

E-maintenance

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Editors

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# 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.

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*The authors*

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# Abbreviations

|      |                                             |
|------|---------------------------------------------|
| ACK  | Acknowledgment                              |
| ACL  | Asynchronous Connectionless Link            |
| ADC  | Analogue-to-digital Converter               |
| AE   | Acoustic Emission                           |
| AI   | Artificial Intelligence                     |
| AmI  | Ambient Intelligence                        |
| ANN  | Artificial Neural Networks                  |
| AoA  | Angle of Arrival                            |
| AP   | Access Point                                |
| API  | Application Programming Interface           |
| AR   | Augmented reality                           |
| ASIC | Application-Specific Integrated Circuit     |
| BDM  | Breakdown Maintenance                       |
| BN   | Bayesian Networks                           |
| BN   | Base Number                                 |
| BP   | Back Propagation                            |
| BSS  | Basic Service Set                           |
| CAD  | Computer-aided Design                       |
| CAM  | Content Aggregation Model                   |
| CAP  | Contention Access Period                    |
| CBM  | Condition Based Maintenance                 |
| CBR  | Case Based Reasoning                        |
| CCD  | Charge Couple Device                        |
| CCK  | Complementary Code Keying                   |
| CEO  | Chief Executive Officer                     |
| CFP  | Contention-Free Period                      |
| CNC  | Computer Numerical Controlled               |
| CM   | Condition Monitoring                        |
| CMI  | Computer Managed Instruction                |
| CMMS | Computerised Maintenance Management Systems |

|          |                                                     |
|----------|-----------------------------------------------------|
| 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         |

|         |                                                                     |
|---------|---------------------------------------------------------------------|
| 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<br>Integration |

|       |                                          |
|-------|------------------------------------------|
| OTAP  | Over The Air Programming                 |
| OWL   | Ontology Web Language                    |
| PAN   | Private Area Network                     |
| PAPI  | Personal and Private Information         |
| PC    | Personal Computer                        |
| PCF   | Point Coordination Function              |
| PDA   | Personal Digital Assistant               |
| PdM   | Predictive Maintenance                   |
| PHM   | Proportional Hazard Modelling            |
| PHY   | Physical Layer                           |
| PIFS  | Priority Inter-Frame Spacing             |
| PLC   | Programmable Logic Controller            |
| PLL   | Phase Locked Loops                       |
| PM    | Preventive Maintenance                   |
| PPDU  | Physical Protocol Data Unit              |
| PPM   | Planned Preventive Maintenance           |
| P2P   | Person-to-Person                         |
| RCM   | Reliability Centred Maintenance          |
| RF    | Radio Frequency                          |
| RFD   | Radio Frequency Device                   |
| RFD   | Reduced Functional Devices               |
| RFID  | Radio Frequency Identification           |
| RISC  | Reduced Instruction Set Computer         |
| RMS   | Root Mean Square                         |
| ROCOF | Rate of Occurrence of Failures           |
| ROIIM | Return on Investment in Maintenance      |
| RPC   | Remote Procedure Call                    |
| RSSI  | Received Signal Strength Indication      |
| RTE   | Run-Time Environment                     |
| RTLS  | Real-Time Location System                |
| RUL   | Remaining Useful Life                    |
| SCADA | Supervisory Control and Data Acquisition |
| SCO   | Synchronous Connection-Oriented          |
| SCO   | Sharable Content Objects                 |
| SCORM | Sharable Content Object Reference Model  |
| SHM   | Structural Health Monitoring             |
| SIFS  | Short Inter-Frame Spacing                |
| SLED  | Super Light-Emitting Diode               |
| SME   | Small-to-Medium sized Enterprise         |
| SN    | Sequencing and Navigation                |
| SNR   | Signal-to-Noise Ratio                    |
| SOA   | Service-Oriented Architecture            |
| SOAP  | Simple Object Access Protocol            |
| SoC   | System on Chip                           |

|        |                                             |
|--------|---------------------------------------------|
| SQL    | Structured Query Language                   |
| SSID   | Service Set Identifier                      |
| SW     | Semantic Web                                |
| TAN    | Total Acid Number                           |
| TBN    | Total Base Number                           |
| TCP    | Transmission Control Protocol               |
| TDIDT  | Top Down Induction of Decision Trees        |
| TDoA   | Time Difference of Arrival                  |
| TDMA   | Time Division Multiple Access               |
| ToA    | Time of Arrival                             |
| TPM    | Total Productive Maintenance                |
| TQM    | Total Quality Maintenance                   |
| TQMain | Total Quality Maintenance                   |
| TTT    | Total Time on Test                          |
| UART   | Universal Asynchronous Receiver-Transmitter |
| UCD    | Use Case Diagrams                           |
| UML    | Unified Modelling Language                  |
| URI    | Uniform Resource Identifier                 |
| USB    | Universal Serial Bus                        |
| UWB    | Ultra Wire Band                             |
| XML    | Extensible Markup Language                  |
| XSD    | XML Schema Definition                       |
| VBM    | Vibration-Based Maintenance                 |
| VET    | Vocational Education and Training           |
| VR     | Virtual Reality                             |
| WEP    | Wired Equivalent Policy                     |
| WINS   | Wireless Intelligent Network Sensors        |
| WILE   | Web-based Intelligent Learning Environments |
| WIP    | Work-In-Progress                            |
| WLAN   | Wireless Local Area Network                 |
| WMAN   | Wireless Metropolitan Area Network          |
| WORM   | Write–Once, Read–Many                       |
| WPAN   | Wireless Personal Area Network              |
| WSN    | Wireless Sensor Network                     |
| WWAN   | Wireless Wide Area Network                  |



# 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), on-line 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

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.

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## Chapter 2

# Maintenance Today and Future Trends

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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.

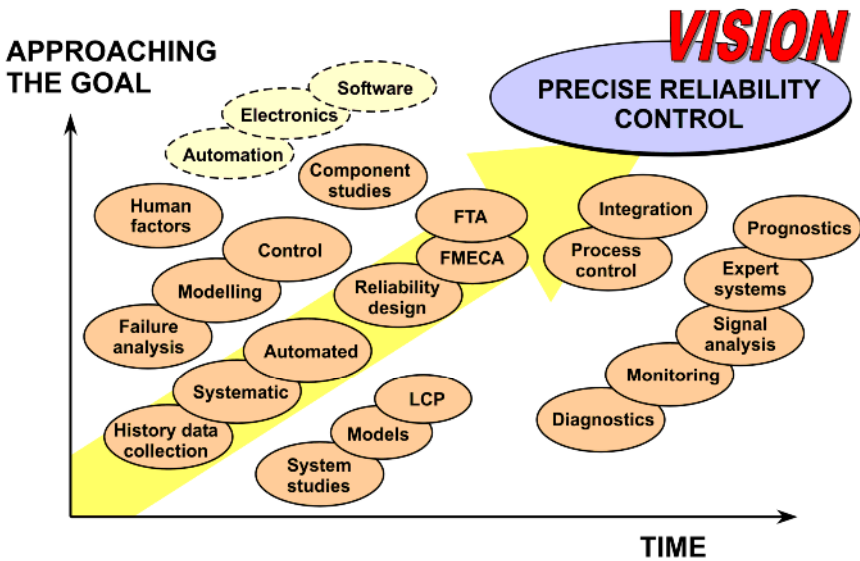
### 2.1 State of the Art in Management

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

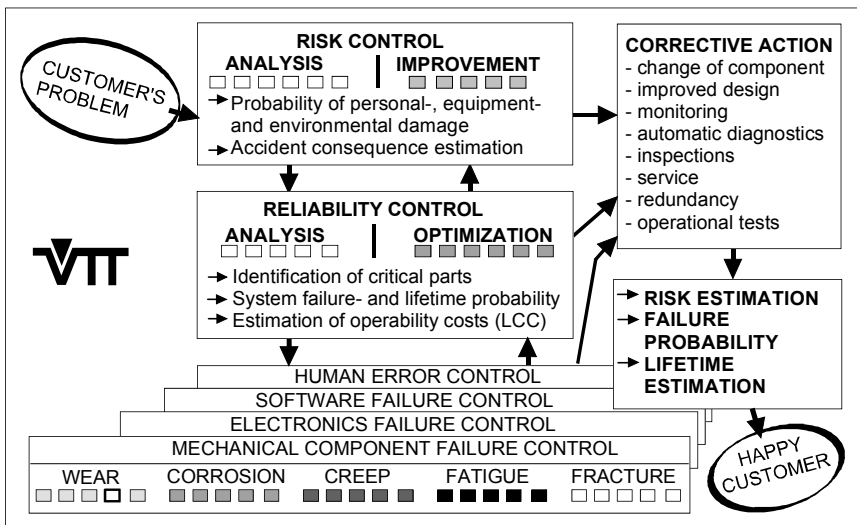
Traditionally, the manufacturer guaranteed the faultless action of a product for a certain warranty period. Nowadays, life cycle profit (LCP) planning is gaining popularity and it is based on the reliability of a product during its whole lifetime. Statistically-defined failure frequency, availability, 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

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