E-maintenance
E-maintenance
Preface

This is the first book to present the topic of e-maintenance, which has appeared in the scientific and technological discussions at conferences and meetings during the last decade. E-maintenance is a synthesis of two large trends in our society: on the one hand the growing importance of maintenance as a key technology to keep machines running properly, efficiently and safely in industry and transportation, and on the other hand, the very rapid development of information and communication technology (ICT). This has opened the way to completely new concepts and solutions with more detailed equipment for health information and more effective diagnostic and prognostic tools and user interfaces to ensure good reliability and availability of plants and vehicles remotely worldwide.

The authors of the book are European top experts on ICT and maintenance technology both from academia and industry. They have worked very intensively together for the last four years, starting in 2005 within the European Commission funded research and development project DYNAMITE – Dynamic Decisions in Maintenance. The R&D group consisted of about 50 experts altogether from nine European countries: Estonia, Finland, France, Germany, Greece, Italy, Spain, Sweden and UK.

This book presents an overview of the subject of e-maintenance including trends, scenarios and needs in industry and advanced ICT technologies and future solutions to global and mobile industrial maintenance needs. The pioneering e-maintenance concept DynaWeb is presented, and the group of experts that were involved in its development describe the detailed technologies, their development and experiences gained with this R&D process, as well as future perspectives.

The book is divided into 16 chapters, which include the new integrated e-maintenance concept, intelligent, wireless, MEMS, and lubricating oil sensors, smart tags, mobile devices and services, semantic web services, strategies for e-maintenance and related cost effective decisions, industrial demonstrations as examples of e-maintenance, as well as related e-training.

The book is intended for engineers and qualified technicians working in the fields of maintenance, systems management, and shop floor production lines.
maintenance. It constitutes a good tool for the further development of e-maintenance in both current and new industrial sites.

It is the hope of the authors that this book will open new views and ideas to researchers and industry on how to proceed in the direction of a sustainable and environmentally stable society.

Europe

October 2009

The authors
Acknowledgements

The authors gratefully acknowledge the support of the European Commission Sixth Framework Programme for Research and Technological Development. This book summarises work performed as part of FP6 Integrated project IP017498 DYNAMITE “Dynamic Decisions in Maintenance”.

The authors are grateful for the support and encouragement received from the European Commission Scientific Officers Andrea Gentili, Philipp Dreiss and Barry Robertson. We also wish to thank the project reviewers appointed by the Commission, Flavio Testi and Christoph Hanisch, for their advice and guidance during the R&D work.

The excellent help and assistance from a great number of colleagues and staff members, as well as the encouragement and financial support from all organisations participating in DYNAMITE is gratefully acknowledged:

- VTT Technical Research Centre, Finland
- Fundación Tekniker, Spain
- University of Sunderland, UK
- University of Manchester, UK
- Université Henri Poincaré, France
- Linnaeus University, Sweden
- Zenon S.A. Robotics & Informatics, Greece
- FIAT Research Centre, Italy
- Volvo Technology, Sweden
- Goratu Maquinas Herramienta, Spain
- Wyselec, Finland
- Martechnic, Germany
- Engineering Statistical Solutions, UK
- Diagnostic Solutions, UK
- Prisma Electronics, Greece
- IB Krates, Estonia
The financial support from the following national funding agency is gratefully acknowledged:

- Spanish Ministry of Science and Innovation (grant no. DPI2007-29958-E)

The authors also wish to thank Ms Christina Vähävaara for the skilful and meticulous editing of the manuscript.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contributors</td>
<td>xiii</td>
</tr>
<tr>
<td>Abbreviations</td>
<td>xvii</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>References</td>
<td>3</td>
</tr>
<tr>
<td>2 Maintenance Today and Future Trends</td>
<td>5</td>
</tr>
<tr>
<td>2.1 State of the Art in Management</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Integrated Programmes and Planning Processes</td>
<td>8</td>
</tr>
<tr>
<td>2.2.1 Reliability-centred Maintenance</td>
<td>8</td>
</tr>
<tr>
<td>2.2.2 Total Productive Maintenance</td>
<td>9</td>
</tr>
<tr>
<td>2.2.3 Total Quality Maintenance</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Strategies</td>
<td>10</td>
</tr>
<tr>
<td>2.3.1 Run-to-failure</td>
<td>11</td>
</tr>
<tr>
<td>2.3.2 Time-based Maintenance</td>
<td>12</td>
</tr>
<tr>
<td>2.3.3 Opportunity Maintenance</td>
<td>14</td>
</tr>
<tr>
<td>2.3.4 Design Out</td>
<td>14</td>
</tr>
<tr>
<td>2.3.5 Condition Based Maintenance</td>
<td>15</td>
</tr>
<tr>
<td>2.3.6 Summary</td>
<td>16</td>
</tr>
<tr>
<td>2.4 Maintenance Information and Control Systems</td>
<td>17</td>
</tr>
<tr>
<td>2.4.1 Features of the Typical Maintenance System: from SME to Global Enterprises</td>
<td>17</td>
</tr>
<tr>
<td>2.4.2 Limitations to the Penetration of Integrated Systems</td>
<td>18</td>
</tr>
<tr>
<td>2.5 State of the Art in Technology</td>
<td>19</td>
</tr>
<tr>
<td>2.5.1 Computing Tools</td>
<td>19</td>
</tr>
<tr>
<td>2.5.2 Measurement Tools and Services</td>
<td>20</td>
</tr>
<tr>
<td>2.5.3 Portable Instruments</td>
<td>21</td>
</tr>
<tr>
<td>2.5.4 Laboratory-based Services</td>
<td>23</td>
</tr>
</tbody>
</table>
2.6 New Paradigms: Customisation and Sustainability ........................................... 23
2.7 New Developments in Decision Making ............................................................ 25
2.8 New Developments in Technological Tools ......................................................... 26
  2.8.1 Wireless Sensors ......................................................................................... 26
  2.8.2 Miniaturisation, Cost Reduction and MEMS ........................................... 28
  2.8.3 Disruptive Technologies and the Future ......................................................... 31
  2.8.4 Pervasive Sensing and Intelligence ............................................................... 33
2.9 Conclusions ......................................................................................................... 35
References .................................................................................................................. 36

3 Information and Communication Technologies
Within E-maintenance .................................................................................................. 39
3.1 Introduction ............................................................................................................ 39
3.2 Introduction to E-maintenance ............................................................................... 40
  3.2.1 Maintenance Today: What Are the Main Issues? ........................................ 41
  3.2.2 E-maintenance: Towards a Consensus or a Lot of Different Definitions? ............ 43
  3.2.3 E-maintenance: a Symbiosis Between Maintenance Services and Maintenance Technologies .................................................. 44
3.3 ICT for E-maintenance ......................................................................................... 45
  3.3.1 Miniaturisation Technologies for Data Acquisition ..................................... 46
  3.3.2 Standards for Data and Information Communication .................................. 49
  3.3.3 Data and Information Processing and the Impact of Machine Learning Systems .......................................................... 55
3.4 Conclusions ........................................................................................................... 58
References .................................................................................................................. 58

4 A New Integrated E-maintenance Concept ............................................................... 61
4.1 Introduction ............................................................................................................ 61
4.2 E-maintenance Scenario Analysis ....................................................................... 62
4.3 DynaWeb Integrated Solution .............................................................................. 64
  4.3.1 Standards and Technologies for Data Interoperability ................................ 66
  4.3.2 Implementing the Solution .......................................................................... 68
4.4 Intelligent Sensors ............................................................................................... 71
4.5 Information and Communication Infrastructure ............................................... 73
4.6 Cost-effectiveness Based Decision Support System ......................................... 77
4.7 DynaWeb Demonstrations .................................................................................. 79
4.8 Conclusions .......................................................................................................... 81
References .................................................................................................................. 82

5 Intelligent Wireless Sensors .................................................................................... 83
5.1 Introduction ............................................................................................................ 83
  5.1.1 Fundamental Definitions ................................................................................. 83
  5.1.2 Benefits of Using Intelligent Sensors ............................................................. 85
5.1.3 Businesses Driven Development of Intelligent Sensors ........86
5.2 State-of-the-art Intelligent Sensors ........................................87
  5.2.1 Several Functions Within One Platform .........................88
  5.2.2 Hardware .....................................................................89
  5.2.3 Wireless RF Standards .............................................91
  5.2.4 Intelligent Sensor Networks ....................................94
5.3 Expected Features and Design of Intelligent Sensors .............95
  5.3.1 Conventional Sensors .............................................95
  5.3.2 Examples of Application of Conventional Sensors ...........96
  5.3.3 Expected Features of Intelligent Sensors ....................97
  5.3.3 Processing Capacity Offered by the Use of Intelligent Sensors .........................................................100
  5.3.4 General Design Requirements for Intelligent Sensors ....103
5.4 Hardware Requirements for Wireless Sensors ......................106
  5.4.1 Hardware Components ............................................107
  5.4.2 ZigBee as a Suggested Communication Technology ....111
5.5 Power Reduction Methods Available in ZigBee Protocol ......117
  5.5.1 Orthogonal Signalling – Used for 2.45 GHz .................118
  5.5.2 Warm-up Power Loss – DSSS ................................118
  5.5.3 Transmitting and Receiving ....................................119
  5.5.4 Recovery Effect in Batteries ..............................119
  5.5.5 Cost Based Routing Algorithm – Link Quality
       and Hop Count ........................................119
  5.5.6 Power Consumption Tests ....................................120
5.6 Conclusions ........................................................................120
References ..............................................................................121

6  MEMS Sensors ......................................................................125
  6.1 Introduction ....................................................................125
  6.2 State-of-the-art of MEMS .............................................130
  6.3 Characteristics of MEMS Sensors ..................................133
  6.4 Specification of Multi-MEMS Sensor Platform .................136
    6.4.1 Introduction .....................................................136
    6.4.2 Objectives .....................................................137
    6.4.3 Possible Profiles of Intelligent Sensors .................138
  6.5 Simulation of Multi-MEMS Sensor Platform ....................145
    6.5.1 Sensing Unit .................................................145
    6.5.2 Processing Unit ............................................147
    6.5.3 Hardware Implementation .................................148
    6.5.4 Data Sampling .............................................150
    6.5.5 Local Decision Making Based on Condition ..........151
    6.5.6 Threshold with Event Triggering .......................152
    6.5.7 Data Pre-processing ..................................154
    6.5.8 Transmission on Intervals ..............................156
6.6 Power Management ......................................................................................... 159
  6.6.1 Sleep Mode ............................................................................................. 159
  6.6.2 Performance versus Power Consumption .............................................. 160
  6.6.3 Energy Harvesting System ..................................................................... 161
  6.6.4 Energy Transducers ............................................................................. 161
  6.6.5 Energy Converting and Storing Subsystems ........................................ 165
  6.6.6 Implementation of an Energy Harvester .............................................. 168
6.7 Conclusions .................................................................................................. 171
References ........................................................................................................... 171

7 Lubricating Oil Sensors .................................................................................... 173
  7.1 Introduction .................................................................................................. 173
  7.2 State-of-the-art .......................................................................................... 174
    7.2.1 Oxidation ............................................................................................. 174
    7.2.2 Viscosity ............................................................................................. 175
    7.2.3 Corrosion ............................................................................................. 176
    7.2.4 Water .................................................................................................. 176
    7.2.5 Particles .............................................................................................. 176
    7.2.6 Others ................................................................................................ 177
  7.3 New Sensor Developments ......................................................................... 177
    7.3.1 Detection of Solid Contaminants ....................................................... 177
    7.3.2 Water Detection ................................................................................. 187
    7.3.3 Lubrication Deterioration by Ageing ................................................. 192
  7.4 Conclusions .................................................................................................. 194
References ........................................................................................................... 195

8 Smart Tags ........................................................................................................ 197
  8.1 Introduction .................................................................................................. 197
  8.2 Overview of the Technology ..................................................................... 198
    8.2.1 Technical Basics ............................................................................... 198
    8.2.2 RFID Software Considerations ....................................................... 203
    8.2.3 RFID Standards ............................................................................... 204
    8.2.4 Costs Involved .................................................................................... 205
    8.2.5 Advantages and Disadvantages ....................................................... 205
    8.2.6 Privacy Issues .................................................................................... 206
    8.2.7 Applications for RFID ....................................................................... 207
  8.3 Real-time Locating Systems Using Active RFID ....................................... 208
    8.3.1 Time of Arrival .................................................................................. 208
    8.3.2 Time Difference of Arrival ................................................................. 209
    8.3.3 Angle of Arrival ............................................................................... 210
    8.3.4 Received Signal Strength Induction ............................................... 211
    8.3.5 LANDMARC ..................................................................................... 212
  8.4 Background to Applications of RFID ......................................................... 212
8.5 Review of RFID Applications in Maintenance .................................. 213
8.6 Applications and Scenarios ............................................................ 214
  8.6.1 Tools ..................................................................................... 216
  8.6.2 Spare Parts ............................................................................ 216
  8.6.3 Machines ............................................................................... 217
  8.6.4 Personnel ............................................................................... 217
8.7 Smart Tag Demonstrators .............................................................. 217
  8.7.1 Inventory Tracking (Passive) .................................................. 218
  8.7.2 Asset Identification and Query System for PDAs (Passive) ........ 219
  8.7.3 Mobile Assets Positioning System (Active) ......................... 221
8.8 Conclusions .................................................................................. 224
References .......................................................................................... 225

9 Mobile Devices and Services ............................................................ 227
  9.1 Introduction ............................................................................. 228
  9.2 Mobile Devices in Maintenance Management ............................. 229
  9.3 Role of PDA Within DynaWeb .................................................... 230
  9.4 Description of Typical PDA Usage Scenario in Maintenance Operations ........................................... 233
  9.5 Wireless Communication ............................................................ 238
  9.6 Technical Requirements ............................................................ 239
  9.7 Practical Limitations Today ......................................................... 239
  9.8 Mobile User Interface Issues ...................................................... 240
  9.9 Trends ..................................................................................... 242
  9.10 Conclusions .......................................................................... 245
References .......................................................................................... 245

10 Wireless Communication ............................................................... 247
  10.1 Introduction ......................................................................... 247
  10.2 State-of-the-art ..................................................................... 250
    10.2.1 WLANs (IEEE 802.11) ...................................................... 250
    10.2.2 Bluetooth (IEEE 802.15.1) ................................................. 256
    10.2.3 ZigBee (IEEE 802.15.4) .................................................... 259
    10.2.4 Assessment of Previous Technologies to Support E-maintenance Applications ................. 262
    10.2.5 Conclusions .................................................................... 266
  10.3 New Developments ................................................................. 266
    10.3.1 Wireless Gateway ............................................................ 267
    10.3.2 Wireless Collector ............................................................ 270
  10.4 Conclusions and Recommendations ....................................... 271
References .......................................................................................... 271
11 Semantic Web Services for Distributed Intelligence ................................. 273
11.1 Introduction..................................................................................... 273
11.2 State-of-art in Application of the Semantic Web to Industrial Automation .............................................................................. 274
  11.2.1 What Is an Ontology?................................................................. 274
  11.2.2 Advantages of Semantic Web Techniques................................. 274
  11.2.3 Semantic Web Languages........................................................... 276
  11.2.4 Semantic Web Platforms ........................................................... 277
  11.2.5 Semantic Web Development in Industrial Automation .......... 280
11.3 Web Services for Dynamic Condition Based Maintenance ............... 282
  11.3.1 Web Service for Condition Monitoring ..................................... 287
  11.3.2 Web Service for Diagnosis Based on Vibration and Oil Data .......... 288
  11.3.3 Web Service for Prognosis .......................................................... 289
  11.3.4 Web Service for Scheduling ..................................................... 292
  11.3.5 Testing Web Services ................................................................. 293
11.4 Conclusions.................................................................................... 295
References ............................................................................................... 295

12 Strategies for Maintenance Cost-effectiveness....................................... 297
12.1 Introduction..................................................................................... 298
12.2 Development of Strategies for Cost-effectiveness ............................ 298
  12.2.1 Theoretical Background............................................................ 299
  12.2.2 The Role of Maintenance Company Business........................... 304
12.3 Development of a Maintenance Decision Support System (MDSS)..... 307
  12.3.1 Objectives of MDSS ................................................................. 308
  12.3.2 MDSS Toolsets and Tools ......................................................... 309
12.4 Conclusions.................................................................................... 341
References ............................................................................................... 342

13 Dynamic and Cost-effective Maintenance Decisions ............................. 345
13.1 Introduction..................................................................................... 346
13.2 MDSS for Dynamic and Cost-effective Maintenance Decisions ...... 346
  13.2.1 Deterministic and Probabilistic Approaches .............................. 347
  13.2.2 Dynamic and Cost-effective Maintenance Decisions .............. 349
  13.2.3 Application Scenario of MDSS .................................................. 351
13.3 Data Required for Running MDSS ................................................... 354
  13.3.1 Datasets .................................................................................. 354
  13.3.2 Data Gathering ....................................................................... 361
13.4 Database Required for MDSS .......................................................... 362
  13.4.1 MDSS Data Model ................................................................. 362
  13.4.2 Mapping to Company Data Models ....................................... 365
  13.4.3 Mapping to CRIS/MIMOSA ................................................... 367
13.4.4 CRIS/MIMOSA Database User-interface.............................369
13.4.5 Test of CRIS/MIMOSA Database User-interface.................371
13.5 Case Studies for Applying MDSS......................................................372
13.5.1 Toolset 1: PreVib, ProFail and ResLife.........................372
13.5.2 Toolset 2: AltSim.................................................................377
13.5.3 Toolset 3: MMME and MainSave.................................384
13.6 Results and Discussions..............................................................387
13.7 Conclusions.....................................................................................388
References ..................................................................................................389

14 Industrial Demonstrations of E-maintenance Solutions...............391
14.1 Global Demonstration in a Milling Machine Environment........393
14.1.1 Objectives of the Test and Demonstrations.........................394
14.1.2 Description of the Test Platform...........................................396
14.1.3 Description of the DynaWeb Components Tested................397
14.1.4 Economical Evaluation...........................................................415
14.1.5 Conclusions...........................................................................416
14.2 Foundry Hydraulic System Demonstrator..........................417
14.2.1 Objectives of the Test and Demonstrations...............418
14.2.2 Description of the Test Platform...........................................418
14.2.3 Description of the DynaWeb Components Tested...............419
14.2.4 Reference Measurements and Software.................................424
14.2.5 Results.......................................................................................424
14.2.6 Technical Evaluation.............................................................425
14.2.7 Economical Evaluation...........................................................426
14.2.8 Conclusions and Recommendations.................................426
14.3 Automatic Strip Stamping and Cutting Machine Demonstrator 428
14.3.1 Objectives of the Test and Demonstrations...............431
14.3.2 Description of the Test Platform...........................................433
14.3.3 Description of the DynaWeb Components Tested...............435
14.3.4 Reference Testing Procedure..................................................439
14.3.5 Results.......................................................................................445
14.3.6 Conclusions...........................................................................449
14.4 Machine Tool Demonstrator...................................................450
14.4.1 Objectives of the Test and Demonstrations...............450
14.4.2 Description of the Test Platform...........................................451
14.4.3 Description of the DynaWeb Components Tested...............453
14.4.4 Reference Measurements/Software.................................457
14.4.5 Results.......................................................................................459
14.4.6 Technical Evaluation.............................................................459
14.4.7 Economical Evaluation...........................................................460
14.4.8 Conclusions and Recommendations.................................460
14.5 Maritime Lubrication System Demonstrator..........................461
Contributors

Addison, Dale
University of Sunderland, UK
E-mail: dale.addison@sunderland.ac.uk
Web: www.sunderland.ac.uk

Adgar, Adam
University of Teesside, UK
E-mail: a.adgar@tees.ac.uk
Web: www.tees.ac.uk

Albarbar, Alhussein
Manchester Metropolitan University, UK
E-mail: a.albarbar@mmu.ac.uk
Web: www.mmu.ac.uk

Al-Najjar, Basim
Linnaeus University, Sweden
E-mail: basim.al-najjar@lnu.se
Web: www.lnu.se

Arnaiz, Aitor
Fundación Tekniker, Spain
E-mail: aarnaiz@tekniker.es
Web: www.tekniker.es

Baglee, David
University of Sunderland, UK
E-mail: david.baglee@sunderland.ac.uk
Web: www.sunderland.ac.uk
Contributors

Bellew, Jim
Martechin Gmbh, Germany
E-mail: jim.bellew@martechnic.com
Web: www.martechnic.com

Eberhagen, Niclas
Linnaeus University, Sweden
E-mail: niclas.eberhagen@lnu.se
Web: www.lnu.se

Emmanouilidis, Christos
CETI/Athena Research & Innovation Centre, Greece
E-mail: chrisem@ceti.gr
Web: www.ceti.gr

Garramiola, Fernando
Goratu Maquinas Herramienta S.A., Spain
E-mail: fgarramiola@goratu.com
Web: www.goratu.com

Gilabert, Eduardo
Fundación Tekniker, Spain
E-mail: egilabert@tekniker.es
Web: www.tekniker.es

Giordamlis, Christos
Prisma Electronics, Greece
E-mail: christos@prisma.gr
Web: www.prisma.gr

Gorritxategi, Eneko
Fundación Tekniker, Spain
E-mail: egorritxategi@tekniker.es
Web: www.tekniker.es

Halme, Jari
VTT Technical Research Centre, Finland
E-mail: jari.halme@vtt.fi
Web: www.vtt.fi

Holmberg, Kenneth
VTT Technical Research Centre, Finland
E-mail: kenneth.holmberg@vtt.fi
Web: www.vtt.fi

Iung, Benoit
Université Henri Poincaré, France
E-mail: Benoit.Iung@cran.uhp-nancy.fr
Web: www.cran.uhp-nancy.fr
Jantunen, Erkki
VTT Technical Research Centre, Finland
E-mail: erkki.jantunen@vtt.fi
Web: www.vtt.fi

Katsikas, Serafim
Prisma Electronics, Greece
E-mail: sekat2004@yahoo.gr
Web: www.prisma.gr

Krommenacker, Nicolas
Université Henri Poincaré, France
E-mail: nicolas.krommenacker@cran.uhp-nancy.fr
Web: www.cran.uhp-nancy.fr

Lecuire, Vincent
Université Henri Poincaré, France
E-mail: vincent.lecuire@cran.uhp-nancy.fr
Web: www.cran.uhp-nancy.fr

Levrat, Eric
Université Henri Poincaré, France
E-mail: eric.levrat@cran.uhp-nancy.fr
Web: www.cran.uhp-nancy.fr

Mascolo, Julien
FIAT Research Center, Italy
E-mail: julienetienne.mascolo@crf.it
Web: www.crf.it

Mekid, Samir
The University of Manchester, UK
King Fahd University Petroleum & Minerals, KSA
E-mail: smekid@kfupm.edu.sa
Web: www.manchester.ac.uk; www.kfupm.edu.sa

Naks, Tonu
IB Krates OÜ, Estonia
E-mail: tonu@krates.ee
Web: www.krates.ee

Nilsson, Per
Volvo Technology AB, Sweden
E-mail: Per.Henrik.Nilsson@volvo.com
Web: www.volvo.com
Pietruszkiewicz, Robert
The University of Manchester, UK
E-mail: rpietrus@gmail.com
Web: www.manchester.ac.uk

Salles, Nicolas
Université Henri Poincaré, France
E-mail: nicolas.salles@cran.uhp-nancy.fr
Web: www.cran.uhp-nancy.fr

Spais, Vasilis
Zenon S.A. Automation Technologies, Greece
E-mail: v_spa@zenon.gr
Web: www.zenon.gr

Starr, Andrew
The University of Hertfordshire, UK
E-mail: a.starr@herts.ac.uk
Web: www.herts.ac.uk/csc

Tohver, Avo
IB Krates OÜ, Estonia
E-mail: avo@krates.ee
Web: www.krates.ee

Tommingas, Toomas
IB Krates OÜ, Estonia
E-mail: toomas@krates.ee
Web: www.krates.ee

Voisin, Alexandre
Université Henri Poincaré, France
E-mail: alexandre.voisin@cran.uhp-nancy.fr
Web: www.cran.uhp-nancy.fr

Yau, Alan
University of Sunderland, UK
E-mail: alan.yau@sunderland.ac.uk
Web: www.sunderland.ac.uk

Zhu, Zhenhuan
The University of Manchester, UK
E-mail: Zhenhuan.Zhu@manchester.ac.uk
Web: www.manchester.ac.uk
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgment</td>
</tr>
<tr>
<td>ACL</td>
<td>Asynchronous Connectionless Link</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue-to-digital Converter</td>
</tr>
<tr>
<td>AE</td>
<td>Acoustic Emission</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>AmI</td>
<td>Ambient Intelligence</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Networks</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle of Arrival</td>
</tr>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>AR</td>
<td>Augmented reality</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
</tr>
<tr>
<td>BDM</td>
<td>Breakdown Maintenance</td>
</tr>
<tr>
<td>BN</td>
<td>Bayesian Networks</td>
</tr>
<tr>
<td>BN</td>
<td>Base Number</td>
</tr>
<tr>
<td>BP</td>
<td>Back Propagation</td>
</tr>
<tr>
<td>BSS</td>
<td>Basic Service Set</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-aided Design</td>
</tr>
<tr>
<td>CAM</td>
<td>Content Aggregation Model</td>
</tr>
<tr>
<td>CAP</td>
<td>Contention Access Period</td>
</tr>
<tr>
<td>CBM</td>
<td>Condition Based Maintenance</td>
</tr>
<tr>
<td>CBR</td>
<td>Case Based Reasoning</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Couple Device</td>
</tr>
<tr>
<td>CCK</td>
<td>Complementary Code Keying</td>
</tr>
<tr>
<td>CEO</td>
<td>Chief Executive Officer</td>
</tr>
<tr>
<td>CFP</td>
<td>Contention-Free Period</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Controlled</td>
</tr>
<tr>
<td>CM</td>
<td>Condition Monitoring</td>
</tr>
<tr>
<td>CMI</td>
<td>Computer Managed Instruction</td>
</tr>
<tr>
<td>CMMS</td>
<td>Computerised Maintenance Management Systems</td>
</tr>
</tbody>
</table>
CMOpS  Computer Maintenance Operational System
CMOS  Complementary Metal-oxide-semiconductor
COTS  Commercial off-the-shelf
CPT  Conditional Probability Table
CRC  Cyclic Redundancy Check
CRIS  Common Relation Interface Schema
CSMA  Carrier Sense Multiple Access
CUSUM  Cumulative Sum
DAG  Directed Acyclic Graph
DCF  Distributed Coordination Function
DIFS  Distributed Inter-Frame Spacing
DPSK  Differential Phase Shift Keying
DSP  Digital Signal Processing
DS  Distribution System
DSSS  Direct Spread Sequence Shifting
Dynamite  Dynamic Decisions in Maintenance
ECU  Electronic Control Units
EEPROM  Electrically Erasable Programmable Read-only Memory
EMC  Electromagnetic Compatibility
ESD  Electrostatic Discharge
ESS  Extended Service Set
EP  Extreme Pressure
ERP  Enterprise Resource Planning
ES  Expert System
FFD  Fully Functional Devices
FFT  Fast Fourier Transform
FMEA  Failure Mode and Effect Analysis
FSO  Full Scale Output
FTA  Fault Tree Analysis
GFSK  Gaussian Frequency Shift Keying
GPS  Global Positioning System
GTS  Guaranteed Time Slots
GTTT  Generalised Total Test on Time
HDD  Hard Disk Drive
HMD  Head Mounted Displays
HR/DSSS  High Rate/Direct Sequence Spread Spectrum
HSI  Human System Interface
HTML  Hyper Text Markup Language
HTTP  Hypertext Transfer Protocol
IBSS  Independent Basic Service Set
IC  Integrated Circuit
IP  Internet Protocol
ICP  Integrated Circuit Piezoelectric
ICT  Information and Communications Technologies
Abbreviations

IEEE Institute of Electrical and Electronics Engineers
ISM Industrial, Scientific and Medical
ISO International Standards Organization
IT Information Technology
ITS Intelligent Tutoring Systems
ITU-T International Telecommunication Union – Telecommunication
KBS Knowledge Based System
KPI Key Performance Indicators
LAN Local Area Network
LCI Life Cycle Income
LCP Life Cycle Profit
LCC Life Cycle Cost
LCMS Learning Content Management Systems
LED Light-emitting Diode
LIP Learner Information Package
LMS Learning Management Systems
LO Learning Objects
LOM Learning Object Metadata
LQI Link Quality Indicators
LRD Light Receiving Device
MAC Medium Access Control
MDAQ Machine Data Acquisition
MDSS Maintenance Decision Support System
MEMS Microelectromechanical Systems
MES Maintenance Execution System
MIL Matrox Imaging Library
MIMO Multiple Input – Multiple Output
MIMOSA Machinery Information Management Open Systems Alliance
MPDU MAC Protocol Data Unit
MMME Man Machine Maintenance Economy
MTBD Mean Time Between Degradation
MTBF Mean Time Between Failures
NC Numerically Controlled
NIR Near Infrared
NIRS Near Infrared Spectroscopy
NDT Non-destructive Testing
OEE Overall Equipment Effectiveness
OEM Original Equipment Manufacturer
OFDM Orthogonal Frequency Division Multiplexing
O&M Operations and Maintenance
OPD Optical Particle Detector
OSA-CBM Open Systems Architecture for Condition Based Maintenance
OSA-EAI Open Systems Architecture for Enterprise Application
Integration
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTAP</td>
<td>Over The Air Programming</td>
</tr>
<tr>
<td>OWL</td>
<td>Ontology Web Language</td>
</tr>
<tr>
<td>PAN</td>
<td>Private Area Network</td>
</tr>
<tr>
<td>PAPI</td>
<td>Personal and Private Information</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCF</td>
<td>Point Coordination Function</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistant</td>
</tr>
<tr>
<td>PdM</td>
<td>Predictive Maintenance</td>
</tr>
<tr>
<td>PHM</td>
<td>Proportional Hazard Modelling</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer</td>
</tr>
<tr>
<td>PIFS</td>
<td>Priority Inter-Frame Spacing</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loops</td>
</tr>
<tr>
<td>PM</td>
<td>Preventive Maintenance</td>
</tr>
<tr>
<td>PPDU</td>
<td>Physical Protocol Data Unit</td>
</tr>
<tr>
<td>PPM</td>
<td>Planned Preventive Maintenance</td>
</tr>
<tr>
<td>P2P</td>
<td>Person-to-Person</td>
</tr>
<tr>
<td>RCM</td>
<td>Reliability Centred Maintenance</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFD</td>
<td>Radio Frequency Device</td>
</tr>
<tr>
<td>RDF</td>
<td>Reduced Functional Devices</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
</tr>
<tr>
<td>RISC</td>
<td>Reduced Instruction Set Computer</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>ROCOF</td>
<td>Rate of Occurrence of Failures</td>
</tr>
<tr>
<td>ROIIM</td>
<td>Return on Investment in Maintenance</td>
</tr>
<tr>
<td>RPC</td>
<td>Remote Procedure Call</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indication</td>
</tr>
<tr>
<td>RTE</td>
<td>Run-Time Environment</td>
</tr>
<tr>
<td>RTLS</td>
<td>Real-Time Location System</td>
</tr>
<tr>
<td>RUL</td>
<td>Remaining Useful Life</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>SCO</td>
<td>Synchronous Connection-Oriented</td>
</tr>
<tr>
<td>SCORM</td>
<td>Sharable Content Object Reference Model</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural Health Monitoring</td>
</tr>
<tr>
<td>SIFS</td>
<td>Short Inter-Frame Spacing</td>
</tr>
<tr>
<td>SLED</td>
<td>Super Light-Emitting Diode</td>
</tr>
<tr>
<td>SME</td>
<td>Small-to-Medium sized Enterprise</td>
</tr>
<tr>
<td>SN</td>
<td>Sequencing and Navigation</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SOA</td>
<td>Service-Oriented Architecture</td>
</tr>
<tr>
<td>SOAP</td>
<td>Simple Object Access Protocol</td>
</tr>
<tr>
<td>SoC</td>
<td>System on Chip</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>SSID</td>
<td>Service Set Identifier</td>
</tr>
<tr>
<td>SW</td>
<td>Semantic Web</td>
</tr>
<tr>
<td>TAN</td>
<td>Total Acid Number</td>
</tr>
<tr>
<td>TBN</td>
<td>Total Base Number</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TDIDT</td>
<td>Top Down Induction of Decision Trees</td>
</tr>
<tr>
<td>TDoA</td>
<td>Time Difference of Arrival</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>ToA</td>
<td>Time of Arrival</td>
</tr>
<tr>
<td>TPM</td>
<td>Total Productive Maintenance</td>
</tr>
<tr>
<td>TQM</td>
<td>Total Quality Maintenance</td>
</tr>
<tr>
<td>TQMain</td>
<td>Total Quality Maintenance</td>
</tr>
<tr>
<td>TTT</td>
<td>Total Time on Test</td>
</tr>
<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver-Transmitter</td>
</tr>
<tr>
<td>UCD</td>
<td>Use Case Diagrams</td>
</tr>
<tr>
<td>UML</td>
<td>Unified Modelling Language</td>
</tr>
<tr>
<td>URI</td>
<td>Uniform Resource Identifier</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wire Band</td>
</tr>
<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
</tr>
<tr>
<td>XSD</td>
<td>XML Schema Definition</td>
</tr>
<tr>
<td>VBM</td>
<td>Vibration-Based Maintenance</td>
</tr>
<tr>
<td>VET</td>
<td>Vocational Education and Training</td>
</tr>
<tr>
<td>VR</td>
<td>Virtual Reality</td>
</tr>
<tr>
<td>WEP</td>
<td>Wired Equivalent Policy</td>
</tr>
<tr>
<td>WINS</td>
<td>Wireless Intelligent Network Sensors</td>
</tr>
<tr>
<td>WILE</td>
<td>Web-based Intelligent Learning Environments</td>
</tr>
<tr>
<td>WIP</td>
<td>Work-In-Progress</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WMAN</td>
<td>Wireless Metropolitan Area Network</td>
</tr>
<tr>
<td>WORM</td>
<td>Write–Once, Read–Many</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td>WWAN</td>
<td>Wireless Wide Area Network</td>
</tr>
</tbody>
</table>
Chapter 1
Introduction

Kenneth Holmberg

Maintenance is a field of technology that consists of technical skills, techniques, methods and theories that all aim at “keeping the wheels in our society rolling properly”. The purpose is to find both technical and organisational solutions for large assets like factories, power plants, transportation vehicles and building technology equipment, as well as for smaller assets such as household machines, hobby devices and consumer products, to function properly, in a cost-effective way, with low energy consumption, without polluting the environment and in a safe, controlled and predictable way.

The huge costs and risks related to improper maintenance have been both observed and documented in the industry. Poorly functioning production machines and unreliable products are not good for a company’s business. Maintenance is directly linked to competitiveness and profitability and thus to the future of a company (Pehrsson and Al-Najjar 2005).

In the last decades several organisational approaches to arrange the maintenance work as efficiently as possible have been developed. Such methods are, e.g., total productive maintenance (TPM), reliability-centred maintenance (RCM) and condition-based maintenance (CBM) (Campbell and Jardine 2001, Márquez 2007). These methods have been implemented in the industry with mainly very good results.

At the same time people have realised that the strategy to wait to repair equipment until it fails is often not a good solution. The break down may come at an inconvenient time and the sudden and unexpected stoppage can be very expensive. The breakdown may even become a source of problem for nearby equipment (secondary damage), the environment (pollution) and may even pose health and safety problems to nearby personnel. One solution is to use scheduled maintenance, stopping the equipment regularly for checking and service. The problem with this
approach is that the equipment is stopped also in unnecessary cases, and sometimes the stop and unnecessary service action may introduce new problems.

The optimal solution is to know continuously the condition of the asset and its components and take repair and service actions only when really needed. It is, of course, a big challenge to have complete control over the asset condition and also know what the optimal maintenance decisions are each time. However, current technological development offers new and advanced techniques and methods to support this approach.

Currently, there is an improved understanding of the physical, mechanical and electrical phenomena initiating and triggering disturbances and failures. There is the potential to develop low cost micro size integrated sensors for observing the behaviour of a device. There are high capacity and advanced methods for condition data collection, signal analysis, data mining, reasoning and decision making. There are methods for computer based diagnostics and prognostics of plant conditions. New wireless techniques and the internet offer the possibility of using mobile hand-held computers (PDA, personal digital assistant) to have access to large information globally and on line (Holmberg and Helle 2008).

This development opens a new possibility in asset maintenance. It is called e-maintenance and has been defined as “The network that integrates and synchronises the various maintenance and reliability applications to gather and deliver asset information where it is needed” (Baldwin 2001). The e-maintenance solutions typically offer answers to the following:

- What: which equipment needs maintenance?
- When: when is the maintenance needed?
- Who: computerised maintenance management systems.
- How: manuals, spare part availability.

The concept of e-maintenance integrates existing telemetric maintenance principles with web services and modern e-collaboration methods. Collaboration allows us to share and exchange not only information but also knowledge and e-intelligence (Han and Yang 2006, Muller et al. 2008).

In this book we present a flavour of advanced techniques and methods that form the basis of an integrated e-maintenance approach, including solutions such as advanced micro sensors, smart tags (RFID, radio frequency identification), online oil sensors, PDA maintenance applications, ontology based diagnostic and prognostic methods, wireless communication, semantic web service for distributed intelligence, dynamic cost effectiveness based decision making tools and a holistic e-maintenance concept.

In this book the development of such techniques and methods is reported and the state-of-the-art is reviewed. Moreover, experiences both from laboratory testing as well as the use of e-maintenance in industrial environments are reported. The reported cases are demonstrations on the global level, with milling machines, machine tools, foundry hydraulics, maritime lubrication systems and automatic
Introduction

Stamping machines. An e-training package for implementing successful e-maintenance applications is presented.

The development work and industrial demonstrations were carried out in the European Commission 6th Framework Programme project “Dynamite” (Dynamic Decisions in Maintenance) by 17 academic and industrial partners in Europe. It is our hope that this book will help the reader to understand the different advanced techniques that e-maintenance is based on and how e-maintenance as a concept can offer new and optimal solutions for asset management in a modern net-based information environment for globally active enterprises.

References

Chapter 2
Maintenance Today and Future Trends

Andrew Starr, Basim Al-Najjar, Kenneth Holmberg, Erkki Jantunen, Jim Bellew and Alhussein Albarbar

Abstract. This chapter describes the state of the art in maintenance and its future trends. The key areas that have influenced maintenance in the last 40 years are management of people and assets, and technological capability. These areas are important because they aim to take the best advantage of expensive resources, whether that advantage be profit, or to provide the best possible service with limited resources. The chapter first sets out the current range of maintenance in industrial practice. It is recognised that many businesses do not undertake the full extent of the work reported here, but it is our purpose to survey the state of the art. The chapter then continues to survey the influences of nascent technologies and ideas, before making some predictions about the future. Indeed, some of the most advanced condition-based maintenance effectively aims to predict the future. However, here we do not offer a crystal ball calibrated to international standards; we will constrain ourselves to an informed, independent opinion.

2.1 State of the Art in Management

Maintenance today contributes to the aim of sustainable development in society, including environmental and energy saving aspects, safety aspects and economical aspects. Advanced maintenance has a critical role to play in improving companies’ competitiveness. Technology will not be effective without excellent management. The reliability and availability of machines and instruments are crucial factors of competitiveness, particularly in applications where safety and availability are important. Automation and integrated production have resulted in larger technical
systems, which are more difficult to control, and more sensitive and vulnerable to diverse consequential effects because of breakdowns.

Reliability, availability and lifetime planning first advanced in the nuclear energy industry. The aerospace industry quickly followed, developing methods to assure reliability by distributing and duplicating the crucial features. Safety and risk analyses have been developed and adapted not only in the chemical industry but to some extent in most industrial fields.

However, existing methods are not always so easily applicable to conventional power plants, or to the process and metal industries, where availability is often a more important criterion than reliability. In other words, the downtime is more important than a small probability of failure. A failure can be acceptable if the repair and restarting times are short. Maintainability and maintenance support performance are therefore most important in such cases.

![Figure 2.1 The fusion and advance of maintenance technologies](image)

Traditionally, the manufacturer guaranteed the faultless action of a product for a certain warranty period. Nowadays, life cycle profit (LCP) planning is gaining popularity and it is based on the reliability of a product during its whole lifetime. Statistically-defined failure frequency, availability, and the lifetime of the product can now be used as a competitiveness argument. This will also give a reliable basis for recycling a product.

Higher reliability of industrial plants and machines means fewer risks, both personal and environmental, and better control, as well as energy conservation and lower expenses during the operating lifetime. The international competitiveness of the industry can be improved by developing new techniques and methods to spec-
ify and control the product reliability more precisely and convincingly. This is a very important sales argument in a situation where the gap between different products, in terms of performance and functional features, diminishes as a result of extremely advanced product development driven by competition.

Today’s product design methods are mainly based on optimising the performance of the products and little attention is given to reliability and lifetime estimations. Few design tools emphasise reliability and availability.

This fusion of technologies is illustrated by Figure 2.1, in which the influence of a wide range of technological advances is considered over the last two decades. Because of the great variety of different techniques, based on expert knowledge in several fields of technology involved, there is a need to approach the reliability and maintainability problems from a general, holistic point of view, starting from the problem of the customer and ending with the satisfied user. The Technical Research Centre of Finland (VTT) has developed a systematic approach (Holmberg 2001, Holmberg and Helle. 2008). This is aimed at improving the synergistic interactions between the different fields of expertise by showing a logical and comprehensive structure, where each expert can find his place and see the connections to experts from other fields, all working with the same aim of a satisfied end user, as shown in Figure 2.2.

![Figure 2.2 Holistic approach to maintenance integration](image)

The probability of personnel, equipment and environmental damage can be analysed and the accident consequences estimated by systematic methods of risk control. The critical parts are identified, the probability of system failure and lifetime are calculated, and the operability costs are estimated by statistically based techniques of reliability control. When the critical parts of the production system