

Preview Edition

Maintenance

Smart and Sustainable Solutions All Along the Asset Life Cycle

Editors:

**H. Akkermans,
M.I.A. Stoelinga,
T. Tinga,
H.J. van Oostveen
and W.W. Tiddens**

**OPEN
PRESS
TiU**



MAINTENANCE: SMART AND SUSTAINABLE SOLUTIONS ALL ALONG THE ASSET LIFE CYCLE

Maintenance

**Smart and Sustainable Solutions
All Along the Asset Life Cycle**

**Editors: H. Akkermans, M.I.A. Stoelinga, T. Tinga,
H.J. van Oostveen en W.W. Tiddens**



This book was made possible by Stichting World Class Maintenance.

This publication is part of the project PrimaVera: Predictive maintenance for Very effective asset management, with file number NWA.1160.18.238 of the research programme 'Onderzoek op Routes door Consortia' which is (partly) financed by the Dutch Research Council (NWO).

Open Press Tilburg University
Tilburg, The Netherlands

© 2026 The editors and the authors. Unless stated otherwise, photographs were kindly provided by ProRail and remain the copyright of ProRail and the respective photographer, credited as 'ProRail / [photographer name]' in the image credits list in this book. The Creative Commons licence under which this book is published applies to the text and not to these photographs.

Design and typesetting: LINE UP boek en media bv
Cover design: Bas Ekkers

ISBN: 9789403866734

DOI: <https://doi.org/10.56675/9789403866734>



This is an Open Access book published under the terms of the Creative Commons 4.0 International license (CC BY NC ND 4.0). The full licence terms are available at creativecommons.org/licenses/by-nc-nd/4.0/legalcode.

Contents

Foreword to the preview edition	vii
PART I Introduction	1
1 Time for a new way of doing maintenance	2
1.1 Introduction to the chapter	5
1.2 Aging assets and aging work forces	5
1.3 Flattening the curve through smart and sustainable maintenance	6
1.4 Innovation, digitalization and collaboration in maintenance	7
1.5 Maintenance 5.0	8
1.6 Aspirations and audiences	9
1.7 A "running case": the Dutch rail sector	9
1.8 Structure of this book	12
1.9 Future perspectives / Conclusions	14
2 Asset management	16
2.1 Why asset management needs a maintenance lens	20
2.2 One reference map, not many islands	24
2.3 From purpose to plans	31
2.4 The asset management system in practice	33
2.5 Maintenance as life-cycle delivery capability	35
2.6 Implementing and improving the system	38
2.7 Future orientation: people, sustainability, resilience and digitalization	41
2.8 Key takeaways	42
Assignments	43
Model answers	44
3 Maintenance	48
3.1 Introduction	51
3.2 Maintenance and availability	51
3.3 Faults and failures	52
3.4 Maintenance strategies	55
3.5 Maintenance policies	56
3.6 Maintenance maturity	59
3.7 Advanced maintenance policy selection tools	60
3.8 Case studies	62

3.9	Future perspectives and conclusions	64
	Assignments	64
	Guided solutions	65

Foreword to the preview edition

The book lying here before you is the Preview Edition of the Maintenance book, which presents the state of the art in the fast-evolving field of maintenance. The complete book consists of 21 chapters and is written by more than two dozen authors.

This preview edition is released on the occasion of the annual event of Stichting World Class Maintenance (WCM) on October 7, 2026. It gives an introductory view of the complete book, which will be published open access in the fourth quarter of 2026.

The Preview Edition contains three chapters: the introduction ‘Time for a new way of doing maintenance’, ‘asset management’, and ‘maintenance’. These are the high-level chapters of the book. They set out the scope, terminology, and frameworks on which the remaining chapters build. The introduction also explains how the full set of chapters is organized and what each of them covers.

The chapters that treat individual topics in detail are not part of this preview edition and will appear in the full publication. The table of contents included here shows the intended scope of the final book.

The complete book will be available in electronic form, free of charge, on the Manifold platform of Tilburg University Press at <https://openpress.tilburguniversity.edu/projects/maintenance>. A physical copy can also be purchased there through a print-on-demand service.

This preview edition aims to give readers a first impression of the structure and content of the complete work. As this is a preview, the content, structure, and chapter numbering may still change before final publication.

The editors

Table of Contents of the complete Maintenance book

Part I: Introduction

Chapter 1	Time for a new way of doing maintenance
Chapter 2	Asset Management
Chapter 3	Maintenance

Part II: Information Systems

Chapter 4	IT architecture
Chapter 5	Data analytics
Chapter 6	Digital twins
Chapter 7	Inspection, monitoring and maintenance: towards automation

Part III: Engineering

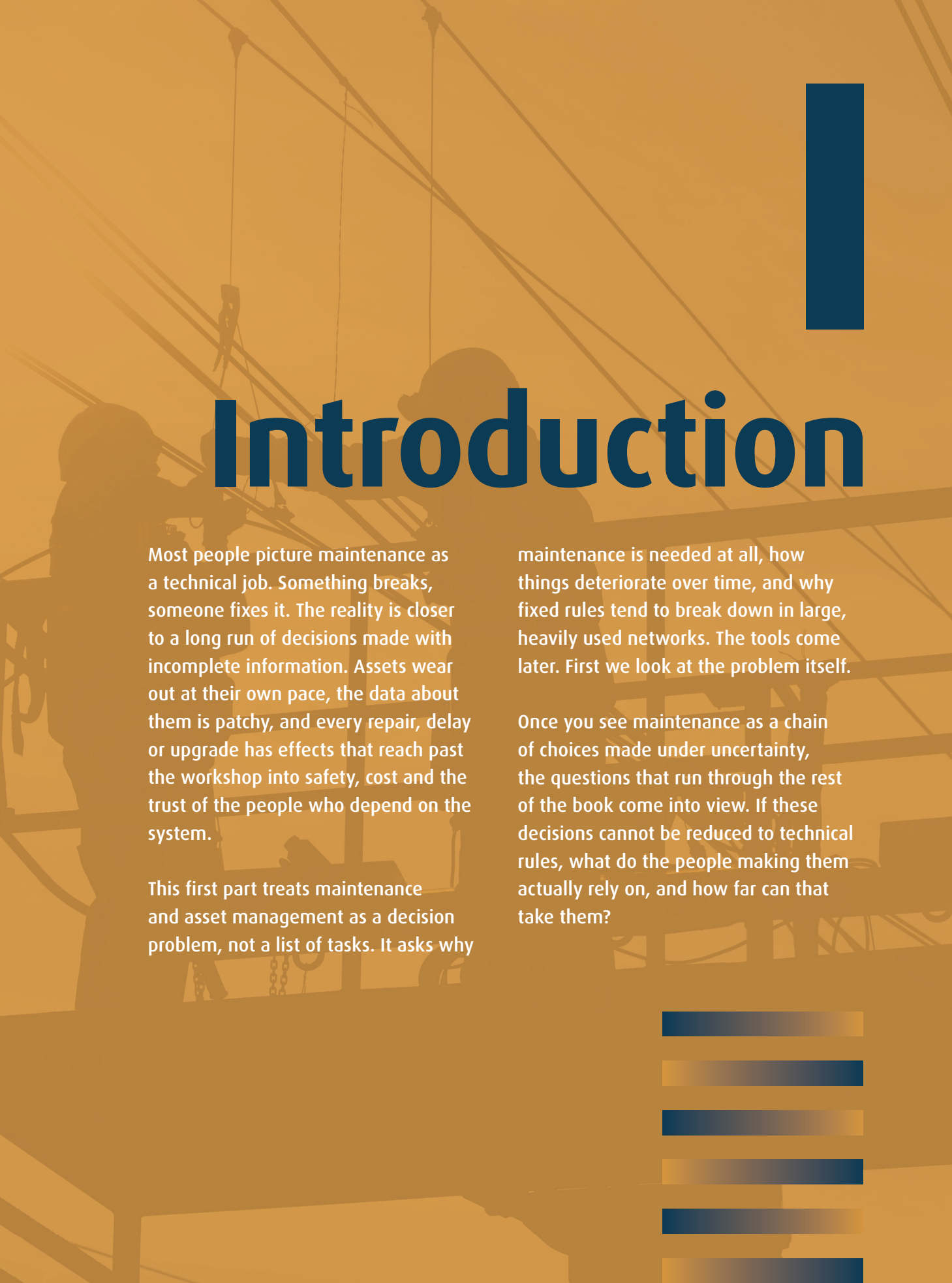
Chapter 8	Reliability, probability, and estimation
Chapter 9	Fault tree analysis
Chapter 10	Failure mode and effects analysis
Chapter 11	Diagnostics and prognostics
Chapter 12	Maintenance decision-making
Chapter 13	Design for maintenance

Part IV: Economics and Management

Chapter 14	Scheduling
Chapter 15	Spare parts management
Chapter 16	Workflow management
Chapter 17	Performance-based contracts
Chapter 18	Life cycle costing

Part V: Human and organizational behavior

Chapter 19	Human behavior
Chapter 20	Organizational dynamics
Chapter 21	Learning and knowledge management



Introduction

Most people picture maintenance as a technical job. Something breaks, someone fixes it. The reality is closer to a long run of decisions made with incomplete information. Assets wear out at their own pace, the data about them is patchy, and every repair, delay or upgrade has effects that reach past the workshop into safety, cost and the trust of the people who depend on the system.

This first part treats maintenance and asset management as a decision problem, not a list of tasks. It asks why

maintenance is needed at all, how things deteriorate over time, and why fixed rules tend to break down in large, heavily used networks. The tools come later. First we look at the problem itself.

Once you see maintenance as a chain of choices made under uncertainty, the questions that run through the rest of the book come into view. If these decisions cannot be reduced to technical rules, what do the people making them actually rely on, and how far can that take them?





1 Time for a new way of doing maintenance

Henk Akkermans¹, Mariëlle Stoelinga² and Henk van Oostveen³



Setting the Stage

Nadia had run maintenance on a single line for eight years. The promotion changed the scale of the job overnight. From Monday she would be responsible for engineering decisions across the whole network, and the briefing on her desk showed how much the ground had shifted while she was busy keeping trains running.

Parts of the list read like a foreign language. Condition monitoring on switches. Machine-learning models that predicted track faults. Digital twins of bridges that did not exist yet. Contracts that paid suppliers on results instead of hours. Data-sharing deals with companies she had never dealt with. None of this had been part of the trade she learned twenty years ago, and all of it now landed on her.

She knew the old craft well. You inspected, you judged, you fixed, and experience warned you something was wrong before any instrument did. That instinct still counted. On its own it was no longer enough. The field had grown outward in every direction at once, into data, into economics, into law, into the way organisations learn and forget. A sound decision now drew on all of it, and no single person held all of it.

What unsettled Nadia was not any one topic. It was the breadth. She could not lead what she did not understand, and she did not have years to spend catching up. So where does someone in her position begin, and how do all these separate worlds fit together into one job?

1.1 Introduction to the chapter

Almost by definition, maintenance is one of the most invisible activities essential for our civilization. The better it is done, the less visible it becomes. The roads we drive on that are well maintained, household equipment that works all the time, the telecom network that doesn't falter, the car that never breaks down: we tend to take all this for granted. How different is this for other business tasks, such as sales or innovation? When those functions excel, everybody cheers: the sales rep when that great order is placed, the R&D specialist when that invention works. But the brilliant maintenance engineers? Who notices them?

And yet, maintenance is essential for our civilization. Without well-working and safe roads, bridges and tunnels, dikes and sluices, without smoothly operating trains and trucks, energy plants that operate round the clock, telecom networks, our society breaks down. Without smoothly operating machines, planes, ships, but also laptops and smart phones, where are we? And yet we take it all for granted.

We believe that in the coming years maintenance will become more alluring, for two main reasons: first, because this taking-for-granted is no longer applicable in a world of aging assets and aging workforces, and second, because maintenance itself is becoming more and more full of innovation and integral part of sales propositions, and therefore much better noticeable. We hope and aspire that this book will assist in that process.

1.2 Aging assets and aging work forces

The post-World War II decades saw a flurry of reconstruction and expansion. In the nineteen sixties, seventies and eighties of the 20th century especially, countless bridges and tunnels and roads were built. Our present-day energy infrastructures, both plants and networks, were laid out and many of the process industry factories in the industrialized world were built back then. Once, these were all shiny and new, with little need for maintenance other than correcting the odd technological teething problem or improper usage. Now, in the mid-twenties of the 21st century, all these assets from back then are fifty or more years old. In the Netherlands, in the 2030s over 50% of Dutch transportation infrastructure will be beyond its 50-year design life. This results in a massive increase in infrastructure renewal rates. In the Netherlands a ten to twenty-fold increase in just a few years is expected. Where do we find the budgets, and, even more important: where do we find the people to do all this extra work? If we don't, maintenance will become very visible indeed, in the form of failing assets that everybody took for granted.

As these technical assets aged, so too did the workforce responsible for maintaining them. Overall, industrialized economies see an aging population and, in most countries, an ageing workforce that is retiring faster than it is being replaced. Now that far more people are needed, they are becoming hard to find. The older staff that are leaving take with them decades of experience and hard-to-replace expertise. All in all, the gap between capacity needed and capacity available in infrastructure maintenance and renewal, in asset management, is growing exponentially year by year. The Netherlands expects a shortage of some 100K technical staff by 2030. We cannot bridge this gap by doing maintenance as we have done in the years past. We need to

innovate, both technically and socially, if we are to “flatten the curve” of replacement of aging assets, in all asset-intensive industries.

1.3 Flattening the curve through smart and sustainable maintenance

If assets are maintained better, they will last longer, they will be safer, their availability will be better, their energy usage will be lower, and their ecological footprint will be reduced. van de Kerkhof, Fang and Lamper (2018) estimate that maintenance driven by condition monitoring, so-called smart maintenance, can realistically extend the service life of new investments and expansions by 12.5% to 25% compared with corrective maintenance. Such an extension would significantly flatten the curve of annual renewal projects in the coming decades. It would also lead to a huge reduction in carbon footprint, all these construction projects that need not take place. So smart maintenance is also sustainable maintenance.

It would also lead to massive reductions in budget required. According to a project looking at the EU (van Groenendaal, H. A. Akkermans and van Kempen 2023), the potential savings through longer service lives and improved maintenance through smart maintenance of investments over the period 2020–2040 are at least some €160 billion for investments and €40 billion on maintenance. Because when maintenance is done smart, it is also much cheaper, since it can be done much more tailored to the actual condition of the asset. Moreover, how about the cost to society? The Dutch Ministry of Infrastructure and Water Management uses as a rule of thumb that when an asset fails the cost to producers and consumers is around ten times that of the cost of repair itself (van de Kerkhof, Fang and Lamper 2018).

Notably, it is not only the renovation of aging infrastructure that presents challenges; new infrastructure is also at risk, particularly in the energy sector. Often, when these new energy technologies, such as huge offshore wind turbines, or bigger hydrogen electrolyzers are designed, all the focus is on bigger, faster, higher. However, why is it that maintenance of turbine blades is a much bigger problem than anticipated? Does anyone really know, and dare to say, how much faster an electrolyzer degrades when it runs on the fluctuating power output of wind and solar? And have we anywhere near enough people trained for this maintenance? How many people do we need, by the way? With what skills, what kind of maintenance work should they be trained in? All these are questions that we need to answer in the coming years, in a smart and sustainable way.

Finally, smart maintenance goes more and more hand in hand with safety and strategic autonomy, for the resilience of our society. Smart monitoring can help to detect sabotage attempts sooner for our critical infrastructure. The same innovative technologies that can monitor disasters such as earthquakes and tsunamis in Japan can also be used for regular maintenance, to spot degradations sooner and more precisely. As we live in an increasingly turbulent world, we also need a greater ability to deal with such low-likelihood but high-impact blows to our assets that make our society work.

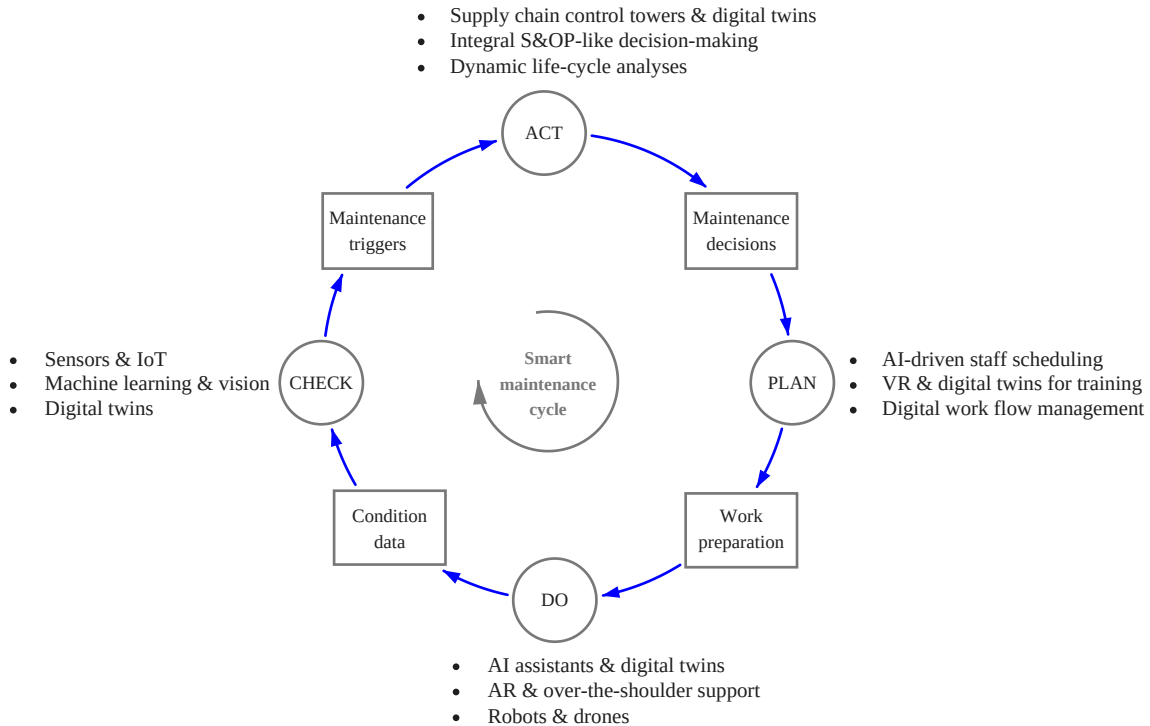


FIGURE 1.1 – Digitalization opportunities in smart maintenance, from H. Akkermans et al. (2024).

1.4 Innovation, digitalization and collaboration in maintenance

So, innovation is needed. And not just technical innovation. Nothing less than what researchers of socio-technological change call a technological transition or even a technological regime change (Geels 2002) is called for. This means that everything has to change, not just one technical thing, if a society moves to an entirely new technology. When our parents and grandparents moved (as they did, in the Netherlands, in the 1960s) from coal to natural gas as energy source, everything had to change. No longer would they use coal burners, obviously, but also coal containers disappeared from every house. No coal distribution with coal ships over the rivers, no coal men walking through the streets. Instead, massive numbers of new gas furnaces, gas pipes, gas distribution, gas fitters, gas... This was a complete energy transition, which today seems all but forgotten.

However, we are on the eve of another technological transition in maintenance. The dominant forms of maintenance in our society are periodic and corrective maintenance. With the rise of condition monitoring and digital maintenance, old methods will vanish, replaced by new technologies and organizational approaches. Figure 1.1 shows a recent overview of digital technologies that will affect maintenance operations greatly in the coming years. Now, most of them are still small scale, often at the piloting stage. But when ramped up, the engineering and IT changes will be massive.

This transition extends beyond engineering and IT; it will range across fields. This will also be a major economic change. The bulk of the contracts for maintenance are input-based, so spending more hours on maintenance is good for the contractor. That shifts around completely with condition monitoring, because then the goal becomes to perform as little actual on-site maintenance activities as possible. So, contracts will need to change, KPIs will need to change, life cycle cost calculations will change. Alignment between asset owner and contractor will need to become much greater, will often move from relations at arm's length to partnerships. And so, this will also mean a major social and psychological change. Maintenance planners and workers will have to work side by side with AI, suggesting actions for them, helping with diagnosis. That will be a complete change in the way of working. How to design the new technologies around the workers?

1.5 Maintenance 5.0

This human-centricity, where workers' well-being is placed at the heart of the work activities, is also a core element of the European Commission's promotion of Industry 5.0 (European Commission 2024). This Industry 5.0 also includes as goals Sustainability, so embracing circular economy and resource-efficient practices and Resilience, the ability to survive major shocks such as COVID-19, or the war in Ukraine.

Industry 5.0 follows on Industry 4.0, the "smart factory" era, a policy concept introduced in Germany around 2011, which focuses on digitalization and automation of manufacturing using IoT, cyber-physical systems, cloud computing, and AI. So, technology-wise, not fundamentally different from 5.0. However, the main goals are efficiency, productivity, and cost optimization, and the worker's role is often secondary: humans are supervisors and operators of automated systems. The term "smart maintenance" is not so specifically defined as the smart factory, but if we assume it shares the same technology focus, i.e. that it is maintenance based on asset data through sensors, then smart maintenance is perhaps not so smart as a term for what society needs. In Industry 5.0 workers become collaborators, decision-makers, co-creators. The Japanese government promotes an even broader policy, called Society 5.0, but from a similar line of reasoning: the seamless integration of cyberspace (digital/AI) and physical space (real life), aiming to solve social issues such as aging population and sustainability challenges.

In line with other recent authors (e.g., Psarommatis, May and Azamfirei 2023) it seems appropriate to label all this as Maintenance 5.0. As in Industry 5.0, Maintenance 5.0 includes digitization and automation of maintenance but in a setting where workers' well-being is placed at the heart of the maintenance work, settings which promote sustainability and resilience. Maintenance 5.0 can be distinguished from smart maintenance by the criteria by which maintenance is judged. Both rely on the same technology, sensors, data pipelines and algorithms. Smart maintenance optimizes for cost and availability; Maintenance 5.0 adds the well-being of the people doing the work, the environmental footprint of the intervention and the ability of the system to absorb and recover from disruption as explicit design criteria. Bukowski and Werbińska-Wojciechowska (2025) position this as the fifth generation of maintenance, following corrective, time-based, condition-based and smart maintenance, and argue that resilience is what makes it distinct: the capacity to withstand disturbances, restore function and learn from what went wrong. They also note that resilience and sustainability can pull in opposite

directions, since redundancy and rapid recovery consume materials and energy, and that models to weigh one against the other barely exist.

This broad scope, which is still more of a research agenda than a description of current practice, is reflected in our broad choice of topics, and corresponds with our aspirations and ambitions for this book.

1.6 Aspirations and audiences

We aim to present a comprehensive vision of all the relevant scientific disciplines of that one multidisciplinary concept of Maintenance 5.0: technical knowledge in line with human- and society centered considerations, computer science findings but also economic and legal insights. Our goal is that this book can form the educational foundation for the socio-technological transition towards smart and sustainable maintenance, towards Maintenance 5.0. So many thousands of people need to learn how to work differently. Our intended audience is therefore large and diverse. We aim for the knowledge level of the various chapters to be at the academic bachelor level, regardless of the nature of the bachelor. All our thirty-odd authors are active researchers in their various fields, so confining their writing to the basics “everybody” needs to know was already challenging. Our audiences include both students and people already working in the various sectors where maintenance is important. It includes people with various backgrounds, as varied as the main sections in this book.

This book is an open access book, so available for free, because we hope that people throughout the world will use it to gain insights into this new and exciting way of doing maintenance. As the book is first of all an e-book, we aspire to keep this book a living text, as some fields are fast-evolving and our knowledge of all fields is still expanding. We hope the book will develop into a standard textbook others will refer to, and develop their own courses and training from, as we as authors also will do. That can be at different levels, e.g. the vocational level, but also for specific industries, or roles within companies. You are all welcome to reference these texts for your own specific learning and teaching needs.

1.7 A “running case”: the Dutch rail sector

Most readers will agree that maintenance is important in all asset-intensive sectors of society. However, it may be hard to believe that all aspects of maintenance as laid out in this textbook are relevant in every sector. To show that this is indeed true, this book uses, in its illustrations and in brief case vignettes, in the Setting the Stages, in every chapter, examples from the Dutch rail sector that are relevant to the topic discussed in that chapter. Why rail? Because the sector combines almost the full range of maintenance strategies in a single network: assets that are run to failure, assets on fixed intervals, assets monitored continuously, and assets that are replaced only once in a generation. In a small and densely populated country, rail carries a large share of daily mobility, and it moves freight from one of the world’s largest ports into the European hinterland.

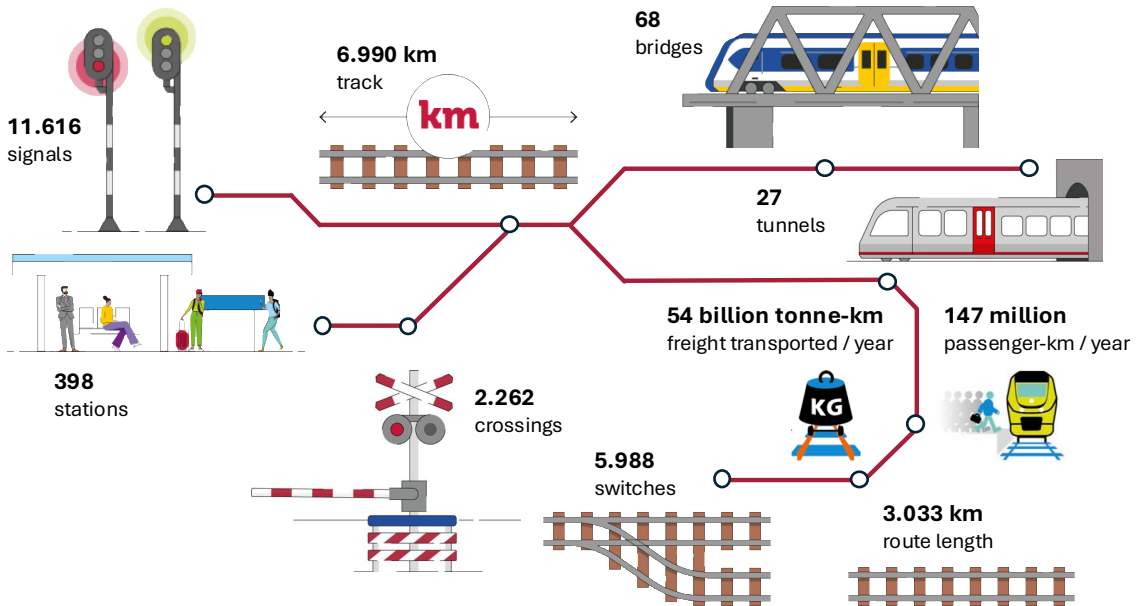


FIGURE 1.2 – The Dutch rail network.

Rail is also large and highly varied. The Dutch network consists of a few thousand kilometres of route, several thousand switches, more than ten thousand signals and close to four hundred stations, plus the overhead lines, bridges, tunnels, level crossings and power supply that keep all of it running. Much of it took its present form in the decades after the Second World War, when the network was rebuilt, electrified and signalled. Its replacement value now runs into the tens of billions of euros, and a substantial annual budget goes into replacing track, switches, overhead lines, signals and stations.

This variety is what makes the sector useful for a textbook on maintenance. Many assets run on life cycles of thirty-five to forty years; bridges and tunnels are built to last for generations. Virtually every maintenance strategy described in this book is therefore in use somewhere on the network right now. It also means that decisions taken today will be judged by people who have not yet started their careers. Managing that spread without losing sight of the whole requires a mature asset management system and a broad view of what an asset is, and of how decisions taken for individual assets contribute to realising value from them. The network is shown in Figure 1.2.

On top of that network runs a fleet of passenger and freight trains, owned by different companies from those that own the infrastructure and maintained in their own workshops under their own maintenance regimes. A modern train is a rolling collection of assets: wheelsets, bogies, brakes, doors, climate control and a growing amount of software. Some of these parts wear out within months, others are replaced only during mid-life updates. Fleet maintenance has therefore moved further towards condition-based maintenance than most of the infrastructure, with on-board diagnostics reporting the state of doors, brakes and traction while the train is in service.

Rail thus offers two very different maintenance worlds in one sector: a fixed network and a mobile fleet. Although maintained by different organizations, they share a single timetable. Work on the network can generally only take place once a section has been taken out of service, which turns almost every maintenance decision into a scheduling decision as well. For that reason, workflow management is a critical part of rail maintenance. The quality of a maintenance decision depends not only on the technical diagnosis, but on whether the required work can be planned, prepared and executed within the narrow windows the timetable allows.

For most of its history the sector lived in the physical world of steel, concrete and electricity. That is changing fast with the information that maintenance decisions are based on. Measurement trains record the geometry of the track, sensors in the train's pantograph measure contact force with the overhead line, and switch motors report the current they draw every movement. Inspection is moving towards automation: work that once depended on an inspector walking the track is now carried out at line speed. Measuring can be done while trains are running; intervening cannot. That asymmetry explains why the information side of rail maintenance is automating considerably faster than the execution side. The resulting stream of data makes strategies feasible that were out of reach before: predicting when a switch will fail rather than inspecting it on a fixed schedule, building a digital twin of a section of the network to test a renewal plan before anyone breaks ground, or letting algorithms flag defects in inspection images so that engineers only look at the ones that matter. It also raises new questions. Who holds the data that a contractor's sensor collects on the infrastructure manager's asset? And how do you keep a data pipeline running when the sensors, the network and the analytics are supplied by different parties?

Nowhere is the complexity of maintenance in the rail sector clearer than at the interfaces. Wear does occur within the track and within the train, but also where the two meet: in the contact between wheel and rail, and between pantograph and overhead line. The interface between train and signalling system is not one of wear but of compatibility, yet it raises the same questions of design, cost allocation and contract. Do you let the wear develop on the train or on the track, or do you treat the two as one integrated system? The answer determines who pays, who plans the work and who carries the risk. The introduction of the European Rail Traffic Management System (ERTMS) makes this even sharper. Safety information that used to be carried by thousands of trackside signals is moving into the train. Less infrastructure to maintain, but more technology, more integration effort and more cost on board every vehicle.

Then there is the way the work is organized, which is fragmented, and deliberately so. The infrastructure manager acts as asset manager, engineering firms prepare the work, contractors carry it out, the railway operators use the result, the ministry pays for it and European agencies set the norms. European regulation hardens where the boundaries between these parties lie. The separation between infrastructure management and transport operations follows from the European railway packages, and procurement rules extend that fragmentation towards contractors and suppliers. The wheel-rail interface is a single physical phenomenon, but it falls under various contracts, budgets and owners. The responsibility for what happens between them rarely sits with one party. Since the European Union has designated rail as critical infrastructure, cyber resilience has become part of maintenance and asset management itself: a risk that must be managed across the infrastructure manager, the railway operator and the suppliers together.

All of this calls for people with a different profile from the ones the sector has traditionally recruited. Track engineers and vehicle engineers remain indispensable, but the questions raised above cannot be answered from within a single discipline or a single organization. They require staff who can read a dataset as well as a drawing, who understand what a contract does to a technical decision, and who are able to work across the boundaries that regulation has drawn. That demand arrives just as the sector's most experienced staff are approaching retirement, taking decades of tacit knowledge with them. Much of what holds rail maintenance together is knowledge about how things actually work in practice, and that knowledge is not in any system.

Each chapter of this book therefore opens with a short vignette from this sector, chosen to illustrate the theory that follows. The examples are Dutch, but the underlying issues are not. Long-lived assets, fragmented responsibilities, scarce execution windows, an expanding stream of data and an ageing workforce are recognisable in energy, water, process industry and aviation alike. Rail puts them all in one place.

1.8 Structure of this book

After this introduction, this evolving book currently contains 20 further chapters, which are all interrelated, but organized around their main field.

1.8.1 Part I: Introduction

This first part, which includes the current chapter, is introductory and definitional in nature. Chapter 2 positions maintenance in the broader concept it is part of, asset management, and in the existing frameworks for asset management and asset categorizations. This is important as this links the field to various formal mechanisms of accreditation and standardization. Chapter 3 introduces and defines the “classical” maintenance topics such as failure modes, failure mechanisms and different maintenance policies. Most chapters after these two introductory chapters will refer, implicitly or explicitly, to these two defining ones.

1.8.2 Part II: Information Systems

Information Systems (IS) is a big field, and we need to address quite diverse subfields within IS. Chapters 4–7 deal with the diverse topics of IT architecture, data analytics, digital twins and automation, respectively. Diverse as they may be, all these are needed to leverage data concerning the condition, the performance and the environment of the assets we want to maintain in good working order. Chapter 4 on IT architecture describes how data and information flow, all the way from sensor data and other technical data to managerial dashboards. Chapter 5 discusses key elements of data analytics and AI, a fast-evolving field indeed. Chapter 6 introduces Digital Twins: the IT artifacts that encapsulate all these data and that are used by different groups in different ways in maintenance and asset management. Chapter 7 extends this line to the work floor. It describes how inspection, monitoring and the maintenance work itself are becoming increasingly automated, and how maintenance activities become increasingly information driven.

1.8.3 Part III: Engineering

This section addresses the many aspects of maintenance that are traditionally studied and taught by engineering faculty. Chapter 8 lays the groundwork by introducing the probabilistic language needed to describe uncertainty, which helps to understand reliability and failure rates, key concepts in maintenance. Chapter 9 looks at failure analysis methods that apply these insights, such as Fault Trees. Chapter 10 takes this discussion further and zooms in on Failure Mode and Effects Analysis, or FMEA. Chapter 11 explains the basic concepts of diagnostics and prognostics, and how these are used in health and condition monitoring, including sensor and signal processing requirements. Chapter 12 gives an overview of optimization techniques for maintenance decision making when lifetimes are stochastic. It gives a formal framework for different kinds of maintenance policies, such as failure-based, age-based replacement and condition-based maintenance decisions. Chapter 13 goes back to the beginning of the asset life cycle, to the design stage. Here, crucial decisions are made for maintenance and performance across the life cycle. It explains the principles of Design for Maintenance (DfM) and the interrelated roles of reliability, maintainability, and supportability.

1.8.4 Part IV: Economics and management

Many innovations in maintenance fail to be developed and implemented not so much for technical as for business reasons. There are multiple economics and management topics that are strongly relevant for maintenance. Chapter 14 starts off by describing the basic maintenance scheduling concepts for maintenance work, integrating both traditional and predictive maintenance activities, and generating appropriate maintenance schedules. Chapter 15 dives into a specific but crucial element of maintenance work: spare parts management. It describes spare parts inventory control models and their relations with maintenance and discusses new developments in this area in practice. Another crucial managerial part of maintenance is workflow management. This is the topic of Chapter 16. Here the importance of structured maintenance processes is explained, and the chapter lays out design and model workflows for maintenance using workflow management principles. Chapter 17 moves into the world of contracts, in particular performance-based contracts. It identifies key components of performance-based contracts and describes for what situations a performance-based contract can successfully be used. Special attention is given to the business practice of servitization and to the role of trust and commitment next to contractual governance. Chapter 18 explains basic concepts from life cycle costing, such as Time Value of Money (TVM), Net Present Value (NPV), Internal Rate of Return (IRR) and Payback period (PB).

1.8.5 Part V: Human and organizational behavior

This final part moves even further away from technology to a crucial set of topics from the perspective of organizational implementation and individual and societal acceptance of maintenance technology. Chapter 19 describes relevant aspects of human behavior for maintenance staff. Chapter 20 moves to the organizational level and describes theories of desired and undesired change. Finally, Chapter 21 points at the strategic importance of learning and knowledge management, crucial if we as society want to retain our existing skills in maintenance and build new ones fast enough to meet the aforementioned societal challenges. This final chapter brings us the full circle to this introductory chapter. It is time for a new kind of maintenance, and this book describes what that looks like.

1.9 Future perspectives / Conclusions

Given its size and scope, this book is unlikely to fit in its entirety into a single course. It could form the backbone for an entire study programme at the bachelor level. Alternatively, parts of the book can be used to remove deficiencies in knowledge on specific aspects, where readers are well-versed in some of the five main parts of the book but are less familiar with others. Also, the book can serve as an encyclopaedic reference work, or as source material for an AI chatbot, which the authors intend to develop. Finally, chapters from the book can form the foundation for other education material, either more advanced, for instance at the academic master level, or more practice oriented, for instance in lifelong learning settings or for education material at the vocational level. Depending on the learning purpose, the use of the book and its 21 chapters will vary accordingly.

Regardless of the specific use intended, the overall use of this book remains the same: to help advance the technological transition to smart and sustainable maintenance and asset management that our society needs so dearly. Because if we do not collectively manage this transition, maintenance, or better the lack of it, will become very visible indeed in our world, with all the detrimental if not disastrous consequences that will entail. Let's make sure we maintain a desirable way of life for all of us.

References

- Akkermans, Henk et al. (2024). 'All along the asset life cycle: Research opportunities for operations and supply chain management'. In: *Journal of Operations Management* 70.6, pp. 864–874. DOI: 10.1002/joom.1332.
- Bukowski, Lech and Sylwia Werbińska-Wojciechowska (2025). 'Towards Maintenance 5.0: Resilience-based maintenance in AI-driven sustainable and human-centric industrial systems'. In: *Sensors* 25.16, p. 5100. DOI: 10.3390/s25165100.
- European Commission (2024). *Industry 5.0*. Directorate-General for Research and Innovation. URL: https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en (visited on 17/09/2026).
- Geels, Frank W. (2002). 'Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study'. In: *Research Policy* 31.8–9, pp. 1257–1274. DOI: 10.1016/S0048-7333(02)00062-8.
- Psarommatīs, Foivos, Gökan May and Victor Azamfirei (2023). 'Envisioning maintenance 5.0: Insights from a systematic literature review of Industry 4.0 and a proposed framework'. In: *Journal of Manufacturing Systems* 68, pp. 376–399. DOI: 10.1016/j.jmsy.2023.04.009.
- van de Kerkhof, Fang and Lamper (2018). *De waarde van smart maintenance voor de Nederlandse infrastructuur*. Breda: World Class Maintenance. URL: <https://www.worldclassmaintenance.com/publicaties/boeken/de-waarde-van-smart-maintenance-voor-de-nederlandse-infrastructuur/>.
- van Groenendaal, Henk A. Akkermans and van Kempen (2023). *Infrastructure maintenance, a necessity and opportunity for Europe*. Breda: Tilburg University and World Class Maintenance. URL: <https://www.>

worldclassmaintenance.com/wp-content/uploads/2023/12/rapport-infra-maintenance-EU-intro.pdf.



2 Asset management

Jan Stoker¹

Learning goals

After reading this chapter, the reader should be able to:

- Explain how asset management, the asset management system and maintenance work together in one asset example.
- Describe how physical assets create value over their life cycle and why maintenance makes that value visible.
- Apply vertical and horizontal line of sight to a maintenance decision, including feedback from field evidence.
- Use the reference map to select the relevant source from the ISO 55000 series, CEN/TC 319, the IEC 60300-3 series or a professional knowledge architecture, including the EFNMS Maintenance Body of Knowledge.
- Formulate basic AMS controls for a decision involving trade-offs among performance, cost and risk in a maintenance-intensive organization.
- Explain how maintenance can contribute to sustainability, resilience, societal value, circularity and SDG-related objectives when these are translated through the AMS, SAMP, SMP, plans and evidence.

Setting the Stage

By the time the room emptied, Amara had three renewal proposals in front of her and money for one. The bridge near the harbour had carried freight for ninety years and would last ten more, or five, depending on whose report she believed. The switches on the eastern approach were newer but failed more often. And a quiet stretch of plain line, unremarkable on every dashboard she owned, sat beneath the busiest commuter service in the country.

As director of asset management at the national infrastructure manager, Amara did not own these assets the way an engineer might. She owned the order in which they were dealt with. Her mandate ran past keeping trains moving: the organisation designed, built and maintained the network, so every choice she signed would outlast the current timetable and the current minister.

Each proposal had its advocates. The freight operators wanted the bridge. The commuter franchise wanted the plain line it ran on. The safety regulator did not rank assets at all; it asked only whether any of them would fail. Every argument was reasonable on its own terms, and none of them added up to a plan. Adding them up was Amara's job.

What unsettled her was that the same decision, taken on three desks in three departments, would be taken three different ways, each locally sensible and collectively incoherent. Asset management was meant to join them up: the line of sight from a board's strategy to a fitter's Tuesday morning. On a good day it felt like that.

Before the next meeting she had to decide what that line of sight should connect, and how. How could one framework guide a decision that played out over a single shift and over fifty years at once, for assets whose owners would never agree on what mattered most? And what would have to be true inside the organisation for the answer to survive next year's budget?

Table 2.1 – Abbreviations used in this chapter. The table gives the minimum vocabulary needed to read the chapter without repeatedly redefining the same terms. Source: author's compilation based on (ISO 2024a; CEN 2017a; CEN 2017b; EFNMS 2023).

Abbreviation	Meaning	Use in this chapter
AM	Asset Management	The coordinated activity used to realize value from assets.
AMS	Asset Management System	The management system that directs, coordinates, controls and improves asset management.
SAMP	Strategic Asset Management Plan	The plan that translates organizational objectives into asset management objectives, strategy and decision logic.
AMP	Asset Management Plan	A plan for an asset, asset system or portfolio that translates objectives into life-cycle activities, resources and controls.
SMP	Strategic Maintenance Policy	The maintenance policy layer that translates asset management intent into maintenance principles, priorities and requirements.
RCM	Reliability Centred Maintenance	A structured method for selecting failure management policies from required functions, failure modes and consequences.
LCC	Life Cycle Costing	A method for assessing costs over the life cycle, including acquisition, operation, maintenance, renewal and disposal.
EAM/CMMS	Enterprise Asset Management / Computerized Maintenance Management System	Software systems that support asset and maintenance information. They can support an AMS but do not replace it.
SDG	United Nations Sustainable Development Goal	Used only when sustainability or societal ambitions have been translated into organizational objectives, asset management objectives, the SAMP, AM plans, SMP and evidence requirements.
EFNMS	European Federation of National Maintenance Societies	The European professional federation whose Maintenance Body of Knowledge structures maintenance knowledge, competences and professional practice.
BoK	Body of Knowledge	A structured professional knowledge base linking maintenance processes and actions to methods, techniques, practices and competence requirements.

2.1 Why asset management needs a maintenance lens

A rail infrastructure manager sees that a group of ageing switches on a critical corridor is degrading faster than expected. The operating timetable demands high availability, the renewal budget is limited and safety margins cannot be reduced. The question is therefore not only: which maintenance task should be executed next? The real asset management question is: which value must the asset system deliver, which risks are acceptable, which costs are justified and which evidence is needed to explain the decision afterwards?

This chapter uses that kind of situation as the practical entry point. Asset management is not introduced merely through a definition to be memorized; it is presented as a way of connecting objectives, decisions, execution and evidence. Maintenance makes this connection visible because it is where degradation is observed, interventions are planned, trade-offs are made and field evidence is produced (ISO 2024b, cls. 4.5, 6.2 and 8.1).

In this book, asset management is understood as the coordinated activity of an organization to realize value from assets. ISO 55000 frames asset management around value, alignment and organizational objectives. In maintenance-intensive organizations, that value is delivered through assets that must keep performing under uncertainty, ageing, changing demand and resource constraints (ISO 2024a, cl. 3.2.1 and cls. 4.2–4.4).

2.1.1 What asset management is and is not

Asset management is an organization-wide way of making, implementing and improving asset-related decisions so that assets deliver required outcomes over their life cycle. It starts with a practical question: what value must the organization deliver, and what role do assets play in creating that value (ISO 2024a, cl. 3.2.1 and cls. 4.2–4.4)?

This plain-language explanation supports the formal definition. “Coordinated activity” becomes visible when strategy, finance, risk, operations, engineering, maintenance, procurement and information management use the same decision logic. “Value” becomes visible when the organization can explain why one intervention is preferred over another in terms of performance, cost and risk (ISO 2024a, cls. 4.2.2–4.2.3; ISO 2024f, cls. 4–6; IEC 2017).

Four common misunderstandings should be addressed at the outset. Asset management is broader than maintenance execution. It is also broader than asset portfolio management, because portfolio choices still have to be translated into asset systems and individual assets. It is not a software tool, although EAM and CMMS platforms can support it. Finally, asset management is not merely a compliance exercise. Compliance can provide assurance, but the purpose is better value realization and disciplined decision-making (ISO 2024a, p. cl. 4.4; IAM 2024, secs. 2–3).

The asset owner does not seek to maximize maintenance activity. The objective is to secure asset function and value through the most defensible combination of intervention, monitoring, renewal and acceptance of residual risk. Sometimes this means doing more maintenance; sometimes it means redesigning, replacing, changing operating conditions or deliberately accepting a temporary risk with explicit review. This is why maintenance evidence must be connected to asset management objectives rather than judged only by the number of completed work orders (ISO 2024b, p. cl. 4.5; CEN 2021, cls. 4–5).

2.1.2 Asset management, the AMS and maintenance

The difference between asset management, the asset management system and maintenance is important enough to state once clearly and then use consistently.

TABLE 2.2 – Asset management, the AMS and maintenance. This table separates the discipline, system and life-cycle activity. Source: author's synthesis based on (ISO 2024a; ISO 2024b; CEN 2014).

Term	Main question	Practical meaning
Asset management	How do we realize value from assets?	The discipline and coordinated activity that balances outcomes, performance, cost, risk and opportunities over the life cycle.
Asset Management System	How do we make asset management repeatable and controllable?	The management system that connects policy, objectives, plans, decision criteria, roles, processes, information, assurance and improvement.
Maintenance	How do we retain, restore or improve required asset function?	The life-cycle activity that helps prevent failures, restores function, supports improvements in maintainability and provides field evidence for asset decisions.

This distinction prevents two errors. The first error is to reduce asset management to maintenance work. The second is to reduce the AMS to documents, dashboards or certification. A useful AMS connects strategy to daily work and brings evidence from assets, technicians, inspections, failures and costs back to strategy (ISO 2024a, p. cl. 4.4; ISO 2024b, cls. 4–10).

The industrial-revolution labels in the figure should be read as a short timeline. The main message is that maintenance moved from reactive repair to planned, preventive, condition-based and predictive approaches, while asset management matured into an organization-wide discipline for value, risk and life-cycle decisions (Stoker 2023; Stoker 2021).

Using maintenance as the lens does not make the chapter a maintenance manual. It makes asset management observable. A policy, objective or plan can sound convincing on paper, but its quality is tested when an asset deteriorates, a work window is cancelled, a supplier reports incomplete information or a budget choice changes the risk profile. Maintenance therefore provides a practical arena in which students can see whether the AMS is only described, or whether it actually influences decisions and learning (ISO 2024b, cls. 4.5, 8.1 and 9–10; GFMAM 2021c).

2.1.3 Value, life cycle and line of sight

Value is not limited to financial return. In asset-intensive organizations, value may include service performance, safety, environmental outcomes, compliance, resilience, customer satisfaction, public value and long-term affordability. These outcomes can conflict. Higher availability can require higher cost. Cost reduction can increase risk. A more resilient asset may require earlier investment (ISO 2024a, cl. 3.3.27 and cls. 4.2.2–4.3; GFMAM 2016).

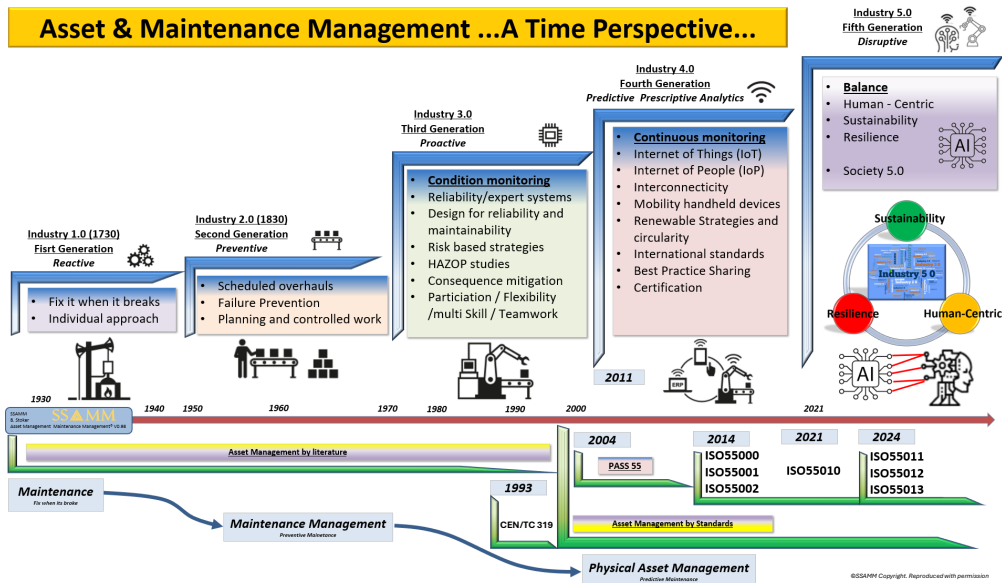


FIGURE 2.1 – Maintenance & Asset Management - The Big Picture. This figure gives a single overview of the historical and practical connection between maintenance, asset management, physical asset management and industrial development. It is used as orientation, not as a second explanation of all concepts. Source: adaptation based on (Stoker 2023; Stoker 2021).

Sustainability, resilience, societal value and circularity should be read through the same line-of-sight logic. When an organization has adopted United Nations Sustainable Development Goals (SDGs), climate objectives or public-service obligations, these ambitions only become actionable for maintenance when they are translated into asset management objectives, value criteria, risk criteria, the SAMP, AM plans and the Strategic Maintenance Policy (SMP). Maintenance then contributes by retaining required function, extending useful life where justified, reducing waste, improving reliability and safety, controlling environmental and social risks, and providing evidence that these outcomes are actually being achieved (ISO 2024b, cls. 4.2, 6.2 and 8.1; ISO 2024c; CEN 2022; Stoker 2021).

A life-cycle view asks what happens from concept and acquisition through operation, maintenance, renewal and disposal. Maintenance has a central role because it reveals the physical reality behind the plan: degradation, failure behaviour, access constraints, spare parts availability, work quality and the actual condition of the asset (ISO 2024b, p. cl. 8.1; CEN 2014; CEN 2022).

From a professional maintenance perspective, the EFNMS Maintenance Body of Knowledge (BoK) positions maintenance within a landscape connecting physical asset management, risk and dependability, and sustainable development. It makes explicit that maintenance comprises both processes and the knowledge and competences required to perform them effectively (EFNMS 2023, pp. 11–13).

Line of sight is the visible and auditable connection between organizational objectives and the work performed on assets. It has both vertical and horizontal dimensions. Vertical line of sight connects purpose to asset management objectives, SAMP, AM plans, the Strategic Maintenance Policy (SMP), work execution and

evidence. Horizontal line of sight connects the functions that must work together: asset management, finance, operations, maintenance, engineering, procurement, risk, data management and suppliers (ISO 2024a, p. cl. 4.2.3; ISO 2024f, cls. 5–8; Stoker 2025d; Stoker 2024a).

A weak line of sight often becomes visible in small inconsistencies. A corporate objective may refer to reliability, while the maintenance contract rewards only response time. Finance may approve a short-term saving without seeing the risk backlog. Engineering may change a maintenance interval without recording the assumptions. These gaps are not administrative details; they are places where value can leak away. The AMS should make such gaps visible by requiring common criteria, clear ownership and evidence that can be followed by another person later (ISO 2024b, cls. 4.5, 5.3, 7.6 and 9–10; ISO 2024f).

Table 2.3 – Vertical and horizontal line of sight from purpose to field evidence. The table shows how direction flows down, evidence flows back and functional alignment prevents local optimization. Source: author’s synthesis based on (ISO 2024b; ISO 2024f; Stoker 2025d).

Step	Vertical line of sight	Horizontal alignment needed
Organizational objective	Defines the value to be delivered, such as safe and reliable service at affordable whole-life cost.	Leadership, finance, operations and asset management agree on value and risk appetite.
Asset management objective	Translates value into portfolio or system performance, risk and life-cycle targets.	Risk, finance, engineering and operations use the same asset hierarchy and decision criteria.
SAMP and AM plans	Translate objectives into life-cycle strategies, investment logic and maintenance requirements.	Planning, procurement, maintenance and suppliers understand the same requirements and constraints.
Strategic Maintenance Policy	Defines maintenance principles, preferred concepts, risk acceptance logic and decision rights.	Maintenance, operations, engineering and asset management agree how performance, cost and risk are balanced.
Maintenance processes	Control preparation, scheduling, execution, reporting and improvement.	Work management, spares, competence, HSE, data and contracting are coordinated.
Evidence and feedback	Returns inspection results, failures, costs, deviations and lessons learned to planning and review.	Data owners, analysts, engineers and managers use the same evidence to update decisions.

2.1.4 Risk and uncertainty

Risk is the effect of uncertainty on objectives. In maintenance-intensive organizations, this becomes practical by asking two questions: what could happen, and what would the consequences be? The likelihood of a failure and its consequence for safety, service, environment, cost or reputation determine whether the risk is acceptable, needs control or must be escalated (ISO 2024a, p. cl. 3.3.8; ISO 2024b, p. cl. 6.1.2).

Risk is therefore not separate from value. It influences whether value is lost, protected or created. For the ageing rail switch, risk can appear as derailment potential, service disruption, emergency repair, loss of capacity or reputational damage. Maintenance contributes to risk control through inspections, preventive tasks, condition monitoring, corrective work, design feedback and renewal advice (CEN 2021; IEC 2017; GFMAM 2016).

Uncertainty remains even when data are available. Inspection intervals, degradation models, budget assumptions and failure consequences all contain uncertainty. The AMS should make the assumptions visible and keep them under review. A good decision is not one that pretends uncertainty has disappeared; it is one that uses evidence, criteria and review points to manage uncertainty deliberately (ISO 2024b, cls. 6.1.2 and 9–10).

Risk appetite and risk tolerance make this practical. Risk appetite describes the level and type of risk the organization is willing to pursue or accept in order to achieve its objectives. Risk tolerance translates that appetite into boundaries for specific decisions, assets or services. For a critical rail corridor, the tolerance for safety risk will be very low, while the tolerance for short-term cost variance may be higher if it protects availability. The AMS should ensure that these boundaries are not hidden inside individual expert judgement but are visible in plans, escalation rules and reviews (IAM 2024, subject 7.9; GFMAM 2024b, subject 2.6).

2.2 One reference map, not many islands

Students encounter many references in this field: ISO 55000, ISO 55001, EN 17007, EN 17485, IEC 60300-3 and others. If every section introduces them again, the chapter becomes heavy. The better approach is to present one reference map and then use it.

2.2.1 How to read ISO, EN, IEC and NEN references

ISO standards are international standards. The ISO 55000 series concerns asset management. ISO 55000 provides the vocabulary, overview and principles for asset management. ISO 55001 contains requirements for an asset management system. Other documents in the family provide guidance on application, financial and non-financial alignment, people involvement and asset data (ISO 2024a; ISO 2024b; ISO 2024f; ISO 2024c; ISO 2024d; ISO 2024e).

EN standards are European standards. For maintenance, many relevant EN standards are developed through CEN/TC 319, the European technical committee for maintenance. When a country adopts a European standard, the national prefix may be added. For example, NEN-EN 17007 is the Dutch adoption of EN 17007 (CEN 2017b; CEN 2024).

IEC standards are international electrotechnical standards. The IEC 60300-3 series is used here as application guidance for dependability topics such as field data collection, life-cycle costing, maintainability and RCM. NEN-EN-IEC indicates the Dutch adoption of a European standard that adopts an IEC standard (IEC 2024a; IEC 2004; IEC 2017; IEC 2025; IEC 2009).

The prefixes therefore tell the reader where a document has been developed or adopted; they do not change the basic logic of the standard. In practice, organizations often use several families together. ISO 55001 can define the AMS requirement, EN 17007 can define how maintenance processes are structured, and IEC 60300-3 guidance can support the analytical method behind a maintenance decision. The important point is not the prefix itself, but the role the document plays in the decision chain (ISO 2024b, cls. 4.5 and 8.1; CEN 2017b; IEC 2024a).

2.2.2 Three standard families and complementary professional knowledge architectures

For this chapter, the reference map has three standard families and complementary professional knowledge architectures. ISO 55000 gives the asset management system logic. CEN/TC 319 provides the maintenance-specific logic for terminology, processes, management, methodologies and resources. IEC 60300-3 supports dependability methods that strengthen evidence and decision quality. The IAM and GFMAM landscape models help explain the broader professional capability landscape (ISO 2024b; CEN 2024; IEC 2024a; IAM 2024; GFMAM 2024b).

Complementing the broader asset management capability landscapes of IAM and GFMAM, the EFNMS BoK provides a maintenance-specific professional knowledge architecture. It links maintenance processes and actions to the knowledge, methods, techniques, practices and competences required by maintenance stakeholders. In this chapter, it is used to connect standardization with professional practice, education, qualification and certification (EFNMS 2023, pp. 11–20).

The IAM Landscape Model should be read as a professional capability landscape around asset management. It is not a requirements standard and it does not replace ISO 55001. Its value in this chapter is that it shows the breadth of capabilities that must cooperate if the AMS is to work in practice: strategy and planning, decision-making, life-cycle delivery, information, people, risk, finance, review and improvement. The model therefore complements the reference map. ISO 55001 tells the organization what the management system must control; the landscape model helps students see which capability areas must actually be connected. In the rail-switch example, the figure explains why the decision cannot be solved by maintenance execution alone. The choice also touches planning, risk, finance, operations, engineering, data and governance (IAM 2024, secs. 5–7; GFMAM 2024b).

This table is deliberately more than a list of titles. It shows why CEN/TC 319 matters for line of sight. The common basis stabilizes language and process. The management layer translates asset management intent into maintenance governance. The methodologies layer supports justified decisions. The resources layer ensures that the people, contracts, documentation, tools and information needed to implement the chosen decisions are in place (CEN 2024, Annex A).

The four-layer view also prevents a common implementation mistake. Organizations sometimes select a method, such as KPI reporting, risk-based inspection or RCM, without first stabilizing the common language, process interfaces and management responsibilities. The result is a technically sound method that produces evidence no one owns or uses. Reading CEN/TC 319 as layers helps avoid that problem: common basis be-

TABLE 2.4 – Reference map used in this chapter. The table is a reading guide. It shows which reference line answers which question, so the chapter can apply standards and professional knowledge sources without reintroducing them each time. Source: author's synthesis based on (ISO 2024b; CEN 2024; IEC 2024a; IAM 2024; GFAM 2024b; EFNMS 2023).

Reference line	Typical question	Use in this chapter
ISO 55000 series	How should the organization realize value from assets through an AMS?	Used for value, alignment, AMS requirements, SAMP, decision criteria, data, people and improvement.
CEN/TC 319 maintenance standards	How should maintenance be defined, governed, executed and resourced?	Used to translate asset management intent into Strategic Maintenance Policy (SMP), process architecture, engineering, competence and resources.
IEC 60300-3 series	Which dependability methods support reliable technical and economic decisions?	Used for field data, LCC, maintainability, RCM, maintenance support and related evidence.
IAM/GFAM professional landscapes	What capabilities are needed beyond requirements compliance?	Used as professional landscape models for capability, maturity, integration and learning.
EFNMS Maintenance Body of Knowledge	Which knowledge, methods, practices and competences are needed to perform, manage and improve maintenance?	Used as a maintenance-specific professional knowledge architecture linking EN 17007 processes and actions to maintenance knowledge, EN 15628 competence requirements, education and certification.

TABLE 2.5 – CEN/TC 319 as a four-layer maintenance standards architecture. The table prevents the standards from being read as a loose list. The CEN/TC 319 family is organised into layers that build from common language to management, methodologies and resources. Source: author's synthesis based on (CEN 2024, Annex A).

Layer and function in the line of sight	Standards and typical use
Layer 1 - Common basis Creates the shared vocabulary and process architecture that all other maintenance standards rely on.	EN 13306 - maintenance terminology. EN 17007 - maintenance process and associated indicators.
Layer 2 - Management Positions and governs maintenance within physical asset management and organizational objectives.	EN 16646 - maintenance within physical asset management. EN 17485 - improving the value of physical assets through the whole life cycle. EN 17948 - maintenance management and functions. EN 15331 - design, management and control of maintenance services for buildings.
Layer 3 - Methodologies Provides analytical, engineering and risk-based methods for justified maintenance decisions.	EN 17666 - maintenance engineering requirements. EN 15341 - maintenance key performance indicators. CEN/TS 17385 - condition assessment of immobile constructed assets. EN 17840 - performance and condition assessment for buildings and civil engineering works. EN 16991 - risk-based inspection framework. EN 17975 - risk control processes for energy and fluid risks in maintenance activities.
Layer 4 - Resources Defines enabling resources such as contracts, documentation and competence.	EN 13269 - guideline on preparation of maintenance contracts. EN 13460 - documentation for maintenance. EN 15628 - qualification of maintenance personnel.



FIGURE 2.2 – The IAM Landscape Model. The IAM model shows the breadth of asset management capabilities. In this chapter it is used as a professional landscape, while the ISO 55000 series remains the formal AMS reference line. Source: © 2026 The Institute of Asset Management – reproduced with permission (IAM 2024, fig. 5, p. 31).

fore management consistency, management consistency before method selection, and method selection before resource and competence requirements (CEN 2024; IEC 2009; GFMAM 2021c).

The EFNMS BoK does not constitute a fifth layer of the CEN/TC 319 architecture; instead, it operates across all four layers. Using the process structure of EN 17007, it links maintenance actions to the knowledge, methods and practices required to perform them, while aligning the competence and qualification perspective with EN 15628. In this way, the BoK forms a professional bridge between the standards architecture and its application by maintenance personnel (EFNMS 2023, pp. 14–20 and 42–43).

2.2.3 The VCS-Line of Sight

Figure 3 shows how the standards can be read as one auditable chain. The left-hand side places maintenance inside the value chain from organizational management to asset management, the AMS, asset portfolio and maintenance layers. The right-hand side shows that ISO 55000, CEN/TC 319 and supporting standards are not competing islands. They each occupy a layer in the chain (Stoker 2025d).

The practical use of the figure is simple. When a decision is challenged, the organization should be able to trace the path from objective to plan, from plan to the Strategic Maintenance Policy (SMP), from policy to process and method, and from work execution back to evidence. This is where line of sight becomes auditable rather than decorative (ISO 2024b; CEN 2017b; Stoker 2025d).

The four maintenance layers in Figure 3 should be read together. The common basis prevents confusion in terminology and process boundaries. The management layer defines maintenance objectives, policy, strategy,

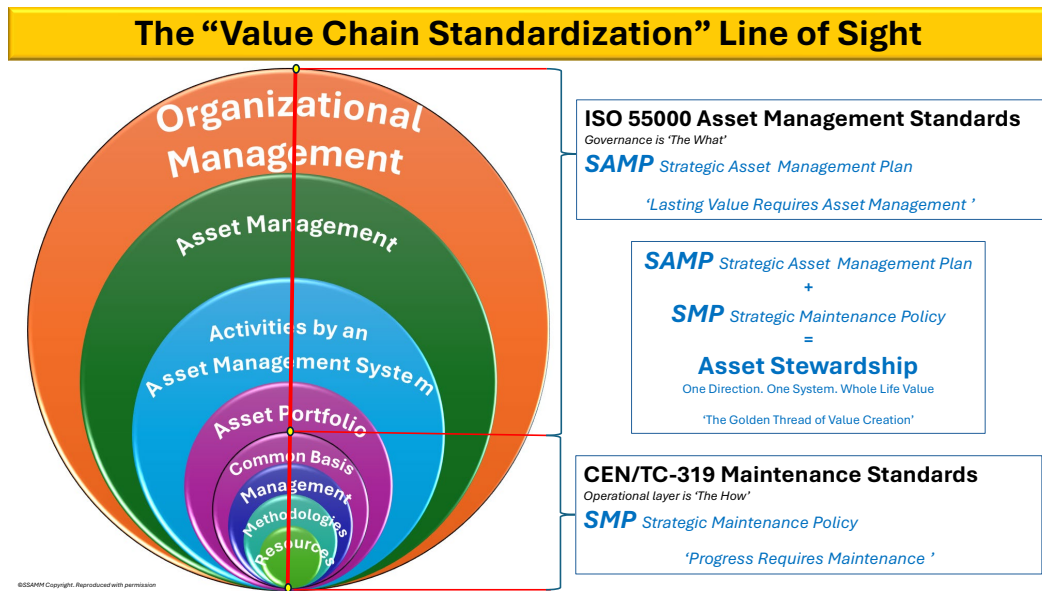


FIGURE 2.3 – SSAMM VCS-Line of Sight. This figure shows how organizational purpose, ISO 55000 system logic, CEN/TC 319 maintenance standards, execution processes and field evidence can be read as one auditable value chain. Source: adapted from (Stoker 2025d).

responsibilities and interfaces. The methodologies layer makes decisions technically and economically defensible. The resources layer ensures that the people, contracts, documentation, tools and information needed to implement the chosen decisions are in place (CEN 2024; Stoker 2024b).

The SSAMM Maintenance Landscape Model zooms in on the maintenance side of the asset management landscape. Its purpose is to show that maintenance is not a single process or department, but a connected capability system. The common basis supplies terminology and process logic. The management layer translates asset management objectives into maintenance objectives, the SMP, plans, responsibilities and interfaces. The methodologies layer justifies technical and economic choices. The resources layer ensures that the people, contracts, documentation, tools and information needed to implement the chosen decisions are in place. Read in this way, the model prevents maintenance management from becoming a list of tools. It becomes a capability architecture for turning AMS direction into consistent maintenance delivery (CEN 2024; GFMAM 2021c; Stoker 2024b).

Figure 5 connects the asset management landscape and the maintenance landscape. It shows the interface where asset management direction must become maintainable and executable. The SAMP and AM plans express value, performance, cost and risk choices at portfolio or asset-system level. The SMP, maintenance processes, engineering methods and resources translate those choices into maintenance concepts, work plans, information requirements and feedback evidence. The figure is useful because it makes the handover explicit: asset management cannot simply hand over objectives to maintenance. It must define the decision criteria, boundaries and evidence requirements that maintenance will use and return (ISO 2024b, p. cl. 6.2.1; Stoker 2024a; Stoker 2025c).

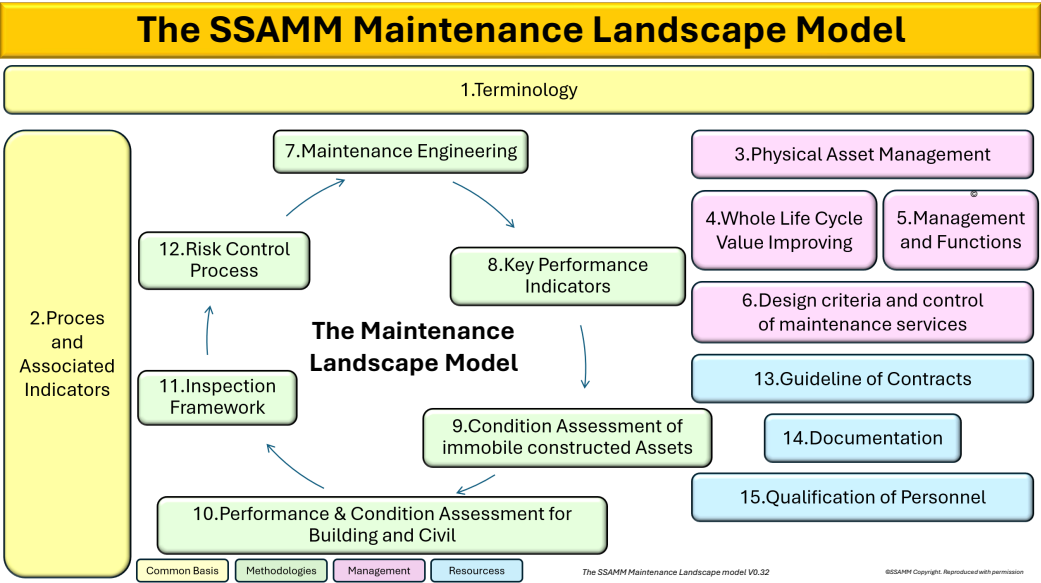


FIGURE 2.4 – The SSAMM Maintenance Landscape Model. This figure narrows the reference map to the maintenance side. It positions maintenance as an operational backbone of the AMS through common basis, management, methodologies and resources. Source: adapted from (Stoker 2024b).

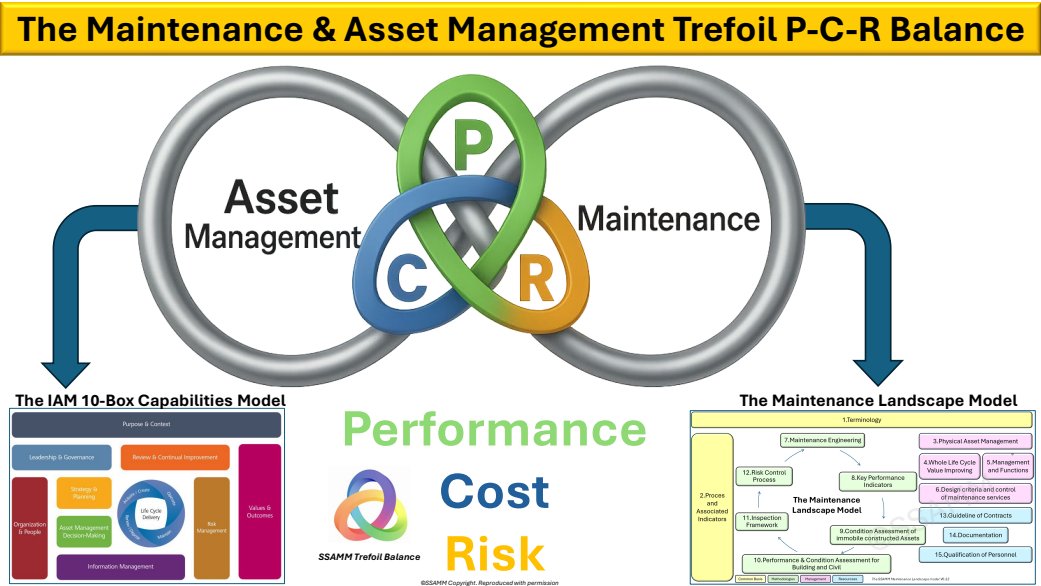


FIGURE 2.5 – Connecting the Maintenance & Asset Management landscape models. This figure explains the handover from asset management direction to maintenance delivery: SAMP and AM plans must become a Strategic Maintenance Policy (SMP), processes, engineering decisions, resources and feedback evidence. Source: author's integration based on (Stoker 2025d; Stoker 2024a).

2.3 From purpose to plans

Asset management becomes practical when purpose is translated into plans. A rail organization may have an objective to provide safe, reliable and affordable service. That objective does not maintain a rail switch by itself. It must become asset management objectives, a SAMP, asset management plans, a Strategic Maintenance Policy (SMP), work plans and evidence requirements (ISO 2024a, cls. 4.2–4.3; ISO 2024b, cls. 4.5 and 6.2; CEN 2021).

2.3.1 Purpose, value criteria and decision criteria

A useful SAMP starts from organizational objectives and stakeholder requirements. It should explain which outcomes matter, how value is understood, which risks are tolerable and how decisions will be made when performance, cost and risk compete (ISO 2024a, cls. 4.2.2–4.3; ISO 2024b, cls. 4.2, 4.5 and 6.2; GFMAM 2016).

Decision criteria are the rules used to compare options. For the ageing rail switch, a decision might compare continuation of the existing time-based maintenance regime, additional condition monitoring, targeted component renewal or full replacement. The criteria should include required function, safety risk, availability impact, intervention windows, whole-life cost, data confidence and implementation constraints (ISO 2024b, p. cl. 4.5; ISO 2024f, cls. 5–8; IEC 2017).

2.3.2 SAMP, AM plans and Strategic Maintenance Policy (SMP)

The SAMP sets the strategic direction for the asset portfolio. Asset management plans translate that direction into plans for portfolios, asset systems or asset groups. For maintenance-intensive organizations, these plans should make maintenance requirements explicit: required functions, critical failure modes, inspection logic, maintenance concepts, resource needs, information requirements and review triggers (ISO 2024b, cls. 6.2.1–6.2.3 and 8.1; CEN 2021).

The Strategic Maintenance Policy (SMP) is the hinge between asset management intent and maintenance delivery. Here, SMP is used as the abbreviation for Strategic Maintenance Policy. The SMP is strategic because it does not define individual work orders; it defines the maintenance principles, preferred maintenance concepts, intervention logic, risk acceptance rules, escalation boundaries and feedback requirements that guide maintenance management across asset groups (CEN 2017b; CEN 2014; Stoker 2025c).

For students, the important distinction is that the SAMP and AM plans do not replace the SMP. They create the conditions for it. The SAMP explains the strategic direction and decision logic. AM plans translate that direction into plans for asset systems or asset groups. The SMP then defines how maintenance will contribute: which risks maintenance is intended to help control, which preventive, predictive, corrective or improvement concepts will be applied, which data and evidence must be returned and which decisions require escalation. This prevents maintenance policy from becoming a stand-alone technical preference (ISO 2024b, p. cl. 6.2.1; CEN 2021; Stoker 2025c).

The SMP is important for maintenance and maintenance management because it protects the line of sight at the point where strategy becomes work. Without an SMP, maintenance can easily become locally optimized:

planners protect the weekly schedule, engineers optimize technical reliability, finance reduces annual cost and suppliers follow contract KPIs. Each action may be rational in isolation, but the asset management objective can still be weakened. A good SMP gives maintenance management a shared frame for prioritization, backlog control, intervention intervals, condition monitoring, risk escalation, competence needs and evidence capture. It also clarifies which decisions remain within maintenance authority and which must be escalated to asset management because they change performance, cost or risk at system level (CEN 2014; GFMAM 2021c; Stoker 2025c).

This policy-to-execution bridge also has a knowledge and competence dimension. By linking maintenance subjects to the processes and actions in EN 17007, the EFNMS BoK helps identify the knowledge, methods and competences required to implement the SMP across maintenance management, engineering, execution and support roles (EFNMS 2023, pp. 14–20).

The SMP is also the right place to translate sustainability, resilience, circularity and societal contribution into maintenance management. If the organization has SDG-related objectives, climate or resource-use objectives, or public-service obligations, the SMP should explain what they mean for maintenance concepts, inspection intervals, refurbishment versus replacement, reuse or remanufacturing, spare-parts strategy, emergency response and evidence requirements. This prevents these themes from remaining high-level corporate statements; it makes them operational criteria for maintenance decisions (ISO 2024c; CEN 2022; Stoker 2025c; Stoker 2021).

TABLE 2.6 – Running example: ageing rail switch from organizational objective to decision logic. Values are illustrative; the purpose is to show the decision logic, not to prescribe a specific rail policy. Source: author’s illustrative case.

Line-of-sight element	Rail switch example	Evidence produced or needed
Organizational objective	Maintain safe and reliable train service on a critical corridor while keeping whole-life cost affordable.	Service targets, safety requirements, budget envelope and risk appetite.
Asset management objective	Reduce switch-related service disruption and control safety-critical degradation before the next renewal cycle.	Failure history, criticality assessment, condition trend and corridor capacity impact.
Options considered	Continue current preventive regime; add condition monitoring; renew selected components; accelerate full switch replacement.	Option comparison using performance, cost, risk, access windows and data confidence.
Decision logic	Add condition monitoring and renew the most critical components now; plan full renewal in the next investment window if degradation trend persists.	Decision record with accepted risk, cost estimate, expected availability gain and review trigger.

TABLE 2.7 – Running example: ageing rail switch from maintenance execution to evidence and review. This continuation completes the bottom-up evidence loop. Source: author’s illustrative case.

Line-of-sight element	Rail switch example	Evidence produced or needed
Maintenance execution	Update inspection tasks, work instructions, spares plan and reporting fields in the CMMS/EAM.	Completed work orders, inspection results, deviations, downtime and repair findings.
Feedback and review	Review after three months and after the next high-load season; adjust maintenance plan or renewal timing.	Trend report, residual risk, cost variance and recommendation to the AM planning cycle.

2.3.3 Line of sight is also feedback

Line of sight is often described top-down, but it only works if bottom-up evidence is taken seriously. A technician who reports repeated difficult access, a planner who sees increasing work-order delays, or a data analyst who detects a rising failure trend is not producing “operational noise”. They are contributing evidence to the asset management system (ISO 2024b, cls. 9–10; ISO 2024e, cls. 4.2.5, 4.4 and 5.1; IEC 2004).

The AMS should define when such evidence triggers review. A single defect may only require corrective work. A pattern of defects may require a revised maintenance concept. A structural pattern across an asset class may require investment replanning, design change or a different procurement specification (ISO 2024b, cls. 8.1 and 9–10; ISO 2024e, cls. 4.2.5, 4.4 and 5.1).

2.4 The asset management system in practice

The AMS connects objectives, plans, decision criteria, roles, information, assurance and improvement into one coherent management system for asset-related decisions. ISO 55001 provides the requirements baseline, but the system only creates value when people use it to make and improve real decisions (ISO 2024a, cls. 3.3.5 and 4.4; ISO 2024b, cls. 4–10; Stoker 2025a).

2.4.1 What the AMS does

In practice, an AMS does five things. It translates objectives into plans. It defines who may decide what. It sets the criteria for trade-offs. It specifies what information is required. It closes the learning loop through monitoring, audit, management review and improvement (ISO 2024b, cls. 4–10; Stoker 2025a).

For the rail switch case, the AMS should make the decision traceable. The organization should be able to show which objective was at stake, which options were considered, what risk was accepted, what maintenance work changed, what data were collected and when the decision will be reviewed (ISO 2024b, cls. 4.5, 6.2, 7.6 and 9–10; Stoker 2025a).

Within this system, maintenance is a strategic function because it influences the performance, cost, risk and useful life of physical assets. This strategic role does not imply that every maintenance task is strategic; many tasks remain routine execution. Maintenance is strategic because the function supplies the degradation knowledge, intervention logic, field evidence, reliability learning and renewal advice that enable the AMS to make defensible life-cycle decisions (ISO 2024b, p. cl. 8.1; CEN 2014; GFMAM 2021c).

2.4.2 Governance, decision rights and assurance

Governance becomes practical when decision rights are clear. A maintenance planner can prioritize work within agreed rules. A maintenance engineer can propose changes to the maintenance concept. An asset manager can approve changes that affect risk, performance or life-cycle cost. Top management owns the risk appetite and confirms that the AMS remains aligned with organizational direction (ISO 2024b, cls. 4.5, 5.3 and 9.2–9.3; ISO 2024f).

Assurance should not be confused with checking whether every document exists. The more useful question is whether the decision chain can be reconstructed. If the rail switch decision is reviewed six months later, the organization should be able to identify which objective was protected, which options were rejected and which assumptions remained uncertain. It should also be able to show who accepted the residual risk and whether the expected evidence was produced. That kind of assurance supports learning because it tests the quality of decisions, not only compliance with procedure (ISO 2024b, cls. 9.2–9.3 and 10; Stoker 2025a).

TABLE 2.8 – Governance questions and evidence. The table shows how an AMS turns governance into practical questions that can be answered with evidence. Source: author’s synthesis based on (ISO 2024b; ISO 2024e).

Governance question	Why it matters	Typical evidence
Who owns the decision?	Prevents unclear authority and unmanaged escalation.	Decision rights matrix, role descriptions, approval records.
Which criteria were used?	Makes performance, cost and risk trade-offs explicit.	Decision framework, option assessment, risk and cost assumptions.
Which evidence was trusted?	Shows whether the decision is based on fit-for-purpose data.	Inspection data, failure history, condition trend, LCC estimate, expert judgement record.
What changed in execution?	Links the decision to maintenance work and resources.	Updated maintenance plan, work instructions, schedule, spares and competence requirements.
When will the decision be reviewed?	Keeps uncertainty under control and enables learning.	Review trigger, management review input, audit finding or improvement action.

2.4.3 Information, data assets and decision quality

Data should be judged by its usefulness for decisions. A larger database is not automatically better asset management. Useful data are determined by the questions the organization must answer: What is the asset? What function must it deliver? What is its condition? Which failures occur? What work was performed? What did it cost? What changed afterwards? (ISO 2024b, cls. 7.5–7.7; ISO 2024e, cls. 4–5; GFMAM 2024a)

ISO 55013 treats data assets as assets in their own right when they have value to the organization. This is important for maintenance because inspection records, condition histories, work-order feedback and failure data can become a strategic asset when they improve renewal, maintenance and risk decisions. They can also become a liability when they are incomplete, inconsistent or not trusted (ISO 2024e, cls. 3–8).

Data quality is therefore contextual. A condition score, failure code or cost record is good enough only if it is fit for the decision it supports. A strategic renewal decision may require trend confidence, degradation assumptions and life-cycle cost comparison. A daily work-control decision may require location accuracy, safety constraints and spare-parts availability. Treating all data as equally important usually overloads the system. The AMS should define critical data elements from the decisions that create or protect value (ISO 2024e, cls. 4.2–5; IEC 2004; GFMAM 2024a).

2.5 Maintenance as life-cycle delivery capability

Maintenance is the life-cycle activity that retains, restores or improves required asset function. It is also a source of evidence. This dual role is why maintenance belongs within asset management rather than being treated only as a parallel function (CEN 2017a; CEN 2014; GFMAM 2021c).

This strategic role becomes visible when maintenance choices change the asset management options available to the organization. A well-designed maintenance concept can defer renewal without increasing unacceptable risk, while poor maintenance data can force premature replacement because the organization cannot justify continued operation. Maintenance therefore protects value not only by executing work, but also by making future options more visible and defensible (CEN 2021; IEC 2017; GFMAM 2016).

2.5.1 Maintenance, maintenance engineering and maintainability

Maintenance execution performs the work. Maintenance engineering develops and improves the maintenance logic. Maintainability concerns how easily and effectively the asset can be maintained. EN 17666 is useful because it places maintenance engineering across the life cycle rather than only in the operating phase (CEN 2022; IEC 2025; Stoker 2025b).

In the rail switch case, maintenance engineering asks whether failures are caused by the maintenance interval, the component design, installation quality, operating load, drainage, access constraints or insufficient feedback data. That question is different from simply asking which work order should be planned next week (CEN 2022; IEC 2009).

From a sustainability and circularity perspective, maintenance engineering is strategic because choices about maintainability, access, diagnostics, spare parts, modular replacement, refurbishment, remanufacturing

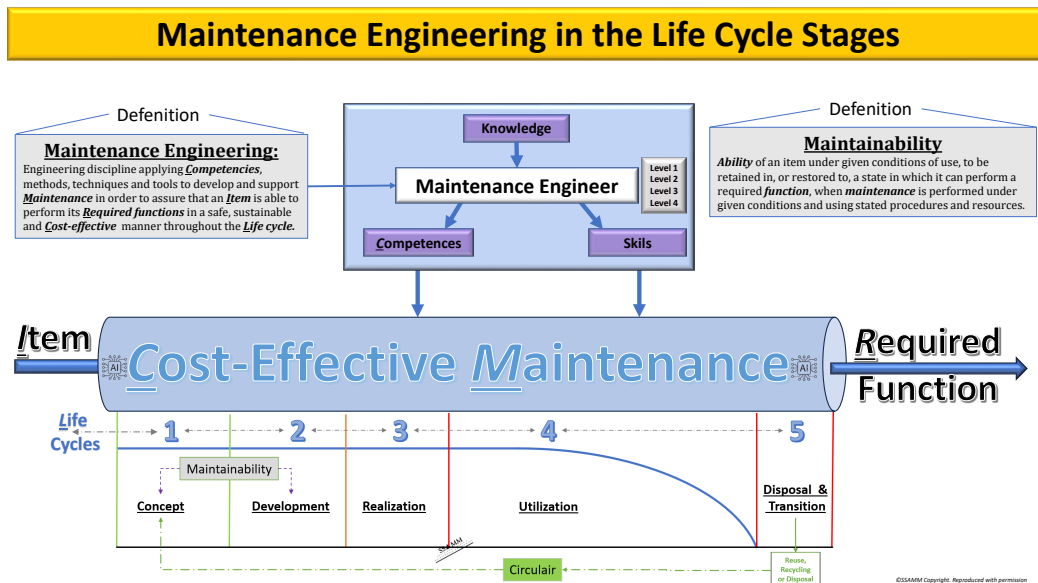


FIGURE 2.6 – Maintenance Engineering Life-Cycle visualized (EN 17666). This figure shows why maintenance engineering should influence concept, design, realization, utilization and disposal. The earlier maintenance requirements are considered, the easier it becomes to control performance, cost and risk later. Source: adapted from EN 17666:2022 (CEN 2022, cl. 6 and Annex D) and (Stoker 2025b).

and end-of-life handling often determine whether useful life can be extended without transferring risk. This is why maintenance engineering belongs early in the life cycle: the ability to maintain, reuse or responsibly dispose of an asset is largely designed before the asset enters operation (CEN 2022; CEN 2025; IEC 2024b).

2.5.2 The maintenance process architecture

EN 17007 describes maintenance as a process architecture with management, realization and support processes. This helps connect work execution to planning, HSE, budgeting, documentation, data, spare parts, tools, resources and improvement (CEN 2017b; CEN 2024, Annex A; GFMAM 2021c).

Building on the EN 17007 process structure, the EFNMS BoK maps more than 75 maintenance subjects to the processes and actions in which the associated knowledge is required. These subjects cover maintenance within physical asset management, maintenance management, execution, health, safety and environment, maintenance engineering techniques and maintenance support. The mapping helps explain not only what a maintenance process must do, but also what people need to know in order to perform and improve it (EFNMS 2023, pp. 14–20 and 22–43).

The value of such a process view lies not in adding bureaucracy, but in helping managers identify where the chain breaks. A good maintenance concept can still fail if work preparation is weak, spare parts are unavailable, competence is missing, data fields are not completed, or suppliers report in a different language (CEN 2017b; GFMAM 2021c).

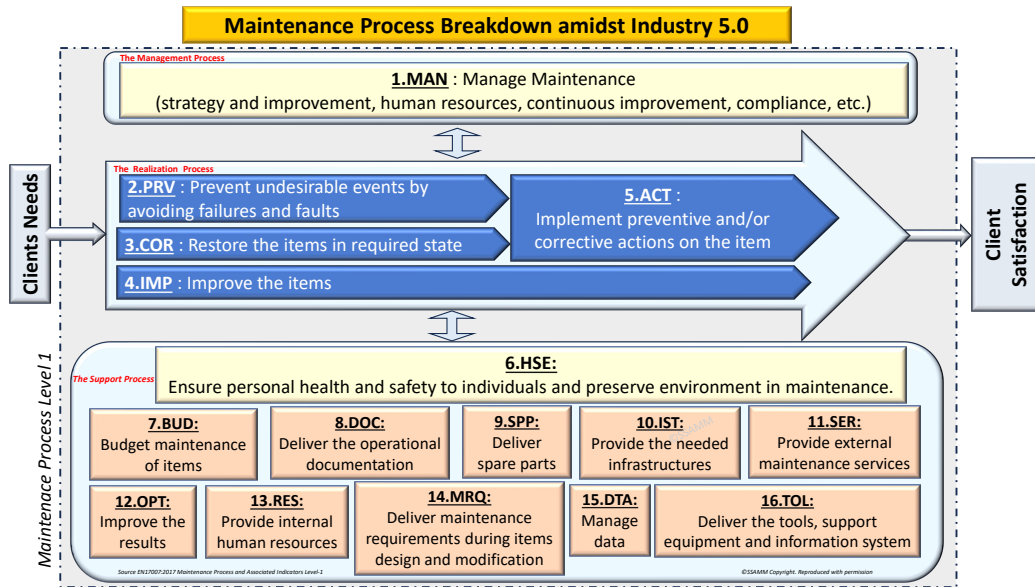


FIGURE 2.7 – Maintenance Breakdown process (EN 17007). Maintenance shown as an integrated process system. Source: adapted from EN 17007:2017 (CEN 2017b, cls. 5–6) and (Stoker 2024b).

2.5.3 Dependability methods: from opinion to justified maintenance decisions

IEC 60300-3 guidance helps move maintenance decisions from unsupported opinion towards justified analysis. Field data collection supports reliability and maintainability learning. Life-cycle costing supports economic comparison over time. Maintainability guidance supports design and intervention choices. RCM supports failure-management policy selection from required functions, failure modes and consequences (IEC 2004; IEC 2017; IEC 2025; IEC 2009).

For the rail switch, an RCM-style question would start with the required function and failure consequences. An LCC question would compare costs over the life cycle rather than only the next budget year. A maintainability question would ask whether design, access, modularity or diagnostics should change to make future maintenance safer, faster or more reliable (IEC 2017; IEC 2025; IEC 2009).

Dependability methods also help make uncertainty explicit and reviewable. They do not remove engineering judgement; they structure it. Field data may be incomplete, failure modes may be partly unknown and cost estimates may be uncertain, but a method forces the organization to state what is known, what is assumed and what consequences may follow. This is especially important when the cheapest short-term option appears attractive. A method-based comparison can show whether the saving is real or whether cost is simply being transferred to future failures, emergency work or earlier renewal (IEC 2024a; IEC 2004; IEC 2024b).

2.5.4 People capability and process-to-competence mapping

Asset management depends on people who can work across boundaries. EN 15628 gives a structured view of maintenance personnel qualifications, while ISO 55012 adds the asset management perspective on involvement and competence. The EFNMS BoK connects these perspectives by starting from the processes and actions in

EN 17007 and identifying the maintenance knowledge, methods, techniques and practices needed to perform them. Together, these sources create a line of sight from process responsibility to knowledge, competence, education, qualification and certification (ISO 2024d, cls. 4–8; CEN 2025; EFNMS 2023, pp. 13–20 and 42–43).

The practical question is simple: who must be competent to make, execute, verify or challenge the decision? In the rail switch case, the technician observes condition, the planner controls the work package and the maintenance engineer assesses failure behaviour. The asset manager balances life-cycle options, finance tests affordability and management accepts or rejects residual risk (ISO 2024d; CEN 2025).

This distinction is important. A job title alone does not demonstrate competence. The required competence should be derived from the decisions, processes and actions for which the role is accountable. The BoK supports this analysis by making the relevant maintenance knowledge domains visible (EFNMS 2023, pp. 18–20 and 42–43).

2.6 Implementing and improving the system

Implementation should not be treated as a linear certification project. It is a governance and learning design challenge. The organization has to decide how objectives become plans, how plans become work, how work produces evidence and how evidence changes decisions (ISO 2024b, cls. 4–10; GFMAM 2021b; GFMAM 2021a).

2.6.1 A practical implementation sequence

- 1) Establish context, scope and boundaries: decide which assets, asset systems and services are within the AMS (ISO 2024b, cls. 4.1–4.4).
- 2) Define the core decision logic: value, risk appetite, performance targets, cost rules and escalation criteria (ISO 2024a, cls. 4.2–4.3; ISO 2024b, cls. 4.5 and 6.1–6.2; ISO 2024f).
- 3) Create or update the core artefacts: policy, asset management objectives, SAMP, AM plans and Strategic Maintenance Policy (SMP) (ISO 2024b, cls. 5.2 and 6.2; Stoker 2025a; Stoker 2025c).
- 4) Build the maintenance backbone: processes, roles, work control, engineering methods, competence, contracts and resources (CEN 2017b; CEN 2022; CEN 2025).
- 5) Define information requirements: what data are needed, for which decisions, at which quality level and by whom (ISO 2024e; IEC 2004; GFMAM 2024a).
- 6) Establish assurance and improvement: audits, reviews, evidence checks, maturity assessment and improvement actions (ISO 2024b, cls. 9–10; GFMAM 2021b; GFMAM 2021a).

Implementation should start at a scale that allows complete implementation and learning. A useful first step is often one asset system, one decision type and one evidence loop. For example, the organization can select a critical corridor, define the switch-related decisions to be improved, agree the decision criteria, clean only the data needed for those decisions and test whether the review loop changes the next plan. This creates learning

and credibility. Scaling the AMS is easier when people have seen one complete line of sight work in practice (ISO 2024b, cls. 4–10; Stoker 2025a).

2.6.2 Minimum artefacts and controls

Table 8 should be read as a minimum baseline, not as a complete implementation manual. It lists the artefacts and controls that should be present, in a form proportionate to the organization, for an AMS to become operational in a maintenance-intensive context. The middle column describes the minimum content expected from each artefact or control; the right-hand column explains why maintenance needs it. The table is also a diagnostic: when a maintenance decision cannot be traced, one of these artefacts or controls is usually missing, outdated or disconnected from evidence (ISO 2024b, cls. 7.2 and 7.5–7.7; Stoker 2025a; Stoker 2025c).

TABLE 2.9 – Minimum AMS artefacts and controls. The table shows a compact implementation baseline. The artefacts are useful only if they guide decisions and are reviewed against evidence. Source: author’s synthesis based on (ISO 2024b; Stoker 2025a; Stoker 2025c).

Artefact or control	Minimum content	Maintenance connection
Asset management policy	Intent, principles and commitment to value, alignment and improvement.	Explains why maintenance must contribute to performance, cost, risk and evidence.
Asset management objectives	Measurable outcomes for asset portfolio or systems.	Translate into availability, safety, reliability, maintainability and renewal priorities.
SAMP	Strategy, decision criteria, planning logic, scope and governance.	Defines what maintenance must support and what evidence is needed.
AM plans	Life-cycle actions, resources, timing and controls for asset groups.	Generate maintenance requirements, inspection logic and renewal interfaces.
Strategic Maintenance Policy	Maintenance principles, concepts, risk logic, decision rights and escalation.	Translates asset management intent into maintenance principles, methods, processes, roles and decision boundaries.
Information requirements	Data needs, owners, quality rules and systems.	Defines condition, failure, cost and work feedback needed for decisions.
Assurance and improvement	Audits, management review, performance review and corrective actions.	Checks whether maintenance evidence supports or challenges plans.

The key point is connection. A policy without objectives does not guide priorities. Objectives without AM plans do not become life-cycle actions. AM plans without an SMP do not define maintenance principles. Work management without feedback does not support improvement. The table therefore links documents, controls and evidence into one operating model (ISO 2024b, cls. 5–10; Stoker 2025a; Stoker 2025c).

2.6.3 Typical tensions and how the AMS should handle them

Table 9 uses typical tensions to show why an AMS must be more than a document set. Asset management decisions often fail not because the organization lacks ambition, but because recurring management tensions pull functions in different directions. The table names these tensions and shows the AMS response that should make the trade-off visible and governable (ISO 2024b, cls. 4.5, 5–6 and 8–9; ISO 2024f; Stoker 2025a).

Table 2.10 – Typical AMS tensions and responses. The table turns abstract governance into recognizable management tensions. Source: author’s synthesis based on (ISO 2024b).

Tension	What can go wrong	AMS response
Budget versus risk	Short-term cost reduction increases hidden risk or backlog.	Use decision criteria, escalation thresholds and life-cycle cost comparison.
Data volume versus data usefulness	Systems collect data that no one uses for decisions.	Define data requirements from decision needs and remove reporting requirements that do not support decisions.
Local optimization versus system value	One department improves its KPI while the asset system performs worse.	Use horizontal line of sight and shared performance, cost and risk criteria.
Outsourcing versus accountability	Suppliers execute work but the owner loses decision evidence.	Specify information, reporting, competence and assurance requirements in contracts.
Digital tools versus human judgement	Analytics are used without explainability or accountability.	Keep human review, thresholds, evidence records and decision ownership explicit.

The table should be used as a check during implementation and management review. If the organization recognizes one of these tensions, the response should not be another isolated rule. The response should strengthen the decision criteria, escalation thresholds, evidence requirements or role ownership. In that sense, the table translates governance into practical management questions (ISO 2024b, cls. 4.5 and 9–10; GFMAM 2021b).

2.6.4 Maturity as learning, not paperwork

Maturity is not the number of documents produced. It is the extent to which the organization can make better asset-related decisions repeatedly, under uncertainty, and learn from the results. A mature AMS can explain why a decision was made, what evidence supported it, what assumptions were used, who owned it and how the outcome was reviewed (IAM 2024, sec. 6.2; GFMAM 2021b; GFMAM 2021a).

2.7 Future orientation: people, sustainability, resilience and digitalization

The future of asset management will not be determined by technology alone. The more digital and data-rich the environment becomes, the more important decision accountability, competence and governance become (ISO 2024d; ISO 2024e; GFMAM 2024a; Stoker 2021).

2.7.1 Human-centric asset management

Human-centric asset management does not mean less technology. It means that technology supports competent people, transparent decisions and safe work. AI can help identify patterns, but people must still define objectives, accept risk, interpret context and remain accountable for decisions (ISO 2024d; CEN 2025; Stoker 2021).

A human-centric AMS therefore requires more than role descriptions. It needs an actively maintained professional knowledge base and pathways for education, continuing professional development, qualification and, where appropriate, certification. The EFNMS BoK provides a maintenance-specific knowledge base for these pathways (EFNMS 2023, pp. 20 and 42–43).

2.7.2 Sustainability and whole-life value

Maintenance can be a sustainability lever because retaining function often avoids unnecessary replacement, waste and disruption. The asset management question is not simply whether an asset can remain in service for longer. The question is whether the extended life still delivers value safely, sustainably and affordably, including environmental impact, resource use, social effects and future obligations (ISO 2024a, cls. 4.2–4.3; CEN 2021; CEN 2022; Stoker 2023).

In relation to sustainability, the EFNMS BoK positions maintenance within a European professional landscape connecting physical asset management, risk and dependability, and sustainable development. It associates maintainability and appropriate maintenance with useful-life extension, reduced demand for replacement materials and energy, protection of people and the environment, economic performance and societal contribution (EFNMS 2023, pp. 12–13).

The link with the SDGs should be formulated carefully. Maintenance does not deliver the SDGs as a separate programme. It contributes when SDG-related ambitions are translated through organizational objectives, stakeholder requirements, asset management objectives, SMP criteria, maintenance plans and evidence. In that chain, maintenance can support safer infrastructure, reliable public services, lower resource consumption,

reduced waste, longer useful life and better control of environmental and social risks (ISO 2024c; ISO 2024b; CEN 2022).

Circularity adds a specific life-cycle test. Maintenance engineering can help decide whether an asset or component should be retained, refurbished, redesigned, reused, remanufactured, recycled or replaced. The most defensible circular decision is not automatically the option with the longest possible life extension; it is the option that best balances function, safety, risk, resource use, total life-cycle cost and stakeholder value (CEN 2022; CEN 2025; IEC 2017).

2.7.3 Resilience and uncertainty

Resilience requires the ability to absorb disruption, recover service and adapt. Maintenance contributes through inspection, condition monitoring, contingency planning, spare parts strategy, emergency response and design feedback. The practical test is whether the organization knows which assets, functions and dependencies are critical when conditions change (ISO 2024b; IEC 2024a; IEC 2024b).

For public or critical infrastructure, resilience is also a societal contribution. The consequences of poor maintenance are not limited to higher costs; they can include losses of mobility, water, energy, production capacity, public safety or public confidence. This is why the AMS should connect maintenance priorities to service-critical functions and stakeholders, not only to internal work-order measures (ISO 2024c; CEN 2014; GFMAM 2016).

2.7.4 Digitalization, digital twins and AI

Digitalization should be assessed with one practical question: does it improve the quality, traceability or accountability of asset-related decisions? A digital twin, dashboard or AI model is valuable only when it improves the line of sight from objectives to work and from evidence back to decisions (ISO 2024e; IEC 2004; GFMAM 2024a).

The future themes should therefore be read as design tests for the AMS. A human-centric approach asks whether people remain competent and accountable. Sustainability asks whether whole-life value includes resource use, environmental consequences, circular options and societal value. Resilience asks whether the organization can respond when assumptions fail. Digitalization asks whether tools improve traceability and decision quality. None of these themes replaces the basic asset management logic; each tests whether that logic remains effective under new conditions (ISO 2024b; GFMAM 2024b; Stoker 2021).

2.8 Key takeaways

- 1) Asset management realizes value from assets by coordinating decisions across functions and over the life cycle.
- 2) The AMS makes asset management repeatable, controllable and improvable; it is not the same as a software tool or a certificate.

- 3) Maintenance is a strategic life-cycle delivery capability and a source of evidence for asset management decisions.
- 4) Line of sight has a vertical dimension from purpose to work and a horizontal dimension across functions, data and decision criteria.
- 5) The reference map distinguishes asset management system logic, maintenance standards, dependability methods and professional knowledge architectures; the EFNMS BoK complements CEN/TC 319 by linking maintenance processes and actions to knowledge and competence.
- 6) A useful asset management decision balances performance, cost and risk using explicit evidence, documented assumptions and defined review triggers.
- 7) Maintenance can contribute to sustainability, resilience, societal value, circularity and SDG-related objectives when those objectives are translated through the AMS, SAMP, SMP, plans and evidence.

Assignments

- 1) Use the ageing rail switch example to explain the difference between asset management, the AMS and maintenance, and show how maintenance evidence makes life-cycle value visible.
- 2) Create a simple vertical and horizontal line of sight for a pump station, bridge or production line.
- 3) Using the reference map, select the most relevant source or source family for a maintenance issue such as terminology, process design, maintainability, competence or maturity. Explain why the selected source is appropriate and how the EFNMS BoK complements, rather than replaces, the CEN/TC 319 standards architecture.
- 4) For a maintenance decision you know, formulate a basic AMS control set that makes the performance, cost and risk trade-off explicit. Include decision criteria, decision authority, evidence requirements, residual-risk acceptance and review triggers.
- 5) Design the minimum AMS controls that should be in place before a digital tool or AI model is used for maintenance decision-making.
- 6) Using one asset or service, explain how maintenance can contribute to sustainability, resilience, societal value and circularity. Then show how these contributions can support SDG-related objectives when translated through organizational objectives, the AMS, SAMP, AM plans and SMP into maintenance requirements and evidence.

Further Reading

The book uses a compact reading list. The items below are selected because they help students understand the main line of this chapter without turning the chapter into a bibliography.

- 1) ISO 55000:2024, ISO 55001:2024 and the wider ISO 55010/55011/55012/55013 guidance - asset management vocabulary, AMS requirements, financial and non-financial alignment, public policy, people and data guidance.
- 2) The Institute of Asset Management, Asset Management - an anatomy, Version 4, 2024, and GFMAM, The Asset Management Landscape, Third Edition, 2024.
- 3) EFNMS, Maintenance: Body of Knowledge, 2023 - maintenance knowledge, methods, techniques, practices, competence, education and certification.
- 4) EN 16646, EN 17485, EN 17666 and EN 15628 - maintenance within physical asset management, whole-life value, maintenance engineering, circular economy and competence.
- 5) EN 17007 and IEC 60300-3 guidance - maintenance process architecture, field data, life-cycle costing, maintainability, RCM and maintenance support.

Model answers

The model answers illustrate one defensible application of the chapter's logic. Other answers can be valid when they use consistent definitions, explicit decision criteria and appropriate evidence.

- 1) Asset management defines what value the rail switch must support and how performance, cost and risk are balanced. The AMS defines the policy, plans, roles, criteria, information and review mechanisms that make this repeatable. Maintenance executes inspections, preventive tasks, corrective work and improvements, while also producing evidence about condition, failures, costs and performance. Maintenance makes life-cycle value visible by showing whether the switch continues to provide safe and reliable service at an acceptable cost and risk, and whether continued maintenance, redesign or renewal is justified.
- 2) Vertically, a pump station line of sight can start with the organizational objective of reliable water service. This becomes an asset management objective for required capacity and acceptable flood risk. The AM plan defines life-cycle actions. The SMP defines inspection, maintenance and response principles. Work orders execute the plan. Field evidence returns as condition data, failure history, cost and service impact. Horizontally, operations, maintenance, engineering, finance, risk and suppliers must use the same asset hierarchy and criteria.
- 3) For inconsistent work-order terminology and unclear competence requirements, EN 13306 provides common terminology, EN 17007 provides process logic, and EN 15628 defines competence expectations for maintenance personnel. The EFNMS BoK complements these standards by mapping maintenance processes and actions to the knowledge, methods and practices that people need. It does not constitute a fifth CEN/TC 319 layer and does not replace the formal standards (CEN 2017a; CEN 2017b; CEN 2025; EFNMS 2023).

- 4) For a decision to extend an inspection interval, the control set should specify the required performance and safety criteria, the cost assumptions, the evidence from inspection history and degradation analysis, and the role authorized to approve the change. It should also record the residual risk, rejected options and a review date or trigger that determines when the decision must be reconsidered.
- 5) Before using a digital tool or AI model, the AMS should define the decision it supports, the required data quality, the model owner, validation rules and human-review requirements. It should also define escalation thresholds, the audit trail and the process for correcting the model when evidence shows that it is wrong (ISO 2024e; GFMAM 2024a).
- 6) For a public rail corridor, maintenance can support sustainability through safe life extension and reduced waste; resilience through condition monitoring, spare-parts strategy and recovery capability; societal value through safe and reliable mobility; and circularity through refurbishment, reuse or remanufacturing. These contributions support SDG-related objectives only when they are translated into asset management objectives, the SAMP, AM plans and SMP criteria, and then into maintenance tasks, indicators and evidence (ISO 2024c; CEN 2022; GFMAM 2016; Stoker 2021).

References

- European Committee for Standardization (2014). *EN 16646:2014 Maintenance – Maintenance within physical asset management*. European Standard EN 16646:2014. Brussels, Belgium: European Committee for Standardization.
- (2017a). *EN 13306:2017 Maintenance – Maintenance terminology*. European Standard EN 13306:2017. Brussels, Belgium: European Committee for Standardization.
 - (2017b). *EN 17007:2017 Maintenance process and associated indicators*. European Standard EN 17007:2017. Brussels, Belgium: European Committee for Standardization.
 - (2021). *EN 17485:2021 Maintenance – Maintenance within physical asset management – Framework for improving the value of the physical assets through their whole life cycle*. European Standard EN 17485:2021. Brussels, Belgium: European Committee for Standardization.
 - (2022). *EN 17666:2022 Maintenance – Maintenance engineering – Requirements*. European Standard EN 17666:2022. Brussels, Belgium: European Committee for Standardization.
 - (2024). *EN 17948:2024 Maintenance management and functions*. European Standard EN 17948:2024. Brussels, Belgium: European Committee for Standardization.
 - (2025). *EN 15628:2025 Maintenance – Qualification of maintenance personnel*. European Standard EN 15628:2025. Brussels, Belgium: European Committee for Standardization.

European Federation of National Maintenance Societies (2023). *Maintenance: Body of Knowledge: Issues, Methods, Techniques and Practices to Be Known by Stakeholders of the Maintenance Process*. EFNMS VZW.

Global Forum on Maintenance and Asset Management (Aug. 2016). *The Value of Asset Management to an Organization*. 1st ed. English version. Global Forum on Maintenance and Asset Management. ISBN: 0-9870602-6-0.

- (Sept. 2021a). *Asset Management Maturity: A Position Statement*. 2nd ed. English version. Global Forum on Maintenance and Asset Management. ISBN: 978-1-7774676-4-7.
- (Sept. 2021b). *Guidelines for Assessing Asset Management Maturity*. 1st ed. English version. Global Forum on Maintenance and Asset Management. ISBN: 978-1-7774676-3-0.
- (Feb. 2021c). *The Maintenance Framework*. 2nd ed. English version. Global Forum on Maintenance and Asset Management. ISBN: 978-1-7774676-0-9.
- (Sept. 2024a). *Digital Transformation in Maintenance and Asset Management*. 1st ed. English version. Global Forum on Maintenance and Asset Management. ISBN: 978-1-0688555-9-7.
- (June 2024b). *The Asset Management Landscape*. 3rd ed. English version. Global Forum on Maintenance and Asset Management. ISBN: 978-1-7774676-8-5.

Institute of Asset Management (July 2024). *Asset Management – an Anatomy*. 4th ed. London, United Kingdom: Institute of Asset Management.

International Electrotechnical Commission (2004). *IEC 60300-3-2:2004 Dependability management – Part 3-2: Application guide – Collection of dependability data from the field*. International Standard IEC 60300-3-2:2004. Second edition. Geneva, Switzerland: International Electrotechnical Commission.

- (2009). *IEC 60300-3-11:2009 Dependability management – Part 3-11: Application guide – Reliability centred maintenance*. International Standard IEC 60300-3-11:2009. Geneva, Switzerland: International Electrotechnical Commission.
- (2017). *IEC 60300-3-3:2017 Dependability management – Part 3-3: Application guide – Life cycle costing*. International Standard IEC 60300-3-3:2017. Third edition. Geneva, Switzerland: International Electrotechnical Commission.
- (2024a). *IEC 60300-1:2024 Dependability management – Part 1: Managing dependability*. International Standard IEC 60300-1:2024. Fourth edition. Geneva, Switzerland: International Electrotechnical Commission.
- (2024b). *IEC 60300-3-14:2024 Dependability management – Part 3-14: Application guide – Supportability and support*. International Standard IEC 60300-3-14:2024. Second edition. Geneva, Switzerland: International Electrotechnical Commission.
- (2025). *IEC 60300-3-10:2025 Dependability management – Part 3-10: Application guide – Maintainability and maintenance*. International Standard IEC 60300-3-10:2025. Second edition. Geneva, Switzerland: International Electrotechnical Commission.

International Organization for Standardization (2024a). *ISO 55000:2024 Asset management – Vocabulary, overview and principles*. International Standard ISO 55000:2024. Second edition. Geneva, Switzerland: International Organization for Standardization.

- (2024b). *ISO 55001:2024 Asset management – Asset management system – Requirements*. International Standard ISO 55001:2024. Second edition. Geneva, Switzerland: International Organization for Standardization.
- (2024c). *ISO 55011:2024 Asset management – Guidance for the development of public policy to enable asset management*. International Standard ISO 55011:2024. Geneva, Switzerland: International Organization for Standardization.
- (2024d). *ISO 55012:2024 Asset management – Guidance on people involvement and competence*. International Standard ISO 55012:2024. Geneva, Switzerland: International Organization for Standardization.
- (2024e). *ISO 55013:2024 Asset management – Guidance on the management of data assets*. International Standard ISO 55013:2024. Geneva, Switzerland: International Organization for Standardization.
- (2024f). *ISO/TS 55010:2024 Asset management – Guidance on the alignment of financial and non-financial functions in asset management*. Technical Specification ISO/TS 55010:2024. Second edition. Geneva, Switzerland: International Organization for Standardization.

Stoker, Benjamin (2021). *Industry 5.0: Deepening the Subject*. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-897-6. URL: <https://ssammeducation.com/industry-5-0-deepening-the-subject/>.

- (2023). *Sustainable Asset & Maintenance Management*. 1st ed. First digital edition. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-890-7. URL: <https://ssammeducation.com/sustainable-asset-maintenance-management/>.
- (2024a). *The Asset & Maintenance Management Lemniscate*. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-895-2. URL: <https://ssammeducation.com/the-amm-lemniscate-cornerstones/>.
- (2024b). *The Maintenance Framework*. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-896-9. URL: <https://ssammeducation.com/maintenance-framework/>.
- (2025a). *Building an Asset Management System (AMS)*. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-894-5. URL: <https://ssammeducation.com/building-an-asset-management-system-ams/>.
- (2025b). *Maintenance Engineering: Future Proof Maintenance Engineering*. 1st ed. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-898-3. URL: <https://ssammeducation.com/maintenance-engineering/>.
- (2025c). *The Strategic Maintenance Policy (SMP)*. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-891-4. URL: <https://ssammeducation.com/the-strategic-maintenance-policy-smp/>.
- (2025d). *The Value Chain Standardization Line of Sight*. Bilthoven, The Netherlands: SSAMM. ISBN: 978-90-8339-892-1. URL: <https://ssammeducation.com/the-value-chain-standardization-line-of-sight/>.



3 Maintenance

Tiedo Tinga¹

Learning goals

After reading this chapter, you will be able to:

- Describe the basic concepts of maintenance, like availability, maintainability, fault, failure mode and failure mechanism.
- Explain the approach followed in several maintenance strategies, like RCM, RBI, PHM and ILS.
- Explain the difference between various maintenance policies, as well as the pro's and cons of corrective, preventive, condition-based and predictive maintenance.
- Describe the various maturity levels in maintenance.
- Execute a maintenance policy selection for a specific application, based on ambition level and data availability

Setting the Stage

The junction outside the capital handled more trains before nine in the morning than some lines saw all day. Diego had come to the operations centre to settle one question: how it should be maintained for the next five years. Three engineers were already arguing about it when he arrived.

The argument was really about method, and the network used several. Some equipment was serviced on a fixed schedule because no one could measure its condition cheaply. Other assets were inspected on a cycle, with work triggered once wear crossed a line. A growing share were watched by sensors that called for attention only when the readings drifted. Most installations used some mix of the three, shaped by what could be measured and what the measuring cost.

This junction made the choice hard. The signalling was safety-critical but gave almost no warning of its own state. The switches carried sensors, yet reading them well took real skill. The overhead lines were old and wore unevenly, in patterns that resisted a tidy rule. A policy that suited one of them suited the others poorly.

Diego listened for a while before he spoke. The team wanted him to pick a method. He suspected the real task was different: to match each asset to the approach that fit its risk, its data, and the cost of getting that data wrong. Choosing well meant reading the situation, not preferring one label over another.

He looked again at the draft plan. For this junction, with these assets and this traffic, which approach actually earned its place, and how should the organisation make that same call the next hundred times it came up?

3.1 Introduction

In this chapter the basic concepts of maintenance will be introduced. In the previous chapter, the high-level asset management process has been explained, which focuses on the wide range of decisions taken during the complete life cycle of a (fleet of) assets. Maintenance is only a small element in asset management, but crucial for an organization to achieve its objectives. This chapter will therefore explain what maintenance decisions can be taken, what policies are available to guide these decisions, and how the most suitable policy can be selected.

This book aims to treat all topics related to maintenance, ranging from technical and engineering aspects to information and economical aspects. Therefore, in this chapter some links will already be made to other chapters in the book, where further details on that topic will be provided.

In the next section, some definitions will be given for the main concepts in maintenance. Then section 3.3 will discuss how faults and failures can be defined and detected. Section 3.4 will introduce the various maintenance strategies, that guide the selection of maintenance policies as discussed in 3.5. The various maturity or ambition levels in maintenance are introduced in 3.6, while the tools for selecting the policy that fits a certain ambition level will be discussed in 3.7. After the demonstration of these tools in some cases studies (3.8), section 3.9 will finally provide some future perspectives on maintenance.

3.2 Maintenance and availability

In the European Standard (EN13306:2001 2001) maintenance is defined as

the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function

This clearly reveals that the primary aim of maintenance is to ensure a properly functioning system. This can be understood from the perspective of the owner or operator of the system: organizations utilize the systems to achieve their organizational goals, like maximizing profit or offering societal services like energy or transport. To reach these goals, the associated assets or systems must be working properly, which is denoted as system availability. Availability is defined as

the probability that the system will be ready to perform its specified function, in its specified and intended operational environment, when called for at a random point in time

This is the point availability, expressing the availability (i.e. system up or down) at one specific point in time. Due to all kinds of uncertainties, it is difficult to estimate the future availability of a system, but the achieved past (average) availability can be determined rather easily by relating the accumulated up-time of the system to the total time in a certain period, as expressed by

$$A = \frac{\sum \text{uptimes}}{\sum \text{uptimes} + \sum \text{downtimes}} \quad (3.1)$$

A proper maintenance policy can assist to reach a specific availability level, either by timely repair of failed systems or by part replacements that prevent them to fail at all. However, maintenance is not the only driver for the system availability, as is shown in Fig. 3.1. The theoretical availability is determined by some properties of the system itself. Firstly, the inherent *reliability* of the system indicates how robust it is, i.e. how probable surviving a certain operational period without maintenance is. This is determined by the quality of the design, as well as the quality of the materials used. A highly reliable system will typically yield a high availability, as failures will be rare. Secondly, the *maintainability* of the system plays a role. If executing maintenance is easy, e.g. by exchanging complete modules, the downtime after a failure will be limited, yielding a higher availability. This aspect will be treated in detail in the chapter on Design for Maintenance. And finally the *serviceability*, indicating how complex the requirements for the support organizations are, affects the theoretical availability of the system. This includes the specialization level of the maintenance staff and the need for tailored tools and equipment. The simpler and more generic these are, the higher the supportability of the system, and the higher the theoretical availability.

The actual availability, i.e. the availability that is realized in practice, is off-course directly related to this theoretical availability. However, it also depends on the applied maintenance strategy and the accessibility of the system. For example, if the system is at a remote location, the maintenance strategy might be appropriate, but execution of the required maintenance might not be directly possible, thus lowering the availability.

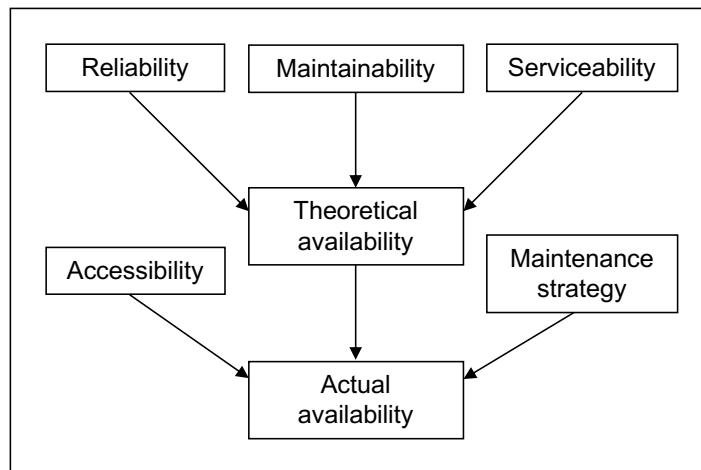


FIGURE 3.1 – Availability depends on system reliability and support processes.

3.3 Faults and failures

As maintenance is always a response to or prevention of faults and failures, this section will focus on defining these terms and their underlying principles. Also the process of detecting and identifying failures will be described.

3.3.1 Definitions

Many documents and standards are available containing definitions of the important terms in this field, but there is no real consensus among these sources. This severely complicates both discussions and registration of failures (as discussed in the chapters on data analytics, reliability, and maintenance decision-making. Therefore, the standardized definitions from Meyer, Tiddens and Tinga (2025), combining all the relevant sources, will be used here:

Function intended purpose and characteristic action, expressed as a verb + object + performance requirement. An item can have one or more primary and secondary functions. *Example* - a pump is required to move water at 80m³/h flow and at 40m head (primary functions), and operate at above 70% efficiency (secondary function).

Failure loss of ability to perform a given function as required. If multiple functions are defined for a system or part, each can fail separately. *Example* - the impeller wear that causes pump inefficiency is accepted until it drops below the functional requirement threshold of 70%, in which case it becomes a failure of the function.

Failure event a failure is an event that occurs at a specific point in time. A failure may occur as a sudden event, or develop gradually, in which case the performance requirement defines the threshold that triggers the event. *Example* - the time at which the efficiency drops below the required 70% is the failure event.

Failure state or *Fault* when a failure event occurs, the item enters the failure state, which in many sources is denoted a fault. In this state, the performance is less than the performance requirement. Every function has one or more failure states and each state can have a different failure effect. *Example* - a pump bearing seizure event will reduce the pump flow to zero and the failure state will be "No Flow". Bearing wear with excessive vibration that forces the pump to operate at half speed will cause a failure state of "50% Flow".

Failure effect consequences of a functional failure. *Example* - loss of product containment (leakage) in a pump's mechanical seal has a different effect if it leaks water, or if it leaks a carcinogenic or flammable product.

3.3.2 Failure modes and failure mechanisms

From the definitions in the previous subsection it can be derived that most systems can fail in multiple ways. For many reasons it is important to distinguish between these ways of failure, e.g. in root cause analyses or when registering failures for future analysis work. The two most common ways of distinguishing these are by describing failure modes or failure mechanisms, as will be discussed in this subsection.

A *failure mode* is the manner in which a system functionally fails, i.e. describing to what extent a function cannot be fulfilled anymore. In terms of the definitions from section 3.3.1, a failure mode is defined as a combination of a failure event and a failure state. As an example: a "worn impeller" that reduces the pump efficiency below the required performance level. Failure modes can have both physical and non-physical causes.

A physical cause is the degradation or failure of a part, while non-physical causes include human errors, contamination and fouling.

Further, a distinction can be made between hard and soft failure modes. A hard failure mode directly causes a functional failure of a primary or secondary function, while a soft failure mode does not directly cause a functional failure, but accelerates the failure mechanism of another hard failure mode.

Finally, failure modes can be defined on different levels of hierarchy within a system. For example, a car can fail due to defects on the engine, tires or structure. But engine failures can again be subdivided into fuel, cooling or lubrication problems, while the issues in the cooling system can originate from the hoses, the pump or the wiring. This illustrates that the list of potential failure modes easily gets very extensive, even for relatively simple systems. Although many analysis methods, like Failure Mode and Effect analysis (FMEA, see the chapter on Failure Mode and Effect Analysis) rely on the identification of failure modes, it might not be the most convenient way, as will be discussed next.

An alternative way of analyzing failures is the identification of the underlying failure mechanism. A *failure mechanism* is a physical or chemical process yielding degradation of a component, ultimately leading to a physical failure. Also failure mechanisms may lead to both immediate failures or gradual degradation. Examples of failure mechanisms are corrosion, wear, static overload and fatigue. As the failure mechanism is defined at the material level, it is independent of the application. Fatigue failure can occur in an aircraft structure, in a bridge or in a rotating part in a compressor, but in all cases the mechanism is the same. This implies that, contrary to the failure modes, the list of potential failure mechanisms is rather limited. With a list of 15 to 20 failure mechanisms an estimated 90% of all failures in any system can be described. This makes failure mechanisms a convenient concept for analyzing failures. A complete overview and thorough treatment of their characteristics and details can be found in the book on this topic by Tinga (2013). Moreover, the chapter on Diagnostics and Prognostics will demonstrate how failure mechanisms can be used in model-based prognostics.

3.3.3 Fault Detection and Identification

As maintenance aims to solve or prevent failures, the fault detection and identification (FDI) process is at the core of maintenance. To quickly solve a system failure, and thus minimize the system down time, it is important that such a failure is detected in time, and it is known what type of failure occurred. Such a diagnosis supports the selection of the proper strategy for repairing or replacing the failed part.

Additionally, switching to a preventive rather than corrective maintenance policy is possible when the health of the system can be monitored. Maintenance tasks can then be triggered by this condition reaching a pre-defined threshold. This condition-based maintenance approach requires that faults (or degradation) are not only detected and identified correctly, but also require quantification of the severity.

A complete description of the fault detection and identification (FDI) steps, including the various health and condition monitoring techniques, can be found in the chapter on diagnostics and prognostics.

3.4 Maintenance strategies

Within an organization, a maintenance strategy (or maintenance concept) determines how the maintenance process will be organized, including the selection of the most suitable maintenance policies. These policies, discussed in more detail in section 3.5, prescribe the required maintenance tasks, activities and timing. In this subsection four commonly used maintenance strategies are briefly introduced.

3.4.1 Reliability Centered Maintenance (RCM)

The most famous maintenance strategy is the Reliability Centered Maintenance (RCM) concept proposed by Moubray (1997), which evolved from the development of a preventive maintenance plan for the Boeing 747 aircraft in the 1960s by the so-called Maintenance Steering Group (MSG-1). The RCM process entails a set of seven questions, which guide the maintenance plan development for a specific application:

- 1) What are the functions and associated performance standards of the asset in its present operating context?
- 2) In what ways does it fail to fulfill its functions?
- 3) What causes each functional failure?
- 4) What happens when each failure occurs?
- 5) In what way does each failure matter?
- 6) What can be done to predict or prevent each failure?
- 7) What should be done if no proactive ask can be found?

The first five questions identify the failure modes and their effects, and constitute a Failure Mode and Effect Analysis. Such a FMEA allows to prioritize the most critical failure modes. In the final two questions, a suitable maintenance policy is selected for each failure mode. Typically, a flow chart or other logical method is used to guide this selection process. Such a decision logic can be found in standards and handbooks, as well as in the RCM book by Moubray (1997).

3.4.2 Risk-based Inspection (RBI)

The risk-based inspection strategy is commonly used in the process industry and oil and gas sectors for systems like pipes and pressure vessels. For these assets, maintenance mainly implies the execution of periodic non-destructive inspections to guarantee safety. The RBI concept is applied to schedule these inspections based on the estimated risk of failure. Risk is defined as a combination of the probability of failure and the consequences of that failure. For high-risk assets the inspections will be executed more frequently than for low-risk assets.

3.4.3 Prognostics and Health Management (PHM)

Prognostics and Health Management is an approach that aims to provide guidelines for managing the health of the system throughout its entire life cycle. It has a strong focus on the predictability (i.e. prognostics) of failures and maintenance. This is generally achieved by adopting some monitoring strategy, which may be a condition monitoring (CM) or structural health monitoring (SHM) technique. The measured data is then

typically processed using data-driven prognostic approaches, like machine learning, but also physical model based prognostic methods have been developed. Refer to the dedicated chapter for more details on the various prognostic approaches, as well as on CM and SHM techniques.

PHM has a background in the military world, especially related to the development of the F-35 fighter aircraft in the 1990s - 2000s. However, PHM approaches are nowadays broadly applied in many sectors, e.g. in electronics and (civil) aerospace systems.

3.4.4 Integrated Logistic Support (ILS)

The final maintenance strategy discussed here is Integrated Logistic Support (ILS). As for PHM, ILS also focuses on the complete life cycle of an asset, enforcing to design the maintenance plan and associated logistic support system already during the design phase of a system. This strategy is therefore much broader than just maintenance, as also the required spare parts, facilities, training and documentation are considered. Within ILS, several analysis tools are available in the Logistic Support Analysis (LSA), like the Level of Repair Analysis (LORA) and the Maintenance Task Analysis (MTA).

The ILS concept also originates from the military world, but is applied much broader nowadays. In recent years the traditional ILS approach has been updated, and is now called Integrated Product Support (IPS). Further, a series of standards has been produced, called the S-Series of Integrated Product Support (IPS) specifications (*S-series of IPS 2025*). The main document is the SX000i, and additional standards are available for e.g. preventive maintenance program design, logistic support analysis (LSA) and training analysis and design.

3.5 Maintenance policies

Maintenance can be done in many different ways, depending on the criticality of the system, the facilities and technologies available, and the maintenance budget. A description of how maintenance is performed in a certain situation is denoted a maintenance policy. A maintenance policies thus prescribes the required maintenance tasks and activities, as well as their timing. Figure 3.2 provides an overview of the most common maintenance policies, where the main distinction between policies is in reactive, proactive and aggressive policies. The remainder of this section will discuss their characteristics and advantages.

3.5.1 Reactive policies

The reactive policies, of which traditional *corrective maintenance* is the main constituent, only trigger maintenance tasks after the system has actually failed. This implies that failures will regularly be faced, which makes this policy only suitable for non-critical systems, for which failures do not lead to severe consequences. However, the advantage of this policy is that the service lifetime of the component or system is fully utilized, and no remaining lifetime is spoiled by premature replacements. Moreover, the policy is simple in its execution: no monitoring or calculations are required, action is only needed when the system fails.

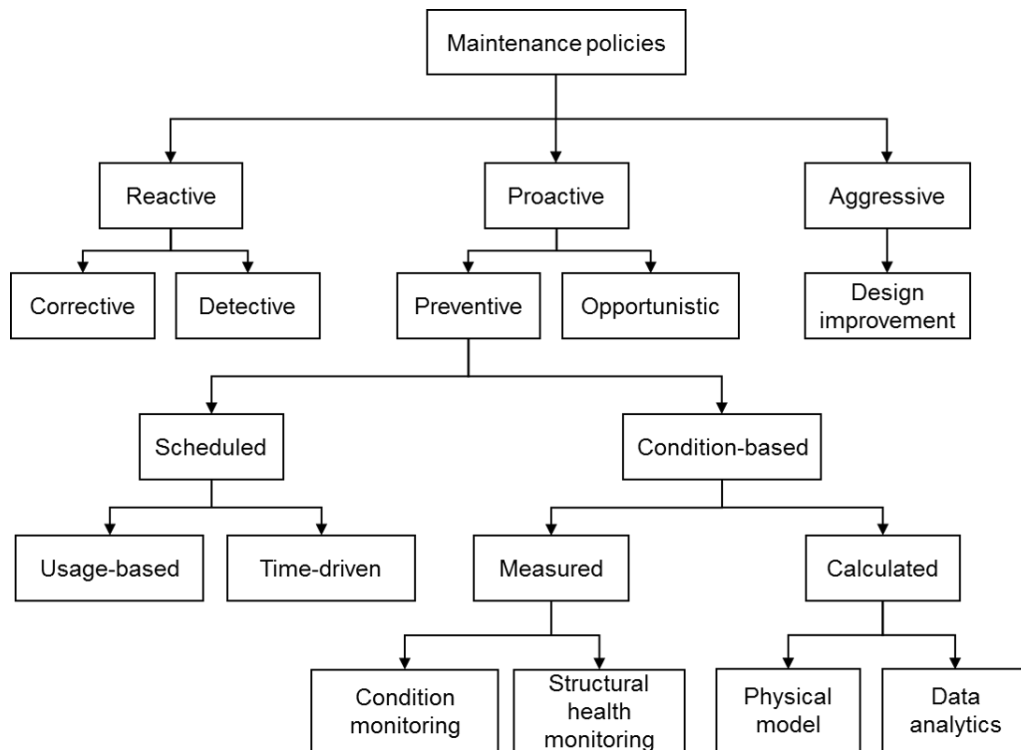


FIGURE 3.2 – Overview of maintenance policies

A special subclass of these reactive policies is *detective maintenance*, which is applied to systems with hidden failures. This means that the failure of the system is not immediately observable, but requires a test or inspection. An example of such a system is a fire alarm, whose failure would only be observed in case of a fire. Otherwise, periodic tests must be executed to detect potential failures, which will then trigger a maintenance task.

3.5.2 Proactive policies

This is the most important type of policies in the modern maintenance field, aiming to replace or repair a system before the failure actually happens. In this way, the consequence of the failure in terms of costs, downtime, or safety issues can be prevented. The general term for these policies is *preventive maintenance*, but there are many ways to implement this. The main distinction is between scheduled and condition-based policies.

In *scheduled maintenance*, the timing of maintenance is based on fixed or static intervals, that are determined for a complete population or fleet of systems before entering service. These intervals can be expressed in terms of either calendar time (e.g. every month / year) or usage (e.g. every 25000 km, 1000 operating hours). This implies that differences in the (severity of) use of individual systems is not taken into account, and conservative intervals are typically prescribed to ensure that also severely used systems are maintained before the actual failures occur. However, this also leads to over-maintenance, i.e. premature replacement of parts, for those systems that are less severely used.

In *condition-based maintenance* preventive tasks are triggered by the actual condition of (individual) systems. This ensures that each system is maintained at the right time and premature replacements are largely reduced. The resulting policy is therefore a dynamic maintenance policy, where maintenance intervals are only determined during operational use and continuously change. However, to enable such a policy, effort must be put in determining the condition of the system. As shown in Figure 3.2, again various options exist.

The first option is to directly measure the condition of the system by either condition monitoring or structural health monitoring. Although closely related, these techniques are typically used in different application domains. *Condition monitoring (CM)* is commonly applied to rotating equipment like engines, compressors, and pumps. Techniques like vibration analysis, oil / lubricant analysis and thermography have matured in the past decades and are very widely applied in industrial practice. *Structural health monitoring (SHM)* is commonly applied to large structures like bridges, aircraft and wind turbines. The dynamic behaviour (vibration) of these structures is measured over time with sensors, and changes in that behavior then indicate the presence of damage. More details on CM and SHM will be given in the diagnostics and prognostics chapter.

The second option is to calculate or estimate the condition of the system with a model or from data. This is also possible when no direct measurements of the condition are available, but either a model or a set of alternative sensor data (e.g. on how the system is operated) is required to allow the condition estimate. In a *model-based* approach, a physical model describing the relation between operational use and degradation of the system is used to calculate the system condition at any moment in time. Examples are fatigue, corrosion, or wear models. Alternatively, in a *data-driven* approach, the condition is estimated from a (large) set of (non-condition) data (e.g. temperature, pressure), using data analytics and AI approaches. When the condition obtained from the models or data is directly used to trigger maintenance tasks, it constitutes a regular condition-based policy. When the models or data are also used to predict the future degradation and remaining useful life (RUL), a *predictive maintenance* policy is obtained, as will be discussed in more detail in section 3.6, as well as in the chapter on prognostics.

Finally, also the *opportunistic maintenance* policy is in this branch of Figure 3.2. In such a policy, maintenance is triggered by an opportunity that appears to efficiently or conveniently perform a maintenance task. In many complex systems, replacing a component typically requires many preparatory tasks, like opening hatches and removing other parts, but also traveling to the fielded system. When another part in the same system, located close to the maintained component, needs maintenance in the upcoming period, it is much more efficient to take the opportunity now to also replace that part. The much reduced effort for preparatory tasks then easily compensates for the slight waste of remaining life time of the part.

3.5.3 Aggressive policies

The final branch of policies in Figure 3.2 is denoted aggressive. This is a very expensive maintenance policy, aiming to ensure a very high level of safety by continuously re-engineering the system. As soon as a specific failure occurs, the system is modified or redesigned in such a way that the specific failure can never happen again. This can, for example, be achieved by choosing better materials or increasing the dimensions of certain components. Due to the high costs of *aggressive maintenance*, this policy is only applied to very critical systems, like a nuclear power plant.

3.6 Maintenance maturity

The previous section has introduced the various maintenance policies that are available. Each organization has to select the policy that best suits the considered system and organization. This is associated to the maturity level of the organization and the ambition it has, as will be discussed in this section. The next section will then introduce a decision support method for selecting the best fitting policy.

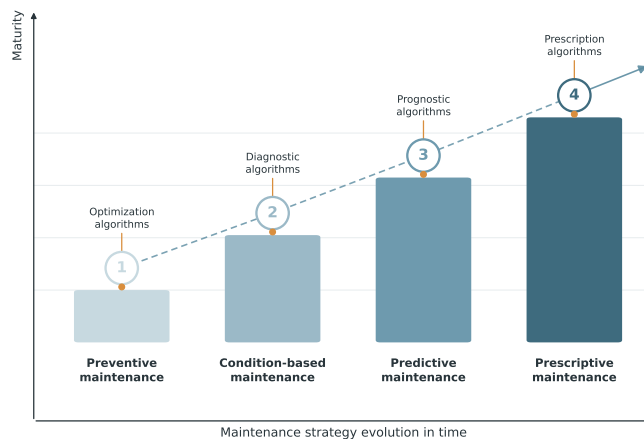


FIGURE 3.3 – Increasing maturity levels in maintenance (modified from Errandonea et al. 2022)

3.6.1 Maturity levels

Over time, maintenance has developed from traditional corrective maintenance in the 1950s to more advanced preventive maintenance in recent decades. Also within companies this evolution can often be observed, where the maturity of the maintenance processes gradually increases. The maturity of maintenance can be divided in five levels as proposed by Errandonea et al. (2022) and shown in Figure 3.3:

- 1) **Reactive:** at this level only corrective maintenance is executed, just reacting to systems that fail;
- 2) **Preventive:** systems are replaced or repaired in a scheduled manner, (far) before expected failure;
- 3) **Condition-based:** maintenance is only performed when the (monitored) condition of the system falls below a certain threshold;
- 4) **Predictive:** the expected future moment of failure is assessed periodically, and based on this the just-in-time replacement or repair is executed;
- 5) **Prescriptive:** not only the time to failure (predictive) is determined, but also the required maintenance action is prescribed;

Although companies typically aim for the highest maturity level, for many applications the most advanced maintenance approaches are not really needed. For machines that are operated in a fixed daily or weekly pattern, failure rates will be rather constant and a scheduled maintenance policy will be quite effective. In those cases

there is little need for more advanced policies that require the (more expensive) collection and analysis of data. Therefore, each organization should be very aware of the ambition level it has for its maintenance activities, as will be discussed in the next subsection and section 3.7 on the policy selection.

3.6.2 Ambition levels

As was mentioned before, it is important for companies to think about what they want to achieve with maintenance. This is called the ambition level, which should be set at a realistic level. When the ambition level is set too high, time and money will be spent on something that is not really needed. Therefore, the following four ambition levels should be distinguished (Tinga 2026):

- 1) **Detection of failures: Is something wrong ?** This activity focuses on the automatic detection of failures (e.g. from sensor readings). The benefit is that the consequences of undiscovered failures can be prevented, thus reducing the impact of failures, especially in more complex systems. In terms of data analytics this is typically an anomaly detection problem.
- 2) **Diagnosing failures: What is wrong ?** This activity focuses on getting more information (from sensor data) than only the occurrence of a failure. Automatic identification of the specific failure mode (out of multiple potential FMs) that occurs in a system yields considerable benefits, as the time required to find the fault and decide on the appropriate maintenance task will be considerably reduced. In terms of data analytics this is typically a classification problem.
- 3) **Health assessment: How wrong is it ?** This activity takes one step further than determining what failure mode is active, as it also assesses the severity of the occurring failure. Rather than a binary (failure mode active / not active) a continuous assessment of the failure or degradation is performed. Both a direct condition measurement (SHM or CM), or an indirect assessment from (sensor) data can be utilized. The determined condition can be compared to a selected threshold value, leading to a condition-based maintenance policy.
- 4) **Prognosis: When is it expected to go wrong ?** Contrary to the previous ambition levels focusing on assessing the present condition, this activity focuses on predicting when the system is going to fail in the future. This implies that the remaining useful life (RUL) is assessed, which can be used to timely plan the required maintenance tasks.

3.7 Advanced maintenance policy selection tools

In the previous sections many different maintenance policies have been introduced, and a range of maturity and ambition levels has been discussed. This implies that the selection of the best fitting maintenance policy for a specific application is not a trivial task. For that reason, several decision support tools have been developed that can guide practitioners in this process.

The first tool addressing this challenge for predictive maintenance policies was proposed by Tiddens, Braaksma and Tinga (2023), and is shown in Figure 3.4. On the horizontal axis five different ambition levels are indic-

ated, that are connected to certain maintenance techniques (MTs), i.e. type I to V. At the lowest ambition level, AL1, a practitioner wants to predict the average time to failure for a fleet of systems (typically denoted as Mean Time Between Failures - MTBF). This implies that no distinction is made between individual systems in the fleet, and specific operating conditions are not incorporated. At the other end of the spectrum, AL5 specifies that the practitioner wants to predict the RUL of a specific system operating in specified conditions that have not been observed before. The tool shows that AL1 can already be achieved with a rather simple MT, i.e. an experienced-based approach, while AL5 requires the most advanced MTs, like physical-model based or data driven (AI) approaches.

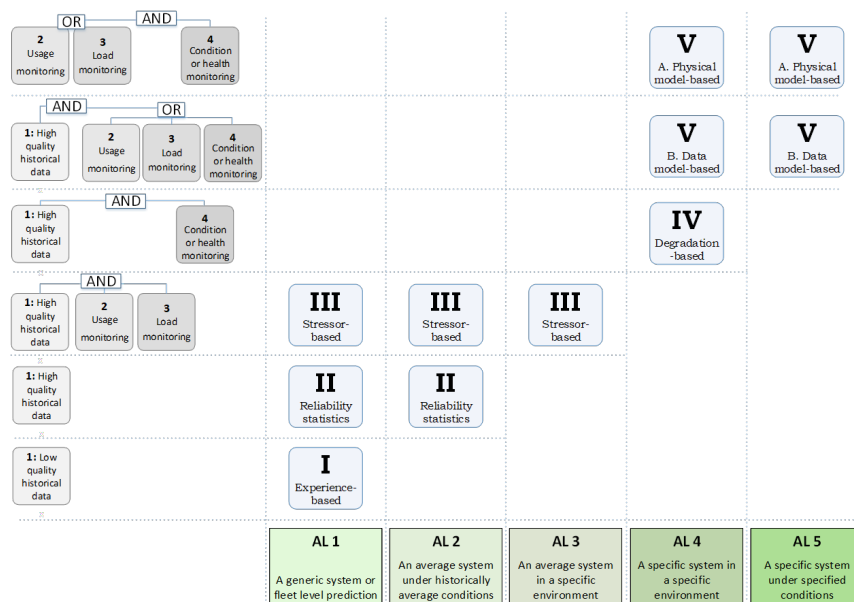


FIGURE 3.4 – Matching ambition level with data availability (Tiddens, Braaksma and Tinga 2023)

At the same time, the tool specifies what each of the MTs requires in terms of (the amount and quality) of data and knowledge. The more advanced MTs also require more and more detailed data, as is shown on the vertical axis of the figure. The key aspect of this tool is that the ambition level and data availability should match. If this is not the case, the implementation of that MT will fail, and stakeholders will get frustrated. Using this tool, an assessment of the feasibility of a certain MT can be made in advance. If the required data appears to be missing, either the ambition level should be lowered, or additional effort must be put in collecting the required data.

More recently, this tool has been extended into a kind of expert system (Alves da Silveira, Meghoo and Tinga 2024). By going through a list of questions on the application, ambition and availability of data and knowledge, the tool provides scores for the *Suitability* and *Feasibility* of six different maintenance techniques. An example of such an assessment is shown in Figure 3.5.

Answers		EB	RS	CE	SB	DA	PB
Is the selected approach required to provide lifetime prediction...	Answer	Result score					
(A1) ... for individual systems? (No for fleet average values).	Yes	0	0	2	2	2	2
(A2) ... for generalized cases?	No	2	2	1	1	1	1
(A3) ... for varying operational conditions?	Yes	0	0	1	2	2	2
(A4) ... for operational conditions that were not observed previously?	No	2	2	2	2	2	2
(B1) ... with only limited accuracy (i.e. a rough estimate)?	Yes	2	2	0	1	0	0
(B2) ... including insight into which parameters play an important role in the prediction?	Yes	0	0	0	2	2	2
(C1) Is an expert with practical experience available?	No	0	0	0	0	0	0
(C2) Is a specialist/ analyst available?	No	0	0	0	0	0	0
(C3) Is a data scientist available?	Yes	0	1	1	1	2	0
(D1) Are the (physical) degradation mechanism and the parameter(s) describing its evolution known ?	Yes	0	0	2	0	0	2
(D2) Is a stressor-base model available?	Yes	0	0	0	2	0	0
(D3) Is a physical model available?	No	1	1	1	0	1	0
(E1) Is run-to-failure sensor data available?	Yes	1	2	1	2	1	1
(E2) Is load/usage data available? Such data should cover the entire analyzed system.	Yes	0	0	1	1	2	1
(E3) Is historical failure data available?	Yes	1	1	2	2	2	2
(E4) Is a threshold value available?	No	0	0	0	0	0	0
(E5) Is real-time or periodic condition monitoring information available?	No	0	0	0	0	0	0
(E6) Are systems monitored individually (usage, loads, situation)?	Yes	0	0	2	0	2	2
(E7) Future operational conditions similar to past?	Yes	2	2	2	1	2	2
Total (T_S)		0	0.62	0	0.76	0.81	0
Suitability (S_S)		0.55	0.55	0.60	1.00	0.82	0.82
Feasibility (F_S)		0	0.70	0	0.60	0.80	0

FIGURE 3.5 – Decision support tool for predictive maintenance policy selection (Alves da Silveira, Meghoo and Tinga 2024)

3.8 Case studies

3.8.1 Differences between industries

Maintenance requirements will differ for each asset in any type of industry. However, the generic concepts of failure modes and failure mechanisms, as well as the introduced maturity and ambition levels, are generic across industries. Also the decision support tools for maintenance policy selection can be generally applied, as will be demonstrated for some cases in this section.

3.8.2 Challenges

As more and more maintenance policies are developed and proposed, the selection of the best fitting policy becomes more complex. For practitioners it is therefore very important to thoroughly analyze their asset or system, its criticality, but also the available (sensor) data and knowledge. The combination of all these aspects will determine what the best option is.

Practitioners should be aware that the most advanced policy, e.g. predictive maintenance, is not always the best choice. For many non-critical systems a scheduled preventive maintenance policy, or even a corrective maintenance policy, will normally do the job, and is typically much cheaper and easier to implement. The challenge therefore is to properly characterize the case at hand, and choose the policy in a well-motivated manner. The decision support tools introduced in section 3.7 can assist in that process, preventing the selection of a policy that would appear to be infeasible later on.

3.8.3 Maintenance policies in the railway sector

In the railway sector many different types of assets are used, ranging from rather static infrastructure elements like track sections to highly technological trains consisting of complex assemblies of mechanical and electronic systems. And since most of these assets are rather (safety) critical, it is crucial to apply an effective maintenance program that ensures safe and economical operation of the complete system. It may also be clear that there is not one single maintenance policy that can be applied to the full range of assets. As has been shown in this chapter, the characteristics of the asset and its environment will determine in each case what the best option is.

For example, the track is a static infrastructure that gradually degrades over time. Especially the rail degradation will be dependent on the operational conditions, i.e. on the number and weight of trains passing that section. Due to its criticality (safety), corrective maintenance is no option here, so any form of preventive maintenance should be applied. The potential maintenance actions are either repairing (grinding, machining) or replacing the rail. The timing of these tasks can be based on a fixed schedule, as was traditionally done. However, as not all sections are used equally, more recently maintenance actions are based on usage parameters like the mean gross tonnage (MGT). Alternatively, as the condition of a rail bar can be measured with non-destructive inspection techniques, like ultrasonics or eddy current, also a condition-based maintenance policy can be applied. In that case the grinding interval can be based on the actual measured degradation state. A similar approach is followed for switches, where deviations in the measured electric current and voltage in the switch motor are indicative of increased resistance and associated degradation or even failure.

For trains, the traditional approach is to execute periodic overhauls, based on either calendar time or driven kilometers. In such overhauls, all systems are maintained, even when not yet necessary, as such a clustering of activities is both economically and from a scheduling perspective more attractive. More recently, increased numbers of sensors are available in on-board systems. By monitoring the associated data, more real-time insights on the state of systems like HVAC, engine and electronics can be obtained, which also allow scheduling of short maintenance tasks in between overhauls. In most cases, the data is only used to detect failures and assess the present state of these systems. Then a diagnostics approach can be applied, resulting in a condition-based maintenance policy. In some limited cases the data is combined with a (data or physics-based) model to predict future failures, which yields a predictive maintenance policy.

3.9 Future perspectives and conclusions

This chapter introduced the basic concepts of failures, faults and availability, and provided an overview of the most common maintenance strategies and maintenance policies. Although new policies will be introduced in the future, a thorough understanding of the underlying basic concepts will allow practitioners to assess these new policies. Further, the discussed decision support tools will assist in policy selection, where a proper match between ambition level (associated to system criticality) and available data and knowledge is crucial.

Assignments

- Assignment 1: Explain the difference between *availability* and *reliability* of a system.
- Assignment 2: What is the difference between a failure *mode* and a failure *mechanism*?
- Assignment 3: Explain what the role of the Failure Mode and Effect Analysis (FMEA) is in the Reliability Centered Maintenance strategy.
- Assignment 4: What are the pro's and con's of corrective, preventive and condition-based maintenance?
- Assignment 5: Explain how each of the four ambition levels in maintenance are associated to types of data analysis, and what the implications for data requirements are.

Further Reading

If you would like to explore the concepts discussed in more depth, the following resources are available.

- **Moubray, J., Reliability Centered Maintenance. 1997. Industrial Press. ISBN: 978-0-8311-3146-3**
This book describes the principles of RCM, which forms the foundation for many modern maintenance policies. Clear definitions of functions and failures of systems are given, and the failure mode and effect analysis (FMEA) is shown to be the starting point of a maintenance policy selection process.
- **Mobley, R.K., An Introduction to Predictive Maintenance, 2nd edition, Butterworth-Heinemann, 2002.**
This book provides an introduction to maintenance in general, with a special focus on condition monitoring and health assessment techniques to be used for predictive maintenance.
- **Tinga, T., Smart and Predictive Maintenance - From theoretical concepts to practical tools and applications. To be released in 2026.**
This book provides a detailed treatment of all smart and predictive maintenance approaches and theory, starting from the basic concepts and theories of physics-of-failure, reliability engineering and data ana-

lytics, and advancing to diagnostics and prognostics approaches and methods. Also practical tools to implement these theoretical concepts in practice are provided.

- **Ben-Daya, M., Kumar, U. and Murthy, D.N.P., Introduction to Maintenance Engineering: Modeling, Optimization, and Management. John Wiley & Sons, Ltd., 2016.**

This book provides an introduction to the main concepts in maintenance, and discusses several technologies and models to be used in maintenance engineering.

Guided solutions

This section provides hints and solutions to the assignments presented earlier. Rather than just giving direct answers, it offers explanations and key insights to help reinforce learning. Use these solutions as a guide to verify your work and to deepen your understanding of the concepts.

- Assignment 1: availability reflects the fraction of (the past) time that the system has been in an up-state, and is therefore looking backwards. Reliability indicates the probability that the system will be in an up-state at any moment in the future.
- Assignment 2: a failure mode is always related to the function of the (sub)system, and can therefore be defined at many hierarchical levels (system, subsystem, component). On the contrary, a failure mechanism is always defined on the material level, and is therefore independent of the application that is considered.
- Assignment 3: the five questions raised in a FMEA constitute the basis of the seven RCM questions.
- Assignment 4: the text in section 3.5 explains all details of these policies. Pro's and con's particularly reflect the timeliness of maintenance tasks and the associated efforts to determine the moment of maintenance execution.
- Assignment 5: data analyses develop along the line anomaly detection, classification, condition monitoring to regression analyses, requiring gradually more complete and advanced data sets.

References

- Alves da Silveira, N.N., A.A. Meghoo and T. Tinga (2024). 'Quantifying the suitability and feasibility of predictive maintenance approaches'. In: *Computers & industrial engineering* 194. doi: 10.1016/j.cie.2024.110342.
- EN13306:2001 (2001). *Maintenance Terminology, European standard*. Generic.
- Errandonea, I. et al. (2022). 'A Maturity Model Proposal for Industrial Maintenance and Its Application to the Railway Sector'. In: *Applied Sciences* 12.16.

- Meyer, W., W. Tiddens and T. Tinga (2025). 'A framework for Standard Failure Modes: unambiguous classification of failure events as a prerequisite for predictive maintenance models'. In: *to be submitted*.
- Moubray, John (1997). *Reliability centered maintenance*. Industrial Press. ISBN: 978-0-8311-3146-3.
- S-series of IPS (2025). <http://https://www.s-series.org/>. Accessed: 2025-10-20.
- Tiddens, W., J. Braaksma and T. Tinga (2023). 'Decision Framework for Predictive Maintenance Method Selection'. In: *Applied Sciences* 13.3. doi: 10.3390/app13032021.
- Tinga, T. (2013). *Principles of loads and failure mechanisms. Applications in maintenance, reliability and design*. English. Springer Series in Reliability Engineering. Germany: Springer. ISBN: 978-1-4471-4916-3. doi: 10.1007/978-1-4471-4917-0.
- (2026). *Smart and Predictive Maintenance. From theoretical concepts to practical tools and applications*. Netherlands: publisher TBD.





Image credits

Cover image: Werkzaamheden op emplacement Westhaven **ProRail/Gerrit Serné †**

Part I - Introduction (p. 1): Bovenleidingswerkzaamheden **ProRail/Chantal van den Berg**

Chapter 1 - Time for a new way of doing maintenance (p. 2): Meetwerkzaamheden aan het spoor
ProRail/Vincent Basler

Chapter 2 - Asset management (p. 16): Corporate fotografie - OCCR **ProRail/Lorraine Bodewes**

Chapter 3 - Maintenance (p. 48): Station Dordrecht Zuid **ProRail/Shane van Hattum**



This book is for everybody who wants to apply the state of the art in the fast-evolving field of maintenance. It is high time for a new kind of doing maintenance, because our society needs it and the theories and applications exist. The irony of maintenance is that when maintenance is done perfectly, nobody notices it. While when, on the contrary, it fails completely, then our entire society comes to a standstill. Bridges collapse, trains don't run, factories cannot produce, energy is failing, communication becomes impossible, hospitals can't work and even agriculture stops. Such scenarios are becoming more realistic every day, as aging assets and workforce combine with greater environmental and political instability.

The good news is that maintenance can be done much smarter and better than current practice. Indeed, smart maintenance can make an active contribution to more sustainable solutions all along the life cycle of assets. This new way combines intensive use of both digitization and social innovation. This book shows the many aspects of this new kind of maintenance. It introduces theories and practical insights from a wide variety of fields. From engineering, its founding discipline, but also from information systems, as smart maintenance leverages digitization and data. And from economics and management, because often business reasons limit innovation in maintenance. Last but not least, also human and organizational behavior is crucial for successful use of smart maintenance and this book also contains key insights from these fields.

The 20 chapters in this book form the joint achievement of over two dozen authors from a variety of academic backgrounds, mostly from Dutch universities and knowledge institutes. This book forms the tangible culmination of a 15-year long fruitful collaboration, under the guidance of the Dutch World Class Maintenance foundation. Its primary intended use is education at the university Bachelor level, both for regular and life-long learning education, but this Open Access text can be used in a wide variety of educational contexts.

**OPEN
PRESS
TiU**




**WORLD CLASS
MAINTENANCE**

