.13 OEE related concepts . . . . . 140
7.14 Evolution of RCM . . . . . 146
7.15 RCM charts . . . . . 148
7.16 Illustration of problem approach in the RCM case study . . . . . 149
7.17 The slice concept in implementing RCM . . . . . 151
7.18 CIBOCOF concept . . . . . 154
7.19 Lean thinking: principles . . . . . 156
7.20 Lean thinking: Muri-Mura-Muda . . . . . 156
7.21 VSM: illustration of symbols . . . . . 158

8.1 From strategy to workable maintenance plan . . . . . 172
8.2 EOH concept . . . . . 172
8.3 Basics of renewal theory . . . . . 174
8.4 Age based and block based replacement models . . . . . 175
8.5 Illustration for the light bulbs renewal example . . . . . 179
8.6 Illustration for the robot renewal example . . . . . 180
8.7 Weibull illustrations for the case study . . . . . 183
8.8 Case study: Result for cost minimization . . . . . 185
8.9 Simulation vs math programming approach . . . . . 187
8.10 Types of simulation approaches . . . . . 189
8.11 Steps in a simulation project . . . . . 203
8.12 Random numbers in a Monte Carlo simulation . . . . . 204
8.13 MRO example: simulation start . . . . . 204
8.14 Illustration of simulation study for assessing the impact of maintenance improvements . . . . . 204
8.15 Illustration of simulation study for the selection of maintenance policies . . . . . 205
8.16 Converted MDCM scores (utilities) . . . . . 205
8.17 Utility plane for the consensus method . . . . . 206
8.18 Warehouse layout for the MCDM example . . . . . 206
8.19 MCDM: sample screen shot . . . . . 207
8.20 AHP/ANP: basic elements . . . . . 207
8.21 Illustration of network structure and supermatrix . . . . . 208
8.22 Illustration on criteria prioritizing . . . . . 208
8.23 Illustration of customized criteria network . . . . . 209
8.24 Cost-effectiveness analysis . . . . . 209

9.1 Network for project planning example . . . . . 218
9.2 Maintenance job characteristics . . . . . 222
9.3 Maintenance planning system . . . . . 223
9.4 Scheduling priority systems: Some examples . . . . . 225

10.1 MRO actors . . . . . 230
10.2 Sources of MRO demand . . . . . 233
10.3 Basic inventory models . . . . . 233
10.4 Typical SMI inventory profile . . . . . 234
10.5 EOQ inventory profile . . . . . 235
10.6 (R,q) inventory profile . . . . . 236
10.7 Nomogram for a SMI model . . . . . 238
10.8 Example of MRO pooling . . . . . 240
10.9 Management implications of spare's criticality and specificity . . 242
10.10Graph for the ABC analysis . . . . . 245
10.11Illustration of AHP procedure . . . . . 248
10.12Illustration of decision tree . . . . . 249

11.1 Organization chart: illustration . . . . . 252
11.2 Maintenance safety cartoon . . . . . 257
11.3 Swiss cheese model . . . . . 257
11.4 UMS: concept . . . . . 259
11.5 Queueing system: concept . . . . . 261

11.6 Organization chart: case study . . . . . 267

12.1 From 'product' to 'product - service' . . . . . 273
12.2 Typology for Product Service Systems . . . . . 274
12.3 Traditional vs functional product . . . . . 275
12.4 Levels in outsourcing . . . . . 275
12.5 Issues in outsourcing . . . . . 276
12.6 Illustration of bonus-malus cost formula . . . . . 278
12.7 FM in the organization chart . . . . . 281
12.8 Level of cooperation . . . . . 282
12.9 Case study: Service level versus stock . . . . . 288

13.1 One-liners in performance reporting . . . . . 294
13.2 Seeing the big picture with KPIs . . . . . 295
13.3 Survey results on KPI use . . . . . 298
13.4 Illustration of the Priel KPI's . . . . . 299
13.5 Illustrations of some typical graph types . . . . . 299
13.6 Illustrations of some KPI representation formats . . . . . 300
13.7 Illustration of a typical indicator . . . . . 300
13.8 Illustration of the Input-Output model . . . . . 301
13.9 Illustration of the Luck approach . . . . . 302
13.10Illustration of the MMT concept . . . . . 303
13.11BSC concept . . . . . 304
13.12Steps in designing a performance reporting system . . . . . 306
13.13Illustration of a KPI identity card . . . . . 306
13.14Survey results on the use of KPI systems . . . . . 307

14.1 Illustration of a maintenance excellence pyramid . . . . . 311
14.2 Illustration of an opportunity map . . . . . 312
14.3 The Kelly audit model . . . . . 313
14.4 The maintenance excellence audit model (Jardine) . . . . . 314
14.5 PAS 55 and levels in asset management . . . . . 315
14.6 Audit matrix . . . . . 317
14.7 Gap analysis . . . . . 317
14.8 Results of an Marcelis audit . . . . . 319
14.9 Different benchmarking alternatives . . . . . 320
14.10Illustration of an external audit output . . . . . 321

15.1 Maintenance excellence framework . . . . . 327
15.2 Management priorities ... . . . . 330

# List of Tables


3.1 Evolution of CMMS . . . . . 36

4.1 Illustration of potential failure causes . . . . . 51
4.2 Discrete failure distributions: Description . . . . . 53
4.3 Discrete failure distributions: Mathematical functions . . . . . 54
4.4 Continuous failure distributions: Mathematical functions . . . . . 55
4.5 Continuous failure distributions: Description (1/3) . . . . . 56
4.6 Continuous failure distributions: Description (2/3) . . . . . 57
4.7 Continuous failure distributions: Description (3/3) . . . . . 58
4.8 Illustration of data ranking . . . . . 65
4.9 Pump data for the Weibull example . . . . . 66
4.10 Data for the $\chi^2$ example . . . . . 68

5.1 Illustration of Duane $\alpha$-values . . . . . 82
5.2 Human error and systems failures: some numbers . . . . . 98

6.1 Illustration of maintenance recording detail . . . . . 113
6.2 Data types in data collection . . . . . 114

7.1 Illustration of maintenance actions and policies (bike) . . . . . 129
7.2 The 5S concept in TPM . . . . . 139
7.3 Illustration of the 6 big losses concept in a brewery . . . . . 142
7.4 Illustration of typical RCM recommendations . . . . . 148
7.5 Alternatives in streamlined RCM . . . . . 152
7.6 The seven wastes in Lean thinking . . . . . 157
7.7 Summary on maintenance concepts . . . . . 159

8.1 Component reliability data . . . . . 168
8.2 Component costs and weights . . . . . 168
8.3 Examples of the use of decision support techniques . . . . . 170
8.4 Costs for the light bulb renewal example . . . . . 179
8.5 Influence of parameter $\alpha$ on the optimal $T_a$ (case study) . . . . . 185
8.6 Data for the MRO simulation example . . . . . 192
8.7 Random numbers for the MRO simulation . . . . . 193
8.8 Simulation results for the MRO example . . . . . 194
8.9 Data for the MCDM example . . . . . 197
8.10 Converted data for the MCDM example . . . . . 198

9.1 Notation for network procedure . . . . . 215

9.2 Data for project planning example . . . . . 216
9.3 Results for project planning example . . . . . 217
9.4 Illustration of some traditional scheduling parameters . . . . . 224

10.1 Component data for inventory example . . . . . 238
10.2 ABC analysis based on rotation and value . . . . . 244
10.3 Business specific vs standard stock articles . . . . . 248

11.1 UMS illustration for pumps . . . . . 260

12.1 Product support implications for customer and supplier . . . . . 273
12.2 Activities outsourced vs kept-in-house . . . . . 282
12.3 Notation for the multi-period repair kit model . . . . . 285

13.1 Overview of different performance measurement approaches . . . 296
13.2 Important issues when designing a KPI system . . . . . 305

14.1 The levels of perfection in the Marcelis audit method . . . . . 318