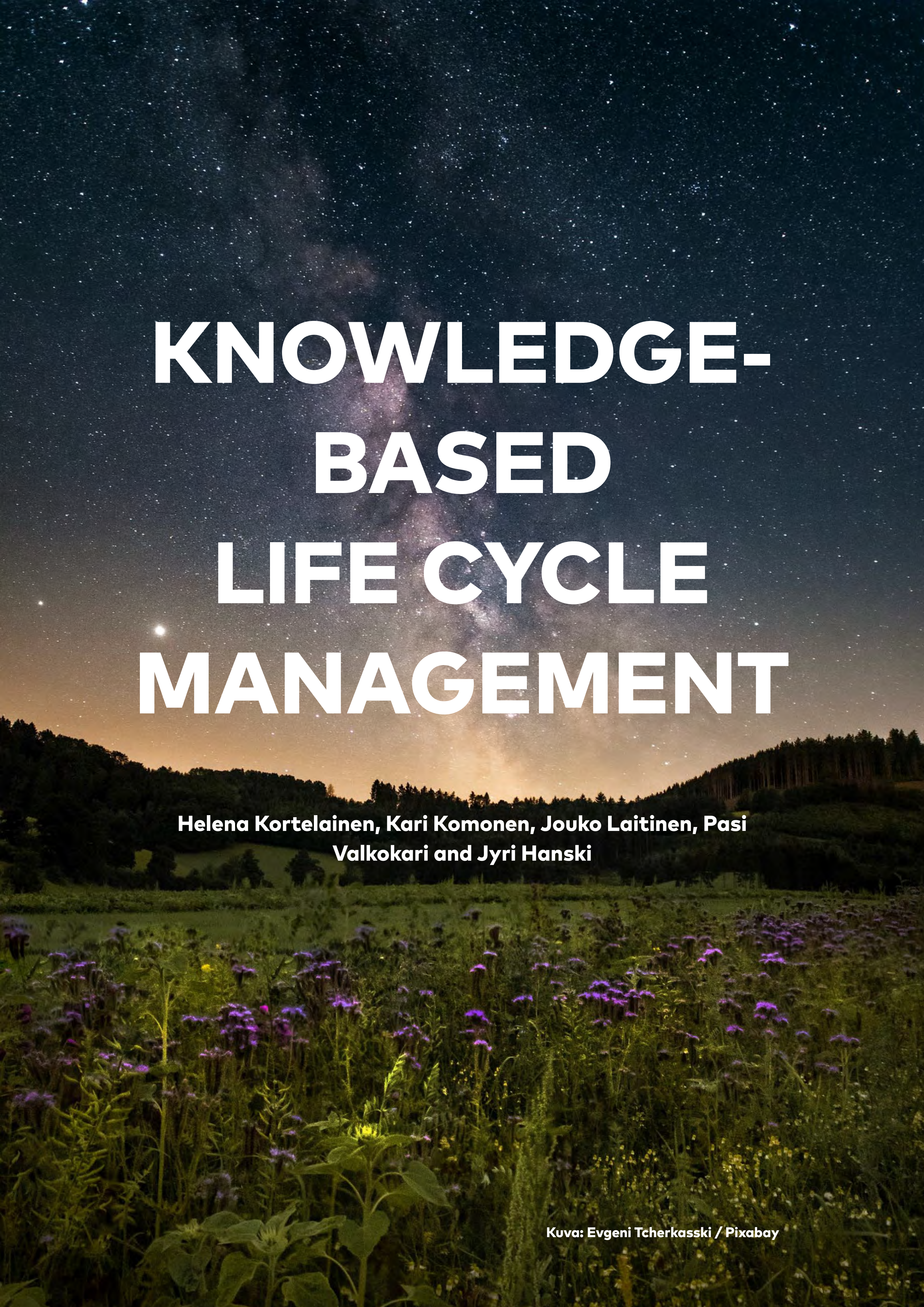

KNOWLEDGE-BASED LIFE CYCLE MANAGEMENT

Helena Kortelainen, Kari Komonen, Jouko Laitinen, Pasi Valkokari and Jyri Hanski

Kuva: Evgeni Tcherkasski / Pixabay

1st edition, March 2021

Publisher
Kunnossapitoyhdistys Promaint ry | Messuaukio 1 | 00520 Helsinki
www.promaint.net

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ISBN 978-952-65320-0-4

TABLE OF CONTENTS

INTRODUCTION

Helena Kortelainen, Kari Komonen, Jouko Laitinen, Pasi Valkokari and Jyri Hanski

Why is life cycle and lifecycle management important?

Product lifecycle management is one of the key challenges for the manufacturing industry: the efficiency and performance of products must meet the initial customer requirements and they must be improved and maintained throughout their life. Companies have identified new business opportunities in this area and have invested in the development of life cycle services. Product lifecycle management encompasses the entire product life cycle from its conception to its use, to its disposal and eventual reuse. To a large extent, lifecycle management is also an end-user activity and a key element of asset management. Good practices in lifecycle and asset management support the decision maker in weighing up, for example, the benefits of introducing a new technology and improving system performance against the costs and risks of acquisition and use. This book examines life cycle and lifecycle management models and management methods from the perspective of different stakeholders, with an emphasis on exploiting data, information, and knowledge in decision making.

What is the life cycle?

The word 'life cycle' has several meanings depending on the context. In engineering domain, life cycle refers to the identifiable life cycle stages, which in general terms are concept, development, realisation, use, enhancement, and retirement. In business context, commercial life cycle starts as the product is launched to the market and ends as market demand and manufacturing ends. In environmental sciences, life cycle refers to the flow of energy and materials through manufacturing system from raw material in ground, through processing to shape, assembly of finished product and disposal following use. This is often referred to as 'cradle to grave' thinking. In this book, the focus is in the technical life cycle but also the other aspects of product or asset system life cycle are addressed.

Change trends

The importance of the life cycle is underlined by several change trends we are aware of, such as the sustainable use of natural resources, climate change, changing business models, digitalisation, and the advance of globalisation. Increasing uncertainty in the business environment and rising demands, for example in terms of safety and environmental impacts, are also important drivers. When investing, companies tie up significant amounts of capital by acquiring products and systems whose costs and returns will be realised in the uncertain future. Decision-making in a rapidly changing business environment, under pressure from changing and increasingly stringent requirements, calls for the ability to anticipate and prepare for change. At the procurement stage, the user must anticipate the cost of maintaining the product, which over years – or even decades - can exceed the initial purchase price many times over. Lifecycle management helps to set the milestones for what costs, requirements and revenues or benefits can be expected in the future.

The sustainable use of natural resources and the looming shortage of many key raw materials are raising the importance of lifecycle management. Extending the lifetime of machinery and equipment improves resource efficiency, but also requires investment in lifecycle management activities such as maintenance, renewal and upgrading investments and technical performance of systems. The circular economy, which emphasises the reuse and recycling of materials, is based on the principles of sustainable development and seeks to address the challenges of a linear 'make-use-dispose' economy. Lifecycle management is also an enabler for the continued use of machinery and equipment in a new application.

Business models are also evolving. Design and engineering phase is often collaborative, product supply chains are long and global, and asset systems are often maintained by variety of service providers and other partners. Taking account of the different stakeholders - both in design and operation - is challenging because of the large number of parties involved, with their own requirements and expectations. Product development and design may be carried out simultaneously in several countries, even on several continents, and dozens of different companies may be involved in different phases and activities of the engineering process. and the novel requirements must be concerned already in the design phase. The demands for the item reliability will increase as the operating and maintenance staff is no longer at the site but monitor the operation from control rooms, which may be located far away.

Lifecycle management, with its policies, models, and methodologies, helps the decision-maker to optimise performance requirements and the costs inevitably associated with maintaining performance, and to assess the risk associated with future uncertainty. System life cycle planning, scenario analysis and the search for robust solutions are particularly important when investing in new technologies with limited field experience and uncertain maturity. A systematic system lifecycle management plan helps to reduce risk and supports decision making.

The growing importance of data and knowledge

Data in its various forms is a key enabler of lifecycle management. Lifecycle management is a very long-term activity: an aircraft or industrial asset system can have a lifetime of decades, and infrastructure structures can be designed for a lifetime of up to 100 years. Lifecycle management therefore requires a very wide range of information and systematic and long-term data management. Comprehensive, high quality and reliable data is needed for planning, for controlling activities during the use phase and to support business development at strategic level. Through Industry 4.0 solutions, components, products, processes, and entire production systems are interconnected so that related information can be monitored and even controlled in real time. Industry 4.0 is part of a wider phenomenon, the digitalisation process, which spreads digital information technologies in everyday life both to consumers and to industrial end users. Digitalisation shifts the focus from data collection to data exploitation. Data is not enough; the focus is on knowledge - the ability to structure and interpret data.

Background of the book

The knowledge-based lifecycle management book draws on the authors' long experience in lifecycle and asset management, and in RAMS research and development. For this reason, we have compiled not only the theory but also numerous examples of practical applications from different industries. In recent years, several standards have also appeared on the market focusing on the efficient and economic management of the life cycle and maintenance of asset systems, machinery, and equipment. The following paragraphs briefly present recent research and standardisation projects that have led to the book.

SmartOtaniemi

Smart Otaniemi[1] is an ecosystem driven by energy systems transformation. SmartOtaniemi seeks new opportunities to transform the energy sector in cooperation with other business sectors. Ecosystem projects develop new energy production and storage technologies towards smarter, more efficient, sustainable, and economically viable solutions. SmartOtaniemi explore the challenges of smart grids from a lifecycle management perspective, and the potential and benefits of new technologies to support grid maintenance.

Digitalisation brings sustainable value to the forest industry - SEED

The SEED[2] ecosystem aims to develop methods and tools for business-driven asset management and to increase productivity by using digital solutions. At the core of the SEED ecosystem development are operational efficiency, digital twins and productivity, future work, and tacit knowledge, and leveraging platform economy. In the SEED ecosystem, forest companies open their doors to application developers and research.

Developing the efficiency of logistics systems and new business models in a port environment - Autoport

The Autoport[3] is developing solutions for data-driven RAMS requirements management, among other things. The project develops new approaches to the challenges of managing risk in the design phase, in particular systemic risk. As systems become more automated and autonomous, new ways of managing risk and safety are needed.

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[1] Smart Otaniemi, see https://smartotaniemi.fi/

[2] SEED, see https://seedforest.fi/

[3] Autoport, see www.autoport.fi

Managing reliability in design - RelSteps

RelSteps-project was developing a dependability management toolkit for the needs of manufacturing industry. The toolkit addresses the dependability management needs of different products and product development projects, and the tools can be integrated into the company's R&D process.

From data to wisdom - Methods to enable the circular economy

At the heart of the Data to wisdom-project[4] are the information flows enabling the circular economy. The project developed methods to create, identify and exploit the data needed to make the circular economy a reality in a completely new way. The project contributed to the refinement the data into wisdom, the ability to act to implement new circular economy business models.

Aircraft Structural Management (Finnish Defence Forces)

Research projects on fleet structure management investigate the reliability of aircraft equipment using both statistical and neural network methods. In support of the maintenance development of aircraft fleets, the projects developed the Foxtrot analysis computer program, which allows for a quick study of equipment reliability, and the Aida program, an EWS (Early Warning System) computer program based on learning machines, which warns of impending equipment failure.

Service Solutions for Fleet Management

Service Solutions for Fleet Management research programme[5] supported the digital transformation of industrial companies towards advanced fleet-level service providers. Among other objectives, the research investigated and developed methods to support maintenance decisions for the F/A-18 Hornet fighter. Process data from the aircraft was used as a data source. The main objective was to detect potential failures before they developed into failures prevent the aircraft from operating.

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[4] Data to wisdom, see https://projectsites.vtt.fi/sites/datatowisdom/

[5] Service solutions for fleet management, see the final report https://www.dimecc.com/final-report-s4fleet-service-solutions-for-fleet-management

Standardisation

Asset management has been an important focus of standardisation in the 2010s. Management system standards have gained a new asset management product family, which includes ISO 55000 (2014), 55001 (2014) and 55002 (2018). The ISO/TC251 project team has been responsible for this project. Maintenance of physical assets is an important part of asset management. In this area, CEN/TC 319 has developed standards that provide a strong basis for quality management of maintenance.

In the IEC 60300 product family, the IEC has defined a wide range of standards related to dependability management, covering all aspects of dependability from management to individual methods. Life cycle costing is also included in the IEC offering. The IEC 60706 product family focuses on the management of the maintainability of assets.

In addition to the above, there are several other individual ISO and IEC standards related to the management of physical assets. These include standards for instance, for quality management, risk management and outsourcing.

Structure of the book

Knowledge-based lifecycle management book consists of five parts the last one being dedicated to the terminology. The parts 1-4 of the book consist of individual chapters that also function as independent entities, so there is some repetition in the book. The authors of individual chapters rely on their own literature and other sources and standards, and there is no attempt to harmonise the terminology used in the different chapters. The literature references are collected to the end of each part.

The first part of the book (Part 1) covers the concepts and basics of life cycle and lifecycle management, as well as safety, RAMS, and risk management. It introduces the modelling of life cycle costs using reliability and its components, as well as different life cycle models, lifecycle management tasks and model applications. The life cycle and life cycle models are considered from the perspective of both the manufacturer and the end-user of the product or system. The importance of the system definition and conceptual design phase is emphasised in both reliability and safety design. In capital-intensive industries and for many infrastructure and other technical systems, the life cycle is often very long, up to decades, so stakeholder interaction and collaboration at different stages of the life cycle is important and complex. Part 1 also describes circular economy solutions, as lifecycle management and the circular economy share the same objectives and approaches, aiming at an efficient use of resources. Part 1 also presents the main methodologies used to assess the performance of lifecycle management, including Overall Energy Efficiency (OEE), Life Cycle Cost (LCC) and Life Cycle Assessment (LCA).

The second part of the book (Part 2) deals with the management of physical assets (productive assets), of which lifecycle management is a key part. It begins with an attempt to introduce the central content and concepts of productive asset management. Next, the tools for modelling an organisation's operational and technological environment and the impact of the operational and technological environment on asset management are examined. Building on the above, a methodology for defining a requirement for productive assets is presented. Chapter 2.3 of Part 2 examines investment decisions and the calculation methods involved, and their suitability for different situations. Next, the definition of a maintenance strategy within the framework of productive asset management is examined. An important part of the definition of the maintenance strategy is the definition of the criticality of the equipment. As management is faced with decisions in increasingly complex environments, the asset management perspective will be extended by examining its important strategic dimensions.

The third part of the book (Part 3) focuses on the acquisition, processing, analysis, and use of information essential for lifecycle management. With digitalisation, the focus shifts from data collection to data exploitation. In addition to the key information systems (PDM, PDM, CMMS and EAM systems), it looks at condition monitoring and information system interfaces and database architectures. Methodologies for collecting expert knowledge and so-called tacit knowledge will also be examined. The focus is on describing methods for analysing and processing data, starting with the application of descriptive data analysis to stochastic simulation. It also looks at the exploitation of data, from the perspectives of the system user, manufacturer and supplier and service provider. Finally, an overview of future development perspectives and needs is provided.

The fourth part of the book (Part 4) presents lifecycle management methods and solutions through practical examples. The examples collected in Part 4 cover the different stages of the life cycle, from identifying development needs using foresight methods to presenting circular economy business models. The product design phase is considered both through the delivery process and through the product development project and maintainability planning. For the use phase, examples of investment selection and replacement investment planning will be discussed. The deployment phase also involves the development of the production system, where new technological solutions and their successful implementation are key. Part 4 also presents models and methodologies for decision support, such as life cycle costing of the system to be acquired and robust strategic asset management models.

In addition to the substance parts, a part collecting the key terms, concepts, and definitions (Part 5), is included in the book. The terminology related to life cycle and lifecycle management is varied and application specific. Commonly applied standards may offer different definitions for key terms. For this reason, we have compiled the commonly used terms with their definitions into a separate section.

Significance and use of the book

On average, manufacturing companies spend around 5% of their turnover on maintenance. In this case, only direct maintenance costs, such as wages and spare parts, as well as purchases of external services and purchases, are included in maintenance costs. A recent master thesis[6] estimated the value of industrial maintenance in Finland at around €4.1 billion, with infrastructure maintenance spending around €2.1 billion and facility maintenance spending around €7.6 billion annually. The monetary value corresponds to 1,9 percent of Finnish GDP. According to the survey, the business volume of maintenance services and spare parts for the Finnish TOP500 companies amounted to around EUR 12.3 billion, most of which was generated outside the country. The economic importance of life cycle and asset management is therefore considerable.

Several textbooks and guidebooks have been published in the areas of lifecycle management, maintenance, production assets and reliability, such as System Reliability Theory (2009) by Høyland & Rausand, Physical Asset Management (2015) by Hastings, and Reliability-Centered Maintenance (2001) by Moubray. There are also numerous works available on product knowledge management, such as Stark's Product Life Cycle Management - 21st Century Paradigm for Product Realisation (2006).

In **Knowledge-based Lifecycle Management**, we look at lifecycle management issues from a multidisciplinary, management and knowledge-based decision-making perspective. We aim to highlight:

- Lifecycle management tasks and objectives and cooperation between stakeholders.
- The importance of security, safety, and risk management.
- Defining requirements for physical assets based on critical success factors in the business and technology environment.
- Defining maintenance strategies as an important part of lifecycle management.
- The diversity of knowledge and skills required to manage the life cycle.
- The growing importance of data, refinement and enrichment of the data, and the exploitation all forms of data in business.
- Statistical and mathematical foundations of data modelling.

The book is intended as a textbook and handbook for university and university of applied science courses in lifecycle management and engineering, asset management, as well as for continuing education in these fields. For this reason, the main content of each chapter is summarised at the end of each chapter under the heading 'Key lessons'. Part 3 of the book will also contribute to the study of dependability and reliability engineering and help to understand the specificities of knowledge-based services. The book will also benefit other experts considering lifecycle management issues and asset challenges and hopefully help in the development of new solutions.

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[6] Repo, T. (2018) Modelling of Finnish maintenance markets and its development. Master's thesis. LUT-University. School of Engineering Science, Industrial Engineering and Management. Lappeenranta. Finland. Available at: https://lutpub.lut.fi/handle/10024/158348

Acknowledgements

A large part of the chapters in **Knowledge-based Lifecycle Management** have been produced as part of recent research projects funded by Business Finland, and by Finnish industrial companies and research institutes and universities. In addition, development work may have been carried out in research programmes such as those of the Defence Forces and national standardisation organisations (PSK, SFS, METSTA) that have contributed to international standardisation work. Finnish national maintenance society Promaint, and the European Society of National Maintenance Societies EFMNS have made possible the publication of the book. The authors warmly thank all those organisations.

EXECUTIVE SUMMARY

Helena Kortelainen

On a general level, Lifecycle Management (LCM) is a business management approach for managing the entire life cycle of goods and services in order to improve their performance and sustainability. For a company developing and delivering goods and services, Product Lifecycle Management (PLM) refers to the business activity of managing company's products through their lifecycles from the very first idea to manufacturing and to the installation at the customer site, and through the utilization phase until the product is retired and disposed. In the utilization phase, the lifecycle management refers to the set of activities consisting of planning and monitoring, and of decision making that is necessary to plan, monitor, operate, maintain, and improve the performance of an item. Assets are items that have potential or actual value to the organisation. Physical products are assets to their owners and users, but assets could be also intangible like employees´ skills or company brand. Asset management refers to the set of coordinated activities that an organization uses to realize this value. Asset management plans over the different timeframes should help to clarify what should be done with assets and when, and to balance these actions with monetary and other benefits, and with risks. Life cycle thinking is thus deeply rooted in asset management.

Industrial assets are becoming increasingly instrumented with sensors, smart and connected. Data is in the core of Industry 4.0 and in the core of the digitalisation process in general. **Knowledge-based lifecycle management** book presents models, methods, and practical examples of lifecycle management activities in capital intensive industries or organisations operating such items. Comprehensive, high-quality data is needed throughout the product/asset life cycle in every stage from planning the items on the drawing board to optimizing the operations in the utilisation phase and to supporting business decisions at the strategic level. Data is the raw material for knowledge - the ability to structure and interpret information that support all the life cycle stages and levels of decision-making.

Knowledge-based lifecycle management book consists of four substance parts and of an additional terminology catalogue part. The first part of the book (Part 1 - Lifecycle management - from concept to use phase and beyond) deals with the basic definitions and rationale for lifecycle management, as well as safety, RAMS factors and risk management. The part introduces the modelling of life cycle costs using availability performance and its components, as well as various life cycle models, life cycle management tasks and applications. The life cycle is viewed from the perspective of the product or system manufacturer and from the perspective o the end user i.e., asset owner. Part 1 also describes the main methods used to assess the performance of lifecycle management, which are e.g., overall equipment effectiveness (OEE), life cycle cost (LCC) and life cycle assessment (LCA). In addition, Part 1 drafts the connections of LCM to circular economy.

Part 2 - Asset management deals with the management of physical assets, the central part of which is also the management of life cycle. Part 2 presents tools for modelling the organization's operating and technology environment and the impact of these factors on asset requirements and management. Furthermore, this Part studies investment decision-making and the calculation methods as well as their suitability for different situations. Part 2 offers methods to define maintenance strategy within the asset management framework. An important part of defining a maintenance strategy is the criticality of asset items. Corporate management makes decisions in increasingly complex environments and therefore Part 2 expands the perspective by exploring strategic dimensions in asset management.

The third part of the book (**Part 3 - Data collection, analysis and utilisation**) focuses on the collection, processing, analysis, refining and utilization of data and information that is central to lifecycle management. With the progress of digitalisation, the focus is shifting from data collection to data utilization. In addition to key information systems (e.g., PDM, PLM, CMMS, and EAM), condition monitoring, information system interfaces and database architectures are examined. In this Part, expert elicitation as well as tacit knowledge are considered as important sources of data and interpretation. The main emphasis is on describing the methods used to analyse and process the data, starting from the application of descriptive data analysis to stochastic simulation. The section also looks at data utilization from the perspectives of the asset user, system supplier, and service provider. Finally, an overview of future development prospects and needs is created.

Part 4 - Methods, tools, technologies and application examples present lifecycle management methods and solutions through practical examples. The examples compiled in Part 4 cover the different stages of the life cycle, from the identification of development needs through foresight methods to the presentation of business models in the circular economy. The product design phase is examined through a project delivery process, incremental product development and maintainability planning. The utilisation phase is covered by examples of the replacement investment decision-making. Often enhancement and improvement of a production system is required and at this stage new technological solutions and their successful implementation play a key role. Part 4 also presents decision support models and methods, such as the life cycle cost assessment and robust strategic asset management models.

Companies engaged in production activities spend on average about 5% of their turnover on maintenance. This figure includes only direct maintenance costs, such as salaries and spare parts, as well as purchases of external services. A recent study estimated that the value of industrial maintenance in Finland is about 4.1 billion euros. According to this study, the maintenance services and spare parts business in Finnish TOP500 companies is approximately EUR 12.3 billion euros (2016), most of which arise in the business units outside Finland. However, often the management and development of such services often take place in Finland. Lifecycle management and the business opportunities that life cycle related services offer is also significant from the economic viewpoint. Decision-making in a rapidly changing business environment under the pressure of changing and ever-tightening requirements emphasizes the ability to anticipate and prepare for change. At the acquisition phase, the user must be prepared for the cost of maintaining the product, and over the years and perhaps decades these incurring costs may exceed the original purchase price many times.

The sustainable use of natural resources and the looming shortage of many important raw materials raise the importance of lifecycle management. Extending the life of machinery and equipment improves resource efficiency, but at the same time requires emphasis in lifecycle management activities such as maintenance, refurbishment and upgrade investment, and technical performance of systems. The circular economy, which emphasizes the reuse and recycling of materials, is based on the principles of sustainable development, and seeks to solve the challenges of a linear “use and dispose” model. Comprehensive life cycle data management is also a necessary enabler for re-use of machines and equipment in a new application.

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[1] Repo, T. (2018) Modelling of Finnish maintenance markets and its development. Master's thesis. LUT-University. School of Engineering Science, Industrial Engineering and Management. Lappeenranta. Finland. https://lutpub.lut.fi/handle/10024/158348

PART 1
LIFE CYCLE MANAGEMENT - FROM CONCEPT TO IMPLEMENTATION

1.1. LIFE CYCLE MANAGEMENT

Helena Kortelainen

Introduction

The importance of the life cycle is underlined by several global change trends such as the sustainable use of natural resources, changing business models, digitalisation, and the advance of globalisation. The life cycle of a product, system or service is the period that starts when an item is defined and ends when it is decommissioned and disposed, or when it is transferred to another use. The planned lifetime of a product has a significant impact on the materials and technical solutions chosen, as well as on the modes of operation and the tasks to be performed during the operational phase. The importance of life cycle management has therefore increased along with the increasing demands of sustainability and resource efficiency, safety, and environmental impact. Decision-making in a rapidly changing business environment requires the ability to anticipate and prepare for change.

Especially in capital-intensive industries and for infrastructure systems, the operational phase is usually long, often several decades. Therefore, improving system performance, productivity or safety, continuous improvement and upgrading, renewing, and upgrading systems through investment are key tasks of life cycle management. Design solutions that consider product life cycle extension, recyclability, and end-of-life dismantling, as well as business models that support resource efficiency, are also part of the circular economy. Consumer products often have a short design life compared to that of capital goods, which is extended through maintenance and other activities. This difference is illustrated by Figure 1.1 which summarises typical consumer products and long-life systems and estimates the maintenance requirements for these products.

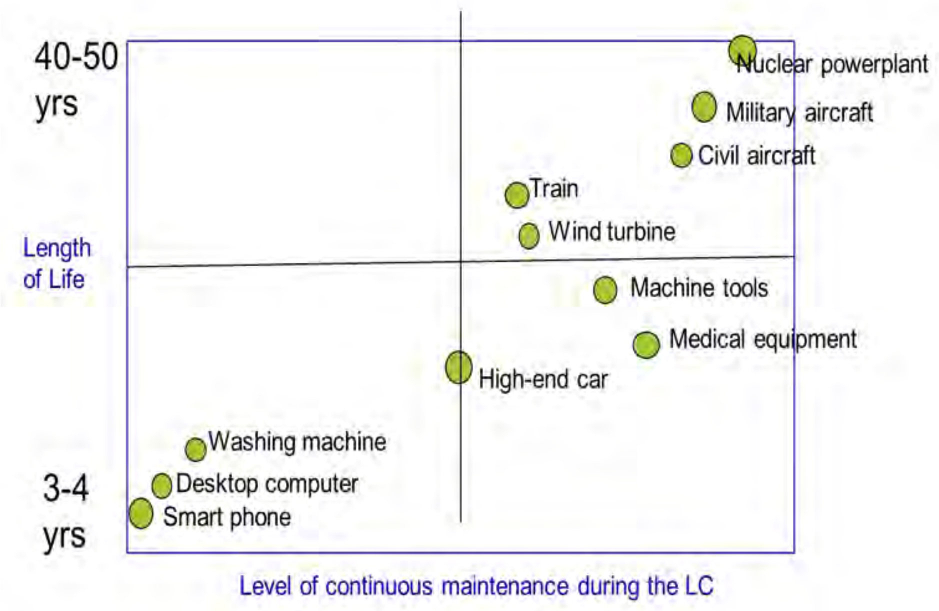

Figure 1.1. The importance of maintenance for long- and short-life products (Roy et al., 2016).

This book focuses on complex products and systems, which are characterised by long life cycles in production operations, and where system reliability and safety, maintenance and active asset management are emphasised during the life cycle. Capital goods (investment goods) are the means of production in which firms invest and through which firms produce new products or services, either for consumers or for other firms. Capital goods often consist of commercial components or parts but are designed and tailored to meet the needs of the customer. Investment goods are therefore different in many ways from consumer goods, which in Figure 1.1 are represented by consumer electronics and household appliances. Life-cycle management, with its procedures, models, and methods, helps the decision-maker to optimise performance requirements and the costs inevitably associated with maintaining performance, and to assess the risk associated with future uncertainty. Consideration of safety issues is also a key element of life cycle management.

Life cycle, life expectation and useful life

The word 'life cycle' has several meanings depending on the context. In environmental sciences, life cycle[1] refers to the flow of energy and materials through manufacturing system from raw material in ground, through processing to shape, assembly of finished product and disposal following use. This is often referred to as cradle to grave thinking. In business context, a product life cycle is the period when the product is on the market. In the life cycle management life cycle means the evolution of a system, product, service, project, or other human-made entity from conception through retirement (ISO/IEC/IEEE 15288).

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[1] Database for scientific terms https://tieteentermipankki.fi/wiki/Termipankki:Etusivu/en

The life cycle of a product consists of identifiable life cycle stages (IEC 60050-192, 2015; IEC 60300-1, 2014; ISO/IEC/IEEE 15288, 2015; DIN ISO 15226, 2017). A generic model is presented in the following Figure 1.2. In general, the life cycle of a machine, equipment or system is composed of the design, development and realisation phases, and the utilisation and enhancement phases during which the item is in service. The life cycle ends with the retirement of the product, after which it is withdrawn from service. Retirement may also mark the beginning of a second life cycle, for example if the equipment has been sold to a new user or transferred to another application.

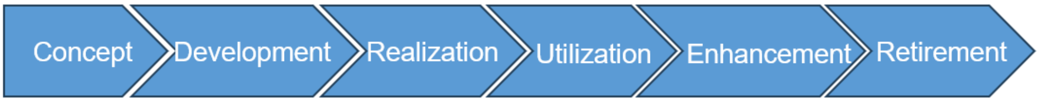


Figure 1.2. Generic life cycle model (IEC 60300-1, 2014).

Every product also has a *commercial life cycle*, during which the product is on the market. A commercial product may be replaced by a better performing or cheaper product variant or by another product, in which case the product's commercial life cycle ends and the product is no longer available on the market. The commercial life cycle may also end up as a more desirable product enters the market or if the product becomes obsolescent due to environmental impact, regulatory or other reasons. Even if a product or a particular product generation disappears from the supplier's product range and from the shelves, the use and lifetime of individual items may continue.

Products and systems designed for industrial applications may have a design life of decades, but usually they contain equipment and components with a much shorter life expectancy. In real industrial and infrastructure systems the subsystems and components are at different stages of their commercial and technical life cycle. Some subsystems may be in the enhancement phase as another item is just taken into use (Figure 1.3).

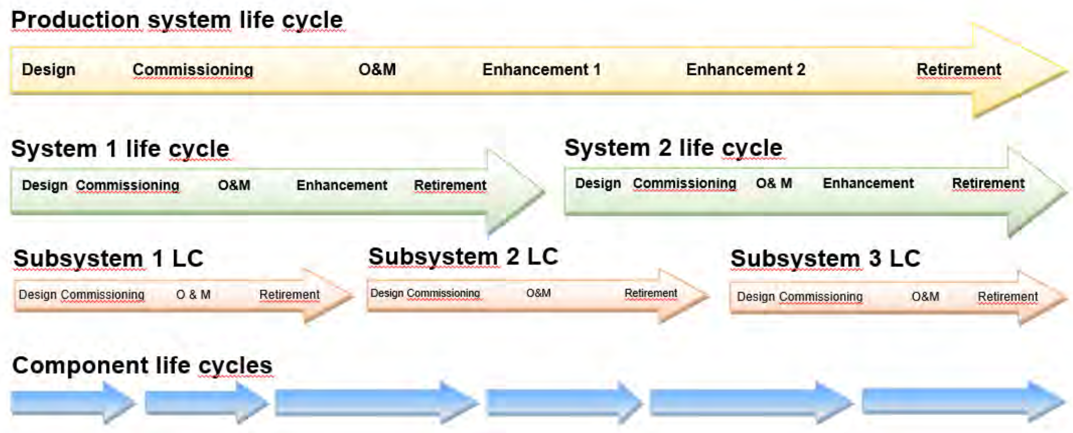


Figure 1.3. Hierarchy of life cycles (Ahonen et al., 2012).

The life expectation of components and other items must be considered already in the design phase where the engineering decisions are made. The life expectation also has an impact on the maintenance resources needed, and to the life cycle costs. Consideration of the plant hierarchy is also very important in managing the reliability of the system (see Plant hierarchy, Part 2).

Each company has its own guidelines for estimating the planned useful life of an investment. The useful life of an investment depends on a variety economic and technical issues; the choice of the most advantageous replacement time is a typical optimisation problem. One guideline for assessing technical obsolescence is the physical lifetime of the equipment. As technology develops, the economic life of an investment may be considerably shorter as the performance of machinery and equipment continuously improves and the market situation changes.

The importance of availability performance

Availability refers to the ability of an item to be in a state to perform as required, under given conditions and assuming that the necessary external resources are provided (EN 13306 & IEC 60050(192)). The definition of availability can be applied to a variety of objects, regardless of their size and purpose. An object can be a single machine, device or component or a large production system consisting of many subsystems. Availability may be quantified using appropriate measures or indicators and is then referred to *availability performance (A)*. The complement of availability is *unavailability (U)*.

Along with operational performance, availability and safety are important product features related to the management of the product life cycle. Therefore, the early stages of product development are of utmost importance. Availability consists of four elements (Figure 1.4) which are reliability, maintainability and recoverability, and maintenance support performance (IEC 60050-192, 2015). Reliability and maintainability are characteristics of the engineered item, and they are influenced by decisions made during the product development and design phase. Recoverability relates to the ability of a system or product to autonomously to recover the data directly affected by the event of an interruption or a failure and to re-establish the desired state of the system. Recoverability of product depends on a recoverability of computer system on which the product operates or a subset of its functions. Maintenance support performance, on the other hand, describes the ability of the maintenance organisation to provide the required service. The development and retaining of the maintenance support performance is the responsibility of the organisation using the product.

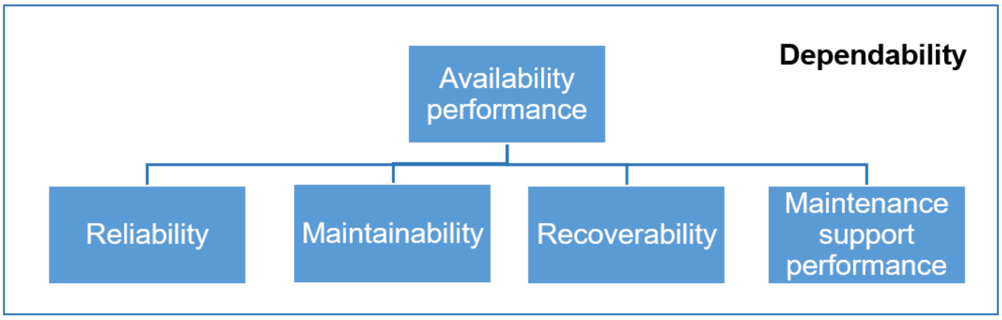


Figure 1.4. Elements of reliability (IEC 60050-192, 2015).

The high availability performance of production facilities, systems and individual pieces of equipment means their uninterrupted, efficient, economic, and safe operation. Dependability is an umbrella concept that can include durability, safety, and security, in addition to the four elements described above. The availability performance of a technical system is also influenced by the competences, skills and knowledge of the operating and maintenance staff, as well as the location and quantity of available resources (including spare parts, accessories, tools). The planning and management of safety at different stages of the system life cycle is discussed in more detail in Chapter 1.3.

Availability performance of a production facility or a system consisting of several machines and devices is a result of complicated interactions and to understand the impacts dependability modelling is needed. The system may consist of various interconnected components and intermediate storage facilities and tanks that affect the operation of the whole system.

An essential part of a dependability model is the logical structure, which define, not only the connections of the subfunctions to each other, but also how the availability of an individual item explicitly influences the system availability performance. Some industrial systems can be modelled entirely as series structures. However, quite often in the process industry, the flow of the processed material is not straightforward, and the logical structure of a system becomes quite complex, especially at a lower level of detail. The calculation and modelling of availability performance is discussed in more detail in Part 3 of this book.

Availability is a key quality factor for the product. Therefore, availability performance targets must be set very early in the product life cycle so that it is possible to plan for their achievement. In practice, the information available at the concept stage is often scarce, and it is difficult to set numeric targets. Instead, it is important to provide guidelines for dependability design and to influence the key factors early enough in the engineering process. An example of setting qualitative objectives can be found in Part 4 of this book. Further elaboration of the objectives to more detailed ones or refining the objectives set is possible and necessary during the product development and design as the information is accumulated. (Ahonen et al., 2012).

RAMS

The components of dependability - *Reliability (R), Availability (A), Maintainability (M)* and *Safety (S)* - are often referred to as *RAMS*. The term was originally introduced in the railway sector. The railway standard (CENELEC - EN 50126-1, 2017) defines the key processes and tasks for RAMS management throughout the life cycle of a system, as well as a systematic process that is customisable and provides methods for managing conflicting requirements.

Life cycle costs

In terms of the life costs and benefits of a product, the most important decisions are made during the early stages of product development. The concept and development phases lay the foundation for the product to be designed, and it becomes more difficult to change these early decisions as the engineering and manufacturing work progress. A frequently quoted estimate in the literature is that up to 80% of the total life cycle cost of a product is tied to decisions made early in the life cycle. These decisions determine the product's features, performance, dependability, and the technology used (e.g., Blanchard & Fabrycky, 2000, p.37). Only a very small proportion of the actual, realised costs are incurred at this stage. The more precisely the product specifications can be defined before the actual product development begins, the more certain it is that the final product will meet its requirements.

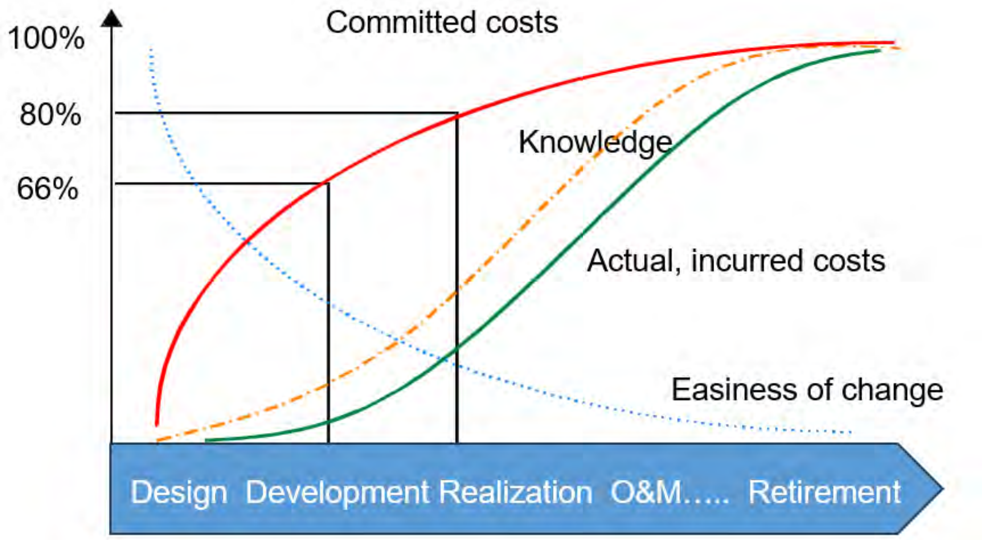


Figure 1.5. Accumulation of the life cycle costs.

Figure 1.5 illustrates the accumulation of life cycle costs. In the graph, committed life cycle costs refer to costs that arise later in the product life cycle, but these cost result from decisions taken early in the life cycle. An example of such a decision is the choice of propulsion system for a machine: it is rarely economically or technically feasible to change the propulsion system during the life cycle of a product. In the figure, the actual cumulative expenditures start to incur from the concept stage, but major part of the expenditures take place in construction and utilisation phases. Anticipating and modelling life cycle costs in early stage of the product life cycle can have a significant impact on design, engineering, and manufacturing decisions.

An example is the development work on Alstom metro trains. When the customer moved to a new way of implementing metro transport and decided to buy the train service instead of purchasing trains, the business model of the supplier changed. As the estimated life cycle cost of the trains over a 30-year service life was around 3-4 times the purchase price, the supplier had to carefully consider choices in terms of availability, reliability, and maintainability during the design phase. Indeed, the supplier made more than 250 changes to make the trains easier to operate and maintain (Davies, 2004).

What is life cycle management?

Life Cycle Management (LCM) refers to the entire life cycle of a product and aims to optimise the design, implementation, and life cycle activities of a product in terms of life cycle costs (Westkämper, 2000). Life cycle management methods thus aim to meet the functional requirements of the system while at the same time minimising the *Life Cycle Cost (LCC)* of the system. Life cycle management is therefore not only a technical issue but includes an economic perspective, and cost/benefit and risk considerations.

Life cycle management allows to define and control the processes and their interfaces in the product life cycle. LCM emphasises the phased approach and the transition from one phase to another can only occur if predefined criteria are met (e.g., IEEE 24748, 2018). Usually, a life cycle is defined for a particular object, for example:

- Application life cycle management (software)
- Facility life cycle management (design and construction of building)
- Product data life cycle management (storing data in information systems)
- Life cycle management of a production system or investment (industrial plants)
- Product life cycle management (marketing)
- Product life cycle management (engineering and manufacturing)

Modern engineered products often contain both hardware and software components, which means that managing the life cycle of the product also involves managing the life cycle of the (software) application.

Life cycle management can also mean assessing and managing the environmental impact of a product throughout its life cycle. This is often referred to as the "cradle-to-grave" model. Life cycle analysis covers the sourcing and production of raw materials, processes and energy, the transport and use phase, up to the end of life of the product. The cradle-to-grave model and impact assessment also covers recycling after the product has been discarded. The recycling process results in new products of the same type (e.g., glass bottles from recycled glass bottles), or different products such as insulating glass wool from recycled glass bottles.

Key lessons

- The life cycle of a product, system or service starts from the moment it is defined and ends when it is decommissioned and disposed, or when it is transferred to another use.
- Managing dependability over the life cycle requires collaboration. The reliability of a product is influenced both by its characteristics, such as reliability and maintainability, and by the maintenance support performance organised by the user.
- Life cycle management starts at the product concept stage, where major decisions affecting operational performance, availability performance, safety and economy of use are made.
- The aim of life cycle management is to optimise product design, implementation, and life cycle activities in terms of life cycle costs.

- Life cycle management means assessing and managing the environmental impact of a product throughout its life cycle. The term is also used to refer to the commercial life cycle of a product.

1.2. LIFE CYCLE MODELS

Helena Kortelainen

Introduction

Standards and the literature on product, product development, project and asset management present a wide range of life cycle models. For example, VDI 2221 (1993) deals with the life cycle from a mechanical engineering perspective, while Ulrich & Eppinger (2004, p.9) deal with the product life cycle mainly from a consumer product design and development perspective. The life cycle model is also the basis for *Life Cycle Assessment (LCA)* (see in more detail Chapter 1.5 Life Cycle Management Performance and Metrics).

All products and systems have a life cycle. A life cycle model is a way of describing this period through different stages. The phasing of the model also supports communication between the different stakeholders involved and the development of a common understanding (ICE 60030-1, 2014). The life cycle model consists of processes, the number and quality of which are determined by the target and the need. The different phases of the life cycle of an object may also overlap or coincide, and different parts of the system may be at different stages of their technical and commercial life cycles.

From the manufacturer's point of view, the starting point of the life cycle is the market need for the product or the idea for the product, while from the user's point of view, the life cycle of a capital good starts with the definition of the need and the decision to purchase. In the following sections, the key models for managing the technical life cycle are discussed.

Generic life cycle model

A generic life cycle of a product, service or system consists of successive life cycle stages from concept to deployment and decommissioning/re-use as shown in Figure 1.2. Each stage is associated with tasks and activities specific to that stage. The life cycle model does not take a position on who or which organisation is responsible for which tasks. Often the division of work between the product supplier and asset owner is very clear: the supplier carries out the first life cycle stages and after the commissioning the ownership and responsibility for managing the rest of the life cycle stages is transferred to the asset owner. However, the responsibility for the implementation of the life cycle management tasks and activities can be agreed upon in different ways. For instance, in customised systems, the customer (asset owner) can have a very significant input into the concept and development phase. On the other hand, the product manufacturer may also be responsible for the maintenance and use of the product, or the product may be returned to the supplier after retirement phase for reuse or scrapping. Some examples of the dependability related activities in a generic life cycle model are listed below (see the complete list in IEC 60300-1, 2014, Annex B):

Concept; The initial idea for a product or solution

- Identification of market needs or other opportunities, definition of the operating environment and needs, regulatory and other requirements, and constraints.
- Determination of item boundaries, operating functions, and performance characteristics.
- Consideration of the *trade-offs* between desired functionality and dependability requirements.
- Modelling (e.g., probabilistic approaches) to predict, for example, dependability and to assess maintenance needs.
- Selection of technologies for design and choice of hardware/software for realisation of functions
- Risk assessments focusing on the *feasibility* of the plan and technology choices.

Development; Development of the concept chosen for implementation

- This stage focuses on the design and implementation of selected design solutions to achieve the desired functions and functionalities.
- Establishing of the dependability programme, formalisation of the dependability requirements for system, subsystems, and functions and setting dependability acceptance criteria.
- Modelling of the system (e.g., probabilistic approaches) to verity that the dependability targets are likely to be reached.
- Detailed risk assessment of developed solutions.

Realization; Putting the product into practice

- Implementation of the dependability programme and failure reporting, analysis, data collection and feedback system.
- Establishing of the test plans and item acceptance criteria, and performing analysis and tests of components, and modules, including tests in which the system components are integrated with each other.
- The realisation process also involves acceptance procedures agreed with the customer and possible test runs both at the supplier's premises and in the customer's environment. Validation based on the results of tests and trials provides objective evidence of compliance with the specifications.

Utilization; The use of a product or solution over its useful life

- The use stage starts when a product or service is put into use and is maintained.
- Monitoring item performance, implementation of the field data collection system and analysing failure trends and maintenance service records.
- Continuous improvement and recommendations for design or procedural changes.

Enhancement; Improving the performance of a product or solution during its utilization stage

- Improving a system can be done, for example, by developing new (product) features to make the system more responsive to customer needs, or by extending the useful life of the system or preparing for *obsolescence*.
- Identification of new features and enhancement requirements.
- Evaluation of the need for change and enhancement requirements and conducting risk and value assessments.

Retirement; the product is decommissioned, scrapped or re-used in another application

- Dismantling the items. Items could be fully or partially reused for another purpose or through the reuse of materials, or they can be scrapped.
- It should be noted that decommissioning issues need to be addressed at the conceptual stage.
- Decommissioning may be accompanied by a *decommissioning* process defined by regulatory requirements.

Each stage of the generic life cycle model can be further divided into more specific stages and more detailed processes. For example, the concept phase can be divided into a feasibility study and concept definition, and the development phase into preliminary design and detailed design. The implementation phase can also be described in terms of construction and implementation. In this case, construction refers to the manufacturing of the item and implementation refers to its deployment. Similarly, in engineering, for example, it may make sense to divide the implementation phase into component manufacture and assembly and, where appropriate, further sub-processes.

Especially in capital-intensive industries and for infrastructure systems, the operational phase of a system is usually long, up to several decades. Developing and improving the performance, operation, economy, or safety of the asset system are therefore key tasks of life cycle management and asset management (see Part 2). Enhancement activities can aim at life extension, for example by improving maintenance, changing the operating profile or environment, or improving the functionality of the asset in other ways. Enhancement activities may also aim to improve performance, productivity, or the quality of the product, and may require upgrade, modernisation, or renewal of the asset system. Enhancement activities may also include software updates or the use of new digital solutions, either on their own or as part of the renewal of machinery and equipment. Refurbishment can be used to implement completely new functions or to improve functionality.

In industrial practice, the distinction between maintenance and enhancement is not always very clear, nor even necessary. Maintenance activities are carried out as a part of normal operation. However, some activities can only be carried out when the production process is interrupted. Major shutdowns (major overhaul, outage), which typically occur every few years, are usually major repairs aimed at restoring machinery and equipment to the required condition. Outages may also involve modifications to individual pieces of equipment and/or to complete systems to improve their performance. In addition, during the outages investments that increase production or introduce entirely new features to the asset systems or are carried out.

Life cycle - a product and manufacturer perspective

From a manufacturer's perspective, life cycle management traditionally focuses on the early life cycle stages associated with product design and manufacture. As physical products are increasingly accompanied by maintenance and other life cycle services, the interest in managing the entire life cycle of the product increases. For example, Stark (2011, p.17) divides the life cycle from a manufacturer's perspective into five phases:

- imagine,
- define,
- realise,
- support/service, and
- retire.

In the model proposed by Stark, the product life cycle starts when the idea of the product is born. The next stage is product definition, after which the product can be realised. From realisation, we move on to support and serve stage that maintains the product's performance. The product life cycle ends with retirement. Blanchard and Fabrycky (2000, p. 19) whose work is often cited in the literature, present the product life cycle stages in a similar way, but in their model the definition stage is divided into a preliminary and the detail design stage.

The stages of life cycle management are interlinked with the company´s product development process. Product development is the process of developing a new or improved product to meet evolving customer needs. The life cycle management activities and tasks can also be found in the product development process descriptions. The product development process is based on the needs assumed or expressed by the customer, and the aspired product characteristics aim to meet these requirements. The manufacturer then aims at incorporating the desired features through development, engineering, and manufacturing.

Product development models divide the development stage into functional phases. The best known and most widely used models are the German VDI 2221 design guideline and the Ulrich & Eppinger product development process. Ulrich and Eppinger's model have the consumer products perspective and it divides life cycle management into six phases (2004, p.9):

1. planning (design of the product/product programme),
2. concept development,
3. system-level design,
4. detail design,
5. testing and refinement, and
6. production ramp-up.

Product programme planning is the process of deciding on the future product portfolio and the timing of its launch. An important task of this phase is also to set the business objectives for the future portfolio, for example, in terms cost structure and quality objectives.

The VDI 2221 model, which was developed to meet the needs of mechanical engineering, is called a systematic approach to the development and design of technical systems and products. This model defines the design process but does not address issues such as the customer interface and business. The model consists of a seven-step workflow (VDI 2221, 1993): specification of the task definition, identification of functions and their structures, search for solution principles and their structures, structuring into feasible modules, structural design of dimensioning modules, structural design of the product package and preparation of manufacturing and operating instructions.

Product data management

Product Lifecycle Data Management (PDM) is the information systems used for product life cycle management (PLM). Figure 1.6. brings together the concepts of product life cycle and product data management, and the life cycle stages of the product and related services.

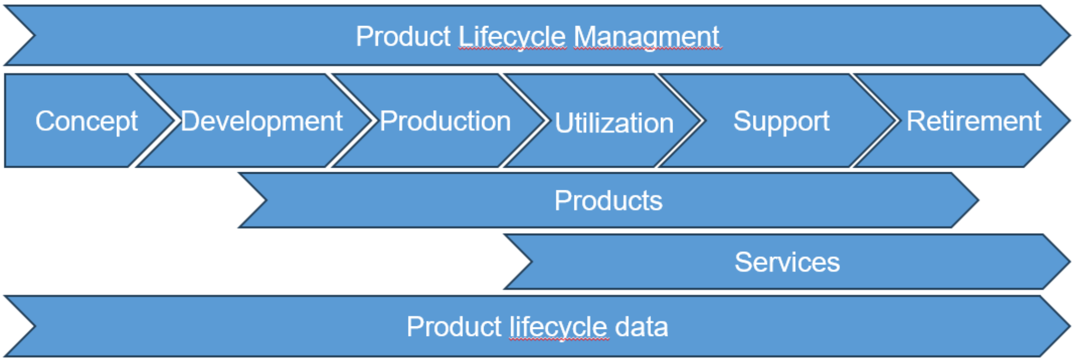


Figure 1.6. Example of life cycle and product information management for a product and associated services

The historical background of PLM solutions and applications is generally seen in the field of mass production of configurable products (e.g., car manufacturing), mechanical detail design and product configuration management. In a sense, PLM has evolved from engineering data management towards covering the entire of the life cycle. Typical users of PDM and PLM systems are engineering and manufacturing companies. There is a strong trend to extend the scope of PLM from mechanics and component design towards multi-technical system design, functional design, and requirements management. The strength and backbone of traditional PDM systems is the systematic structure for physical products and item names. (Granholm, 2013)

Life cycle - a production system and user perspective

The life cycle stages and descriptions of key tasks identified in the generic life cycle model also include the product user´s perspectives. The tasks of the product user or asset owner focus on the acquisition phase and the exploitation and maintenance of existing production equipment.

Procurement phase

The procurement process can take many different forms, in which the roles of the contracting parties vary. The procurement may focus on a readily available product (e.g., *Commercially-Off-The-Shelf, COTS*), with no modifications or customisation. However, entirely novel, and unique design may be required, or the system to be procured may be built from commercially available components or products, but the system-level design is done according to the requirements of the application. Meeting the customer requirements may also require technology development or product development and research, in which case the procurement will require a high level of collaboration between the customer, the supplier and other stakeholders. In this case, the end-user has a significant input in the requirements definition. The procurement process also reflects the complexity of the system to be procured, and issues related to the availability of logistical support.

Instead of buying a physical product, the desired functionalities can be acquired in other ways. The procurement process can therefore also focus on a service provision without a physical product. Examples of service business models include performance-based contracts with suppliers or leasing. In these models, the ownership of the product, the responsibility for life cycle management and the risks remains with the supplier or service provider, and this fact is reflected in the service fee. The service provider aims to set a price that allows for a profitable business. The client, on the other hand, tries to anticipate costs and prevent them from rising out of control. An example of service contract models and their implications is shown below (Table 1.1).

Table 1.1. Example of contract models for service procurement (Jokinen, 2011)

OPTION		**CONCLUSION**
Comprehensive service package (*All included*)	**1**	Easily leads to overcharge the customer to cover the risks.
Equal partners *(Equal play)*	**2**	Define the spare parts/works covered by the contract and exclude e.g., the most expensive items. Service fee is easier to determine as some risks are transferred to the customer.
Defined services *(Open case)*	**3**	The contract includes certain basic services (e.g., scheduled maintenance), but major maintenance and spare parts are charged separately. This model is almost risk-free for the supplier, but it is difficult for the customer to budget the annual costs.
Open books *(Open books)*	**4**	Model 1 or 2 is used. The producer submits e.g., every 12 months a service performance report to the customer. If the profit is within the mutually agreed limits, the service continues at the previous price. If the profit is too low or too high, the service fee for the following year will be adjusted accordingly.

A life cycle service contract and a comprehensive service package simplifies the management of the user's costs. For the supplier, pricing a long-term service contract is difficult and it is a challenge to prepare for risks. Similarly, a defined service, as shown in the table above (Table 1.1), shifts the risk of unexpected events to the customer. Contracts may also seek to share risks (equal partners, open books). Risk management will be discussed again in Chapter 1.6.

Operation and maintenance phase

For some systems, organising maintenance in a cost-effective way can pose particular challenges. Logistics performance becomes a key issue when the production system is geographically dispersed or difficult to reach (e.g., offshore wind farms). Systems may also form a mobile fleet, such as a truck or aircraft fleet, or maintenance activities must be carried out on the premises of a manufacturer, which may be located far away. The importance of logistics is underlined by the business life cycle model described by Hastings (2015, p.12). Hastings divides the life cycle of the product or system to be procured into six phases or tasks:

- Business Need. Identification of business opportunities or need,
- Pre-acquisition analysis, physical and financial—options selection,
- Acquisition, including implementation into operation,
- Logistic support provision, such as maintenance facilities, consumables, and spares,
- Operation and maintenance, and
- Disposal.

A life cycle management plan is an asset management tool (Hastings, 2015). The plan is developed by identifying the maintenance tasks required to maintain the performance of each asset, the development needs for the coming years and the resources required to do so. This is complemented by an assessment of the potential service life and the identification of decommissioning tasks. The asset life cycle management plan (ALMP or asset management plan, AMP) thus provides a starting point for planning maintenance resources and replacement and development investments over a longer time horizon. As life cycle management plans change in line with changing business objectives and under pressure from many external and internal factors, they also need to be updated regularly. As technology evolves, new solutions are constantly coming onto the market and companies need to weigh up the potential benefits of their introduction.

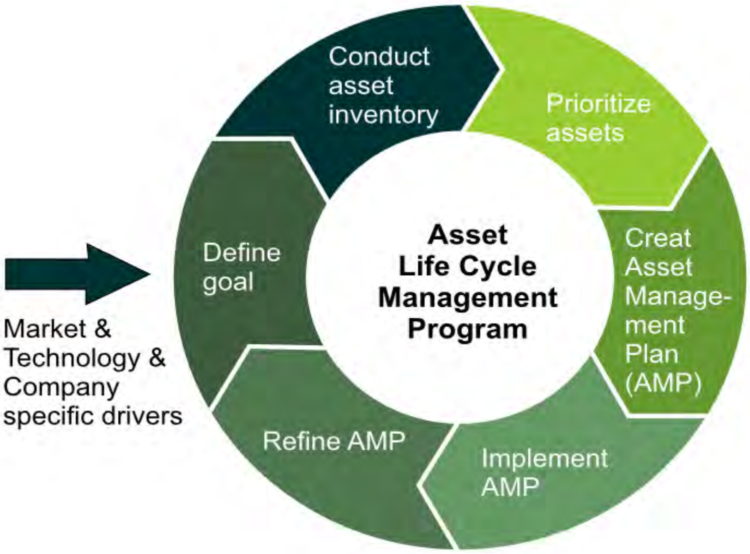


Figure 1.7. Managing the life cycle of a system is a continuous activity (Kortelainen et al., 2020)

The implementation of life cycle management plans for multiple items in an asset system should consider the harmonisation of plans across organisational units and levels, change management, leadership, and culture (ISO 55002). Collecting feedback, evaluating results, and improving plans are also essential elements of the plan. Life cycle management and planning (Figure 1.7) is therefore a continuous activity in line with the philosophy of continuous improvement.

Life cycle management of production equipment is an important part of asset management. Asset management is covered in Part 2 of this book.

Performance improvement and investments

Maintaining and improving the performance of asset systems also requires investment in new equipment and skills, as well as continues improvement of maintenance and operating practices. The term *CAPEX (capital expenditure)* is often used in this context to refer to the investments made by a company to modernise its existing assets (property, machinery, equipment) or to acquire new ones. *Operating expenses (OPEX)* are the company's recurrent costs, such as wages, raw materials, and consumables. CAPEX investments may be made to achieve higher production volumes, improve quality, improve overall efficiency, protect the environment, or are necessary to comply with changes in legislation and regulations. CAPEX can also be used to reduce operating costs (OPEX), for example by replacing a machine or piece of equipment that requires a lot of maintenance and man-hours with a completely new one. In addition to economic profitability, investment decisions are influenced by a wide range of other aspects, such as technological, environmental, social, legal, and ethical dimensions, whose monetary value is not unequivocal. This requires a comprehensive investment appraisal, as illustrated in Figure 1.8.

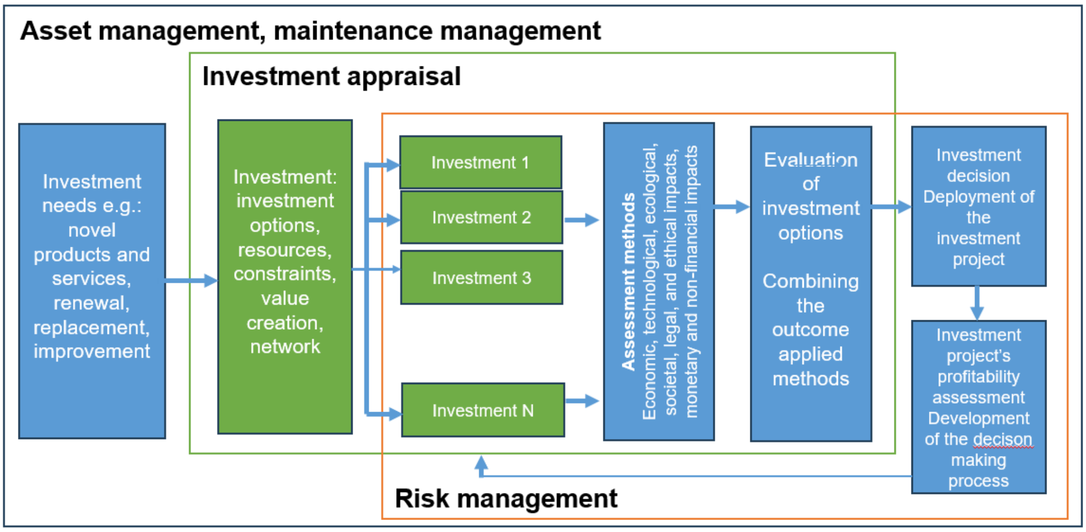


Figure 1.8. A broad approach to evaluating maintenance investments (Räikkönen et al., 2019a)

The decisions on tangible investments require the application of rational and analytical calculation methods. Well-known methods include *net present value (NPV),* annuity, payback time, *return on investment (ROI)* and *internal rate of return (IRR). Life-cycle cost (LCC)* and *life cycle profit (LCP)* calculations emphasise the estimation of costs and benefits over the entire life cycle of a product (see Chapter 1.5 for more details). The benefits of an investment can also be estimated using either cost-benefit or cost-effectiveness analysis. In this case, costs are converted into money, but impacts can also be described and quantified in other ways. Managing risk and uncertainty is an essential element of the success of an investment project at all stages of the process.

Stakeholder cooperation and interaction during the life cycle management phases

The design of complex, customised systems and equipment requires close collaboration between stakeholders. A complex system is not only made up of machines and equipment, but also includes software, information, people, processes, practices, infrastructure, and materials. The complexity of an engineering system is due to the large number of components interacting in a predetermined way, but a complex system involves several independent actors (Amaral & Uzzi, 2007). As the number of stakeholders increases, a unified conceptual framework is required for better communication. Product development and design today are often highly networked and decentralised activities. Development teams are made up of people with different languages and educational backgrounds, and they are working in different locations and organisations.

Systems Engineering (SE) is an interdisciplinary field of engineering. Systems engineering aims to manage the design, integration, and implementation of complex systems to ensure that the requirements of the system are met in the final product. Systems engineering considers the impacts of all life cycle stages and the perspectives of stakeholders. Emphasis on requirements management and the decomposition of the system into more manageable subsystems are key approaches. Of the various systems engineering standards, ISO/IEC 15288 (2015) is the most generic and covers the broadest life cycle. ISO/IEC 15288 (2015) follows the general life cycle model framework (Figure 1.2) and tasks, but also defines a set of life cycle processes:

- agreement processes,
- organisational project-enabling processes (OPEP),
- technical management processes, and
- technical processes.

These four main processes all have their own sub-processes (see Table 1.2). Each process and sub-process has a defined purpose, activities and tasks, and outcomes that the successful implementation of the process will produce. This ensures that the transition from one stage of the process to another can be monitored and measured.

Table 1.2. System life cycle management processes (ISO/IEC 15288)

AGREEMENT PROCESSES	ORGANISATIONAL PROJECT ENABLING PROCESSES	TECHNICAL MANAGEMENT PROCESSES	TECHNICAL PROCESSES
Acquisition process – used by organisations for acquiring products or services. **Supply process** - used by organisations for supplying products or services	Life cycle model management Infrastructure management Project Portfolio Management Human resources management Quality management Knowledge management	Project planning Project assessment and control Decision management Risk management Configuration management Information management Measurement management Quality assurance	Business or mission analysis Stakeholder needs and requirements definition. System requirements definition Architecture definition system definition Implementation Integration Verification Transition Validation Operation Maintenance Disposal

In a networked business environment, product life cycle processes extend beyond organisational boundaries of the buyer and supplier. During the utilisation stage, a wide and varying number of organisations may be involved in the operation and maintenance of the systems, and their responsibilities change over time. The combination of external services and other intangible issues, dynamic processes and organisations makes almost all products and asset systems complex. Collaboration at different stages of the system life cycle is therefore often intensive, and cooperation between stakeholders is particularly needed when new technologies or approaches are introduced.

Choosing a life-cycle model

Life Cycle Assessment (LCA) aims to assess the environmental impacts of a product or service throughout its life. The "cradle-to-grave" life cycle model covers the sourcing of materials from nature, their processing and transportation, and the manufacturing, distribution, use, reuse, maintenance, recycling, and disposal of the product. The results do not include the time dimension and they are not presented as a function. *Life Cycle Cost (LCC)* analysis is usually based on a time bound life cycle model (Figure 1.2), which considers the stages of the product life cycle from conception to end-of-life. The life cycle model applied for LCA, and the life cycle models used for optimisation of the LCC of technical systems differ from each other (Räikkönen et al., 2019b and Räikkönen et al., 2020).

The life cycle model may also have different levels of detail or focus on specific life cycle stages. For example, the standard EN-50126 (2017) on managing the RAMS issues of delivery projects in the field of railway applications emphasises the role of the management issues. This could be highlighted by posing practical questions like:

- What is the appropriate life cycle model for the product and application?
- What are the required reliability management tasks at different stages of the product life cycle?
- Who is responsible for the implementation of the safety and reliability management tasks?
- What are the guidelines, tools and reference documents needed to carry out these tasks?
- How are RAMS management activities implemented into the company's operational processes?

The choice of a life cycle model is therefore a pragmatic solution based on practical needs.

Key lessons

- All products and asset systems have a technical life cycle and commercial life cycle. A life cycle model is a way of describing this period through different stages. In cradle to grave thinking, the life cycle covers to the flow of energy and materials through manufacturing system from raw material in ground, through processing to shape, assembly of finished product and disposal following use.
- The tasks of the product user/asset owner are focused on setting requirements in the procurement phase, and on the use and maintenance of existing equipment and performance improvement.
- In the design and implementation of complex and extensive systems, it is particularly important to manage requirements in a structured manner from the early concept stage, and to involve all stakeholders when setting requirements and evaluating their implementation.

1.3. MANAGING SAFETY AT DIFFERENT STAGES OF THE LIFECYCLE

Eetu Heikkilä and Risto Tiusanen

Introduction

Safety generally refers to the absence of danger and threat (risk), as well as the psychological experience of their absence. Safety occurs as a phenomenon wherever there is some form of danger. As the world becomes more complex, safety also takes on new characteristics. Safety is always a relative measure as it is impossible to achieve absolute safety. As it is often not possible to eliminate completely all threats or dangers, safety considerations concentrate on reducing the probability of threat or risk, and on how much effort one is willing to invest. This is particularly true in activities and situations where people and technology interact.

In the industrial environment - workplaces where people interact with industrial systems, machinery, and equipment - the concept of safety has been defined in many ways. Leveson (2012) defines safety as the *absence of accidents*. In this context, an accident is broadly defined as any unforeseen loss that is unacceptable. Safety is also defined as freedom from conditions that could cause death, injury, or damage to property or the environment (MIL-STD-882E, 2012).

The safety of new machinery is the responsibility of the manufacturer

The *safety management* of new industrial machinery and equipment is based on the manufacturer's safety policy and the stated safety objectives, as well as on the laws and regulations that set minimum safety requirements for industrial machinery and equipment. In the past, national safety varied from country to country and from company to company. International cooperation and the various standardisation organisations have made it possible to harmonise safety requirements, and this collaboration has improved the safety of industrial systems and removed barriers from the international trade. In Europe, machinery safety is regulated and harmonised by the Machinery Directive (Directive 2006/42/EC, 2006) to ensure the establishment and functioning of the internal market and to ensure a high level of protection of people's health and safety and of the environment, and the directive has had a significant positive impact in ensuring safety. The Machinery Directive defines the manufacturer´s obligations and sets essential health and safety requirements for machinery and machine systems.

In Finnish legislation, the obligations concerning the safety of machinery are based on the Machinery Act (2004). The Act is intended to provide guidance to manufacturers, suppliers and other actors involved in the supply of machinery and other work equipment for use or on the Finnish market. The Machinery Act obliges the machinery, equipment, and other accessories to be safe and manufactured in accordance with the regulations. In Finland the

Government decree (VnA 400/2008) is equivalent to the Machinery Directive (Directive 2006/42/EC, 2006). The purpose of the Government Decree is to specify the requirements presented in the Machinery Act. The requirements of the Government Decree are complemented and refined by European harmonised and mandatory safety standards. The standards have been developed to meet both general safety requirements for all industrial sectors and requirements for specific machinery or its safety systems.

Safety design

Safety must be considered in all system life cycle stages and by all actors, by using methods and procedures that are appropriate for the purpose. From the point of view of safety design, the key measures include identification, assessment, and management of the safety risks associated with the machinery or system. Safety design should not be seen as a separate process that adds on the system design. The basic objective should be that the system is designed from the outset with safety in mind (Leveson, 2012). In this way, safety-related problems can be detected as early as possible and laborious and costly corrective and modification measures later in the life cycle can be avoided.

Often industrial machines operate as a part of machine assembly and continuous production process. To design and ensure the safety of these increasingly large and complex systems, more sophisticated safety design, analysis and verification methods are needed.

As it is not possible to achieve absolute safety and all hazards cannot be eliminated, safety analyses are needed to identify risks and to assess their magnitude, and to define the acceptable level of risks. Traditionally, the safety risk is defined in terms of the probability of a hazardous event and the severity of the consequences. In addition to meeting minimum requirements, the principle of *As Low As Reasonably Practicable (ALARP)* is applied to safety. The ALARP principle involves a process in which all risk-reduction options are considered in terms of benefits and costs.

Safety design methods for different life cycle phases

In practice, there are numerous methods for assessing safety risks and for supporting design phase. The suitability of an individual method depends, among other things, on the scope of the system and its intended use. It should also be noted that a single method is usually not sufficient to cover the entire system life cycle (Tiusanen, 2014). This chapter outlines the main tasks related to risk assessment (Figure 1.9) and describes some of the most common methods for different stages of the life cycle.

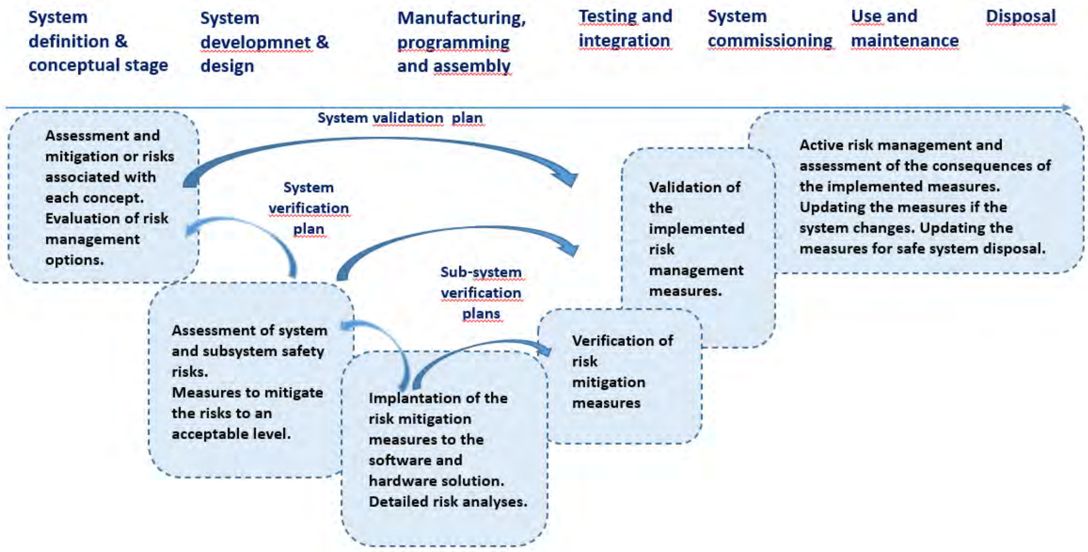


Figure 1.9. Tasks related to the identification, assessment, and management of safety risks at different stages of the system life cycle. Adapted from the original by Tiusanen (2014).

Safety must be considered already in the very first system definition and in the early stages of conceptual design. In particular, the role of requirements management is highlighted, as a large proportion of accidents can be traced back to inadequate requirements definition. At the conceptual design stage, the implementation of the system is not yet known precisely, which is why various generic ideation methods are typically used to identify potential risks and any problems in the operation of the system. It is also often necessary to compare different alternative concepts. Typical methods include:

- *The Preliminary Hazard Analysis (PHA)* focuses on identifying risks of the initial system concept and potential risk mitigation measures. When developing new products, information from previous similar systems can be used to help.
- *Potential Problem Analysis (POA)* is a brainstorming method that uses keywords to identify and assess system risks and intervention needs.

As design progresses, more detailed risk analysis methods will be used. At this stage, it is typically necessary to assess risks at both subsystem and component level. This involves the need to assess the magnitude of the risks and to prioritise risk management measures. Commonly applied methods include:

- *Operating Hazard Analysis (OHA*, also known as Operating and Support Hazard Analysis (O&SHA) in some contexts) focuses on the safety risks associated with the operation and maintenance of the system, as well as various abnormal situations. In particular, the human factor in the operation of the system is highlighted (Rausand, 2011).
- *Failure Mode and Effects Analysis (FMEA)* (IEC 60812, 2018) is an inductive method that aims to identify the effects of failure of system functions or components. The analysis can be performed at function or component level, as appropriate. There are several variations of the method that extend its scope (e.g., FMECA; which also includes a failure criticality assessment, or FMEDA, which emphasises diagnostics and failure detection).

- *Fault Tree Analysis (FTA)* (IEC 61025, 2006) is a deductive graphical method that focuses on identifying chains of causes that can lead to system failure. First, an accident, failure, or other undesirable situation (a fault tree top event) is defined, and then a tree structure is used to describe the chain of failures that could cause the top event. The fault tree is often used for quantitative analysis.
- *The Hazard and Operability study (HAZOP)* (IEC 61882, 2016) originated in the process industry, but its use has since been extended to other industrial sectors. It systematically reviews system design documentation using keywords to identify potential deviations from the intended operation of the system.

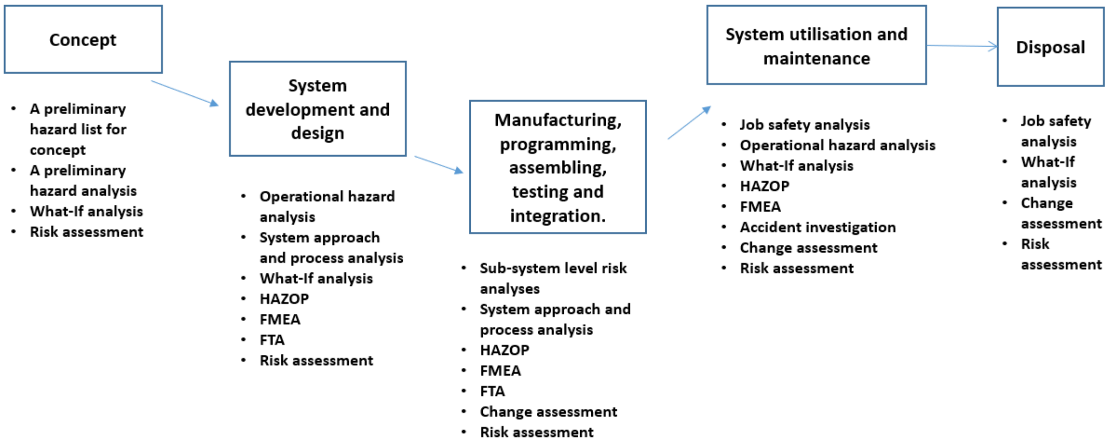


Figure 1.10. Safety design and maintenance methods at different life cycle stages.

During the phase of defining the safety requirements for machinery and its control systems, decisions are made that have an impact on the safety of the entire subsequent life cycle of the machinery. Errors in the definition of safety requirements have been identified as the cause of a large proportion of accidents (Hietikko et al., 2009). New methods based on systems theory, such as *STAMP (Systems-Theoretic Accident Mode and Processes)* and *FRAM (Functional resonance analysis method),* have also been recently proposed for the safety assessment of complex and software-intensive systems, focusing on the interactions between different parts of the system rather than on failures (Heikkilä & Tiusanen, 2020).

The design of safety-critical software should be carried out in accordance with the relevant international industry standards. The software safety design process should be closely integrated into the overall system and its control system development process, so that safety-related tasks are performed in a timely and systematic manner. The software safety design process covers the process steps from initial hazard analysis to functional testing and safety validation. For more information on standards related to safety design of control systems and software, see e.g., Alanen et al. (2022).

From a safety assurance perspective, Verification and Validation (V&V) of the system are tasks with major importance. The purpose of verification is to ensure that the system meets its design requirements. Verification is carried out repeatedly at different stages of the life cycle. Validation activities are intended to ensure that the system can accomplish its intended use, goals, and objectives (i.e., to meet stakeholder requirements) in the intended operation environment.

The importance of the comprehensive documentation to managing safety at all life cycle stages cannot be overemphasised. Different industries have their own practices regarding the preparation and required content of documentation. For example, Machinery Directive (2006/42/EC) defines the technical file for machinery, which must contain, among other things, the general description of the machine, technical drawings of the machinery and control circuits, standards and other technical specifications used in the design of the machinery, and risk assessment documents.

Maintaining safety during the utilisation stage

When machinery and equipment are used and maintained in the workplace, the employer is responsible for the *workplace safety*. In Finland, the Occupational Safety and Health Act (738/2002) obliges employers to take the necessary measures to ensure the safety and health of their employees. The act also emphasises the importance of cooperation between employers and employees. In Europe, the minimum safety requirements for machinery in use at the workplace, which may be old or modified, are expressed in Directive 2009/104/EC (2009). In Finland, the corresponding Government Decree on the 'Safe Use and Inspection of Work Equipment' (403/2008) covers the purchase, use, maintenance, safety, and inspection of work equipment in the workplace. It applies to all work covered by the above-mentioned Occupational Safety and Health Act (738/2002).

Machines, equipment, and industrial systems are used and maintained for many decades in the workplace. During operation, the focus is on monitoring the adequacy of risk management measures and correcting any shortcomings identified. Any modifications to the system or changes in its operating profile or environment must be given special attention. The safety of maintenance operations and other activities that deviate from normal operational activities should also be evaluated. Safety management requires a goal-oriented, planned, and comprehensive approach. The starting point is that only safe machinery and systems that comply with EU requirements are purchased and deployed in the workplace. The hazards of the utilised machinery are identified, risks are assessed, and the findings lead to appropriate conclusions and measures to improve safety. The whole organisation must be involved in safety work. Company top management plays a crucial role in safety management. Top management must define the safety policy to be followed in the company, make available the necessary resources, and monitor that the activities are in line with the safety policy.

Key lessons

- Machinery, equipment, and systems must be safe. Safety is a mandatory requirement and should be a built-in feature of the system.
- The product manufacturer is responsible of the safety of a new machinery and equipment. Safety must be considered as part of the system design process from the early stages of the life cycle.
- Safety is considered in different ways at all stages of the life cycle. The methods used to identify, assess, and manage safety risks should be chosen according to the application and life cycle phase.
- Maintaining safety across the system life cycle requires active action, monitoring and change management by all parties involved.

1.4. LIFE CYCLE MANAGEMENT AND CIRCULAR ECONOMY

Helena Kortelainen, Jyri Hanski and Pasi Valkokari

Introduction

The Ellen MacArthur Foundation (2013) defines the *circular economy (CE)* is an industrial system that is restorative or regenerative by intention and design. It is based on the principles of sustainable development and seeks to address the challenges of traditional linear "take-make-dispose" consumption patterns as are coming up against constraints on the availability of resources. Circular economy concept emphasises durability and longevity, maintenance, refurbishment, reuse, remanufacturing, and recycling of the products. Circular economy emphasises durability and longevity, maintenance, refurbishment, reuse, remanufacturing, and recycling of the products. With these methods, circular economy aims to substitute for an inflow of virgin materials into the economy and to increase material productivity.

It is evident that circular economy and life cycle management and asset management have common objectives and all these approaches aim at the efficient use of resources. Effective life cycle and asset management can therefore support the achievement of circular economy objectives. Business models for the circular economy are described with examples in Part 4.

According to a current international report (Sitra, 2018), the circular economy could significantly reduce global climate emissions. Circular economy models can be divided into biological cycles, which focus on consumption, and technical cycles, which focus on the reuse of materials and products. The next chapter will discuss the technical cycles of the circular economy in more detail.

Technical cycles of the circular economy

Closing material loops and extending the machinery and equipment life seem preferred options from a resource efficiency perspective. Figure 1.11 outlines opportunities for circular economy services and activities from the perspective of technical product supply chain. Life cycle extension includes service solutions such as maintenance, repair, reuse, and remanufacturing, as well as design solutions that considering the circular economy requirements.

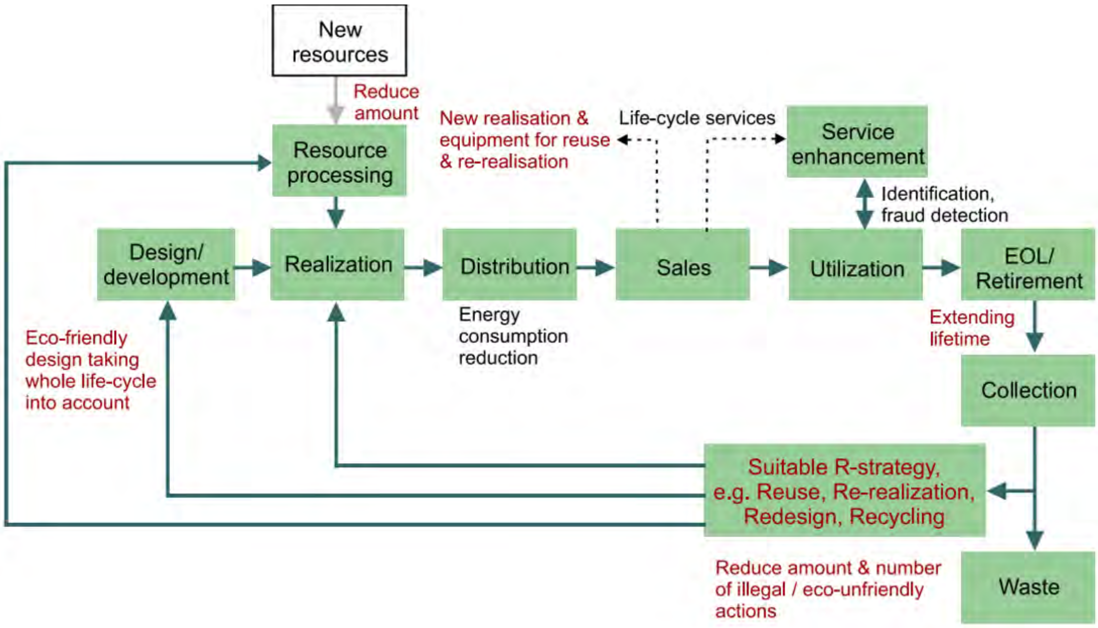


Figure 1.11. Life cycle model that considers the circular economy (Valkokari et al., 2016)

From a circular economy perspective, fundamental decisions are made at the design and procurement stage of a product or system. The trend towards sustainability favours product longevity and overall resource efficiency. The circular economy emphasises the management of the entire life cycle of products and services, including modernisation or refurbishment, decommissioning and possible subsequent life cycles (Bocken et al., 2016).

Ecological design of products

Since the 1990s, environmental considerations and design methods that consider the entire product life cycle have become more widespread. Ecodesign aims to ensure that consumers are offered products with high energy efficiency and low environmental impact. Ecodesign requirements integrate environmental considerations and life cycle thinking into the product design phase. The eco-design framework emphasises the following aspects:

- minimising life cycle impacts (see Chapter 1.5 for more details) in material choices,
- reducing the use of materials,
- optimisation of production methods,
- optimising supply chains,
- minimising the life cycle impacts of the utilisation phase,
- optimising the life cycle impacts of the first life cycle,
- optimising end-of-life impacts, and
- design of new concepts.

Another important framework for sustainable design is product longevity. Longevity can be achieved by developing the product, for example, from the point of view of reuse and recyclability, and by carrying out maintenance, repair and replacement of the product and its components during its life cycle. The product characteristics to be achieved are therefore durability, repairability, upgradeability, optimised energy and material consumption and recyclability.

Circular economy combines the principles of eco-design and longevity in the same design framework. In addition, circular design considers the reuse, dismantling and recycling of products, and the safety and reusability of materials used in products. The design of circular solutions should also incorporate business model, as well as the assessment of the impacts on the different actors in the ecosystem and wider on the society (Chen, 2015).

Key lessons

- The circular economy includes solutions to slow (use longer), narrow (use less), close (use again), and regenerate (make clean) of products.
- Circular economy solutions for technical systems include maintenance, repair, reuse, and remanufacturing solutions, as well as design solutions that consider the requirements posed by circular economy.
- The principles of ecology, longevity and the circular economy should be emphasised in the design of products, services, and systems.

1.5. LIFE CYCLE MANAGEMENT PERFORMANCE AND INDICATORS

Helena Kortelainen, Toni Ahonen, Minna Räikkönen Saija Vatanen and Lotta Hepo-oja

Introduction

The indicators can be used to set targets, identify areas for improvement, compare alternative solutions and monitor the quality and development of activities. The indicators make it possible to compare equipment and production units within a company and between different units within a company, and to compare the performance of a company with other companies in the industry or with appropriate peer organisations. Performance indicators and key performance indicators are also needed to establish and monitor the performance of contractual terms and conditions relating to the quality and effectiveness of the maintenance and other life cycle services.

Internal efficiency can be examined e.g., in terms of labour productivity, capital productivity, cost efficiency and quality. The traditional labour productivity ratio is a metric expressing the number of work units produced per time worked. Capital productivity shows how efficiently capital is used to generate output and capital investment at firm level can have both short-run and long-run effects on labour productivity. For instance, labour productivity improves if the machinery is upgraded to be less labour-intensive. Cost efficiency means producing a product for sale at the lowest possible unit cost. Effective and profitable investments contribute to cost efficiency. The final dimension of efficiency is quality, which can be lost if efficiency is sought without regard to quality (Laine, 2010).

Key Performance Indicators (KPIs) represent the measures that are most important for the current and future success of a company. Performance metrics and indicators are necessary to manage, operate and maintain asset systems and their components in the most efficient way throughout their life cycle. They can be used to set objectives, identify areas for improvement, compare alternative solutions and monitor the quality and evolution of operations. This chapter discusses three important concepts from a life cycle perspective - OEE, LCA and LCC - that can be used to measure life cycle efficiency, performance, or profitability.

Overall production effectiveness (OEE)

Overall equipment effectiveness (OEE) is a commonly applied key performance indicator that summarizes the impact of availability, performance, and quality. OEE represents a balanced approach that helps to align the activities in production, maintenance, and logistics with a common goal to minimize downtime, disturbances, and defects. OEE concept is not standardized, so there is no "right" reference value and the measurement practices across industries vary. Net total production time is less than planned as the "six big losses" hamper production. The overall equipment effectiveness is a ruthless indicator: if all three factors are at 90%, the OEE is only 73%.

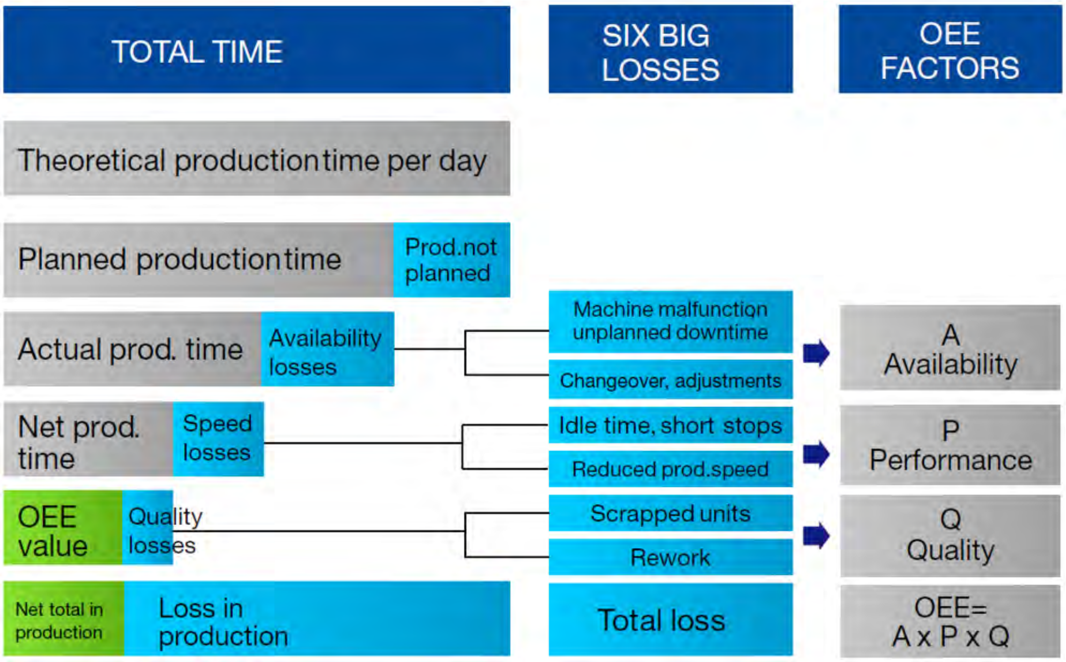


Figure 1.12. A schematic presentation of OEE and its components (Ahonen et al., 2018)

Maintenance activities have a particular impact on availability performance. Equipment failures, unplanned downtime and other unexpected disruptions affect the availability performance. In many industrial organisations, also planned maintenance is regarded as a lost production time when calculating availability performance. This encourages the organisations responsible of maintenance and operation to cooperation and joint planning of activities that interrupt production.

OEE aims at maximizing utilization of the current, designed capacity. A part optimization or trade-off, e.g., production rate vs. product quality, may not yield the best solution. The system may, however, contain upgrade potential. Debottlenecking, process optimization or upgrading equipment with the latest technology may increase capacity. The OEE model can be used to estimate how much an investment in reducing some loss factor can improve overall effectiveness, and further to calculate the value of this additional output in the current market situation.

Overall equipment effectiveness therefore affects the return on capital: correctly planned and resourced maintenance is a prerequisite for profitable production. Efficient maintenance can improve the capacity utilisation of existing equipment and improve the quality of final products. Through these factors, higher production volumes can be achieved and, potentially, a higher profit. The OEE model, combined with the economic models, provides a rough idea of the benefits of improving maintenance with a reasonably simple calculation.

Life Cycle Costing (LCC)

Life Cycle Costing (LCC) is a concept created by the US Department of Defence in the 1960s to improve the efficiency of defence material procurement process. It introduced a longer planning horizon that covers future operational, support and maintenance costs. Subsequently the concept of life cycle costing has spread to other industrial and infrastructure sectors. Life-cycle costing aims to support long-term decision making and planning. Applications include:

- Comparing and evaluating procurement options in purchasing and procurement decisions
- Allocation and selection of dependability requirements
- Comparison and evaluation of alternative implementation options (e.g., buying or leasing)
- Comparison and evaluation of technology choices
- Planning the life cycle of the machine, equipment or system, budgeting for maintenance activities and possible replacement or modernisation investments
- Assessing the profitability of replacement or modernisation investments
- Maintenance planning, e.g., assessing the viability of condition monitoring systems.

Depending on the application, either a comparison of alternative solutions or cost projections can be used. The key factor in comparison is relative accuracy, whereas in forecasting, for example for budgeting, absolute accuracy is sought.

Life Cycle Cost (LCC or Whole Life Cost, WLC) is the sum of all direct and indirect costs incurred during the life cycle of a product or system. The costs incurred by different actors during the life cycle of a product are very diverse and case specific. An example, the costs incurred over the product life cycle to the purchaser may include (Ferrin & Plank, 2002):

- purchase price,
- operating costs,
- quality costs,
- logistics,
- technology,
- maintenance,
- storage,
- life cycle management,
- opportunity cost,
- disposal of the product, and
- costs related to technical or other obsolescence of the product.

When a product is disposed from its original use, a residual value can be assigned to it. The residual value can be the resale value or, for example, the price of recyclable materials. Most of the costs incurred during the life cycle of a product are not visible at the procurement stage, and this fact is often illustrated by the iceberg metaphor (Figure 1.13).

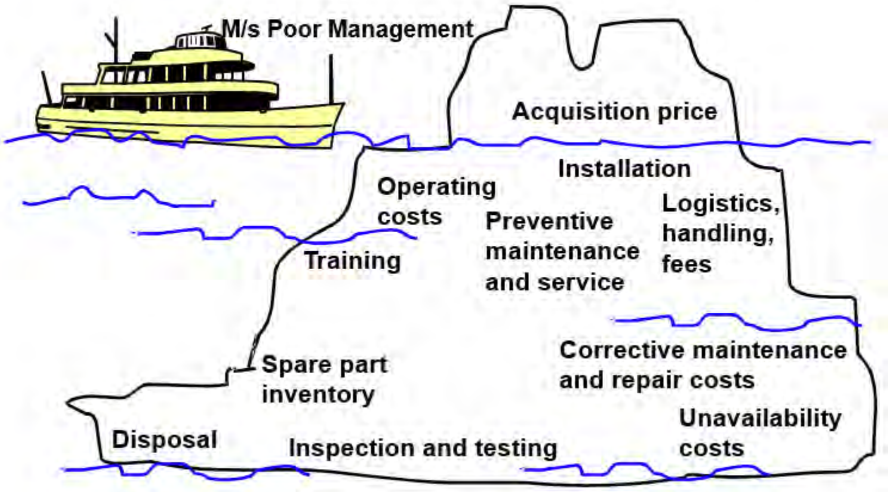


Figure 1.13. Most of the costs incurring during the life cycle of a product are not visible at the procurement stage.

The process for life cycle costing (LCC) is described in general standards such as IEC 60300-3-3 and in industry-specific standards. Examples of industry-specific standards include ISO15663-1 and NORSOK Z-014 for the oil and gas industry and EN 15459-1 (2017) for the construction industry. In addition, specific guidelines have been developed for different industries, such as the defence industry (e.g., NATO guide, 2007). However, the calculation of LCC is very case specific due to the large number of potential cost factors and the different use cases of the models.

At different stages of the life cycle, costs are incurred to different actors. At the acquisition stage, the *acquisition cost* of a product - that the buyer pays - includes not only the manufacturing costs, but also all the costs associated with developing, designing, testing, delivering, and installing the product. The allocation of costs between the buyer and the supplier may, of course, be agreed otherwise. The ownership cost includes the costs of acquiring, using, and maintaining the product and the costs of disposing of the product. *Total cost of ownership (TCO)* is also used as an abbreviation for ownership cost (Ellram & Siferd, 1993).

The cost of ownership may also include the system development activities and possible improvement and modernisation investments occurring later in the product life. It should be noted that ownership costs also include the costs associated with the planning and procurement of developments and investments made during the utilisation stage. A significant part of the product life-cycle costs is incurred during the utilisation stage. For example, for weapon systems, Rachuri et al. (2006) estimate that around 70% of the total costs are incurred during operation and maintenance stage. For mobile machinery (Chen and Keys, 2009) and rolling stock (Davies, 2004), it is estimated that in-service costs are 3 to 4 times that of the purchase price. In-service costs are significantly influenced by, among other things, the operating mode and conditions, and the need for consumables.

The impact of availability performance on the product life-cycle costs

The availability performance of a product or asset system and the corresponding life cycle cost are closely related, such as Figure 1.14 illustrates.

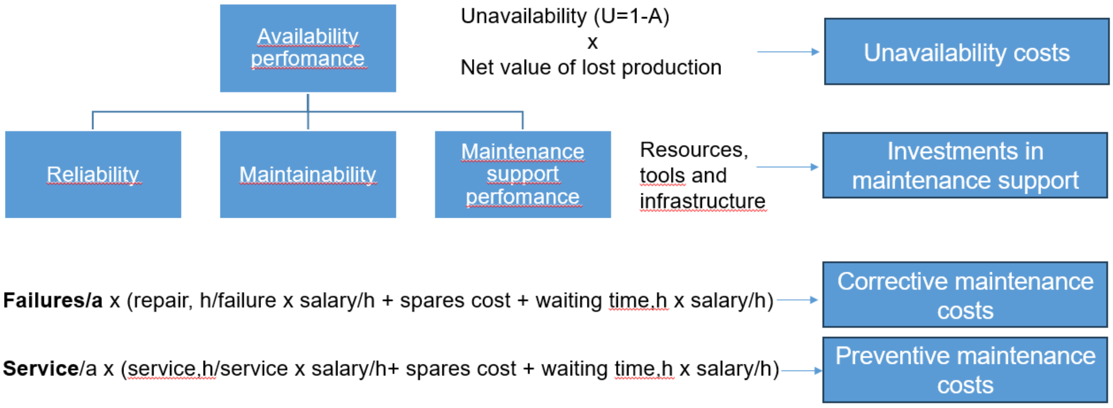


Figure 1.14. The role of reliability components in the cost of the operational phase.

The life cycle costing process

Life-cycle costing is the process of conducting an economic analysis to assess the economic impact of often complex decisions at different stages of the life cycle. The life cycle cost can be determined for the entire life cycle of a product or part of it. The aim of the calculation is to support decision making and trade-offs between the costs incurred at the time of decision making and those that will be incurred in the future. A key part of the design of the LCC analysis involves the selection of economic performance indicators. Common indicators include *Net Present Value (NPV) and Discounted Cash Flow (DCF), Return on Investment (ROI)* and payback time.

Life-cycle cost calculations must also reflect the fact that the value of money depends on time and the payments at different points in time must be made comparable. This is done by means of a discount factor. The discount factor (or rate) is influenced by, among other things, the expected return on capital, the price of capital and the riskiness of the investment. The discount rate can be set, for example, at the highest rate of return that can be obtained by investing capital in the best possible financial asset or at a rate that reflects the average return on the capital of the company over a long period of time. The discount rate strongly influences the results of the LCC process.

Table 3. Life cycle costing process and steps (modified from IEC 60300-3-3)

PROCESS STEP	**TASKS AND ACTIVITIES**
Organisational context	• Defining the objectives and scope (product, system, subsystem, etc.), • defining the problem, describe the target of the assessment, • Identifying alternatives and • identifying constraints.
Define the approach	• Choosing the methodology and rules, • selecting or developing the LCC model, • defining the *Cost Breakdown Structure (CBS*) and the life-cycle cost functions, and • identifying areas of uncertainty.
Data acquisition	• Determining the needs for data collection based on the assessment scope and objectives, and the framework of the calculation model, • identifying available data sources and assess the availability and reliability of the data needed for the calculation; and • carrying out data collection.
Build and test the calculation model	• Analysing the data produced by the data collection and using it to develop the calculation model, • refining the calculation model and calculation methods, and • testing the functionality of the calculation model and finalising the model.
Perform the analysis	• Performing the LCC calculations with the selected/developed model, and
Evaluation of results and conclusions	• Analysing the behaviour of cost drivers and forecasting trends based on historical data from the data collection and other available sources, • evaluation of the impact of uncertainty on the results by sensitivity or other appropriate analysis, and • evaluation of the results and recommendation for a decision.
Documentation	• Identification of follow-up activities, • updating the data: monitoring and comparing user experience with calculated data, identifying the causes of deviations, storing data for future calculations and to improve the model used, and • documentation of the process, objectives, data, constraints, assumptions, and applied methods.

The unavailability of a physical product or service (Figure 1.14) can result in high 'unavailability costs', especially if the unavailability results in significant production losses. Examples of costs arising from unavailability include:

- warranty cost
- liability cost,
- the lost revenue resulting from unrealised production; and
- costs for providing an alternative service.

A warranty protects the buyer against the cost of product defects. The costs of the warranty are usually borne by the manufacturer or supplier. Liability costs are also considered part of the LCC costs. Product failure can cause, for example, personal injury or environmental pollution. If necessary, risk analysis methods, expert assessments or analysis of the field data can be used to assess the liability costs. The cost of lost production depends both on the preparedness of the user and the circumstances prevailing at the time (e.g., stock levels and order books) and on the ability and possibilities of the customer to reduce the damage caused to his own customers.

Quantitative analysis of costs is often not enough but requires qualitative analysis. Not all factors that influence a decision, such as environmental impact or corporate image, can be translated into numerical values. In such cases, qualitative factors influencing the decision can be assessed separately alongside the LCC analysis, as illustrated in Part 4.

Managing uncertainty

Life-cycle cost assessment is challenging as it calls for looking at future that is characterized by uncertainty. Uncertainty can be viewed from three different perspectives (Goh et al., 2010):

- data uncertainty,
- model uncertainty, and
- uncertainty associated with the scenario.

Data uncertainty is caused by a variety of factors, only some of which can be influenced by acquiring more data. Data uncertainty is influenced by factors such as (Goh et al, 2010) inherent randomness due to variability (e.g., active correction time), statistical error due to lack of data (e.g., incomplete or low confidence data), linguistic vagueness (e.g., data uncertainty may also result from the subjectivity of the experts (e.g., overconfidence in the timeline) and from the fact that future decisions are not yet known (e.g., supplier A or B).

Estimating life-cycle costs requires a model that calculates costs from given input data. The data associated with the input can be uncertain, but so can the model itself. Typical sources of model uncertainty include:

- incomplete or missing definitions,
- assumptions and approximations,
- the cost estimation methods chosen,
- selected level of detail, and
- interdependencies between cost factors and elements.

Since life cycle costing deals with events and conditions in the far future, scenario uncertainty is the main source of uncertainty. Scenario uncertainty is difficult to address, but uncertainty in data and models can be reduced by careful groundwork. Typical methods used to assess uncertainty are sensitivity analysis and simulation. The role of risk analyses as part of LCC analyses should also be emphasised (Markeset & Kumar 2001; Komonen et al., 2012).

Life Cycle Assessments (LCA)

Clear changes in our environment, awareness of the importance of environmental protection and circular economy thinking have led to an interest in developing and using methods to assess the impact of activities on the environment. One of these methods is life cycle assessment. *Life Cycle Assessment (LCA)* is the identification and assessment of the environmental impacts of a product, service, or activity over its life cycle. It can also assess the environmental impacts of different processes. Life cycle assessment can be used to

- improve the environmental performance of products at different stages of their life cycle,
- support decision making for industry, public administration, and organizations (e.g., strategic planning, priority setting),
- help choose environmental performance measurement methods and indicators, and
- help marketing and communication (e.g., environmental product descriptions and claims).

Life Cycle Assessment is part of the environmental management tools and provides information that will help the development of environmental management. Other management tools include e.g., environmental performance assessment, risk management and environmental auditing.

Life cycle assessment is an ISO standardized method. ISO standards are published by the International Standardization Organization. ISO 14040 (2006) defines the main principles and outline of life cycle assessment, while ISO 14044 (2006) defines the requirements for life cycle assessment and provides guidelines for carrying out the assessment. ISO 14067 (2018) focuses on the carbon footprint of a product, how to calculate it and how to communicate it. In addition, the European Union has published the Product Environmental Footprint (PEF) methodology for assessing the environmental impact of products and services. PEF is based on life cycle assessment and allows for a harmonized environmental impact assessment within different product categories across Europe.

Life cycle assessment focuses on the environmental aspects and potential environmental impacts of a product throughout its life cycle, from raw material sourcing, through production, use and disposal, to waste disposal and possible recycling. Figure 1.15 shows the main features of life cycle thinking.

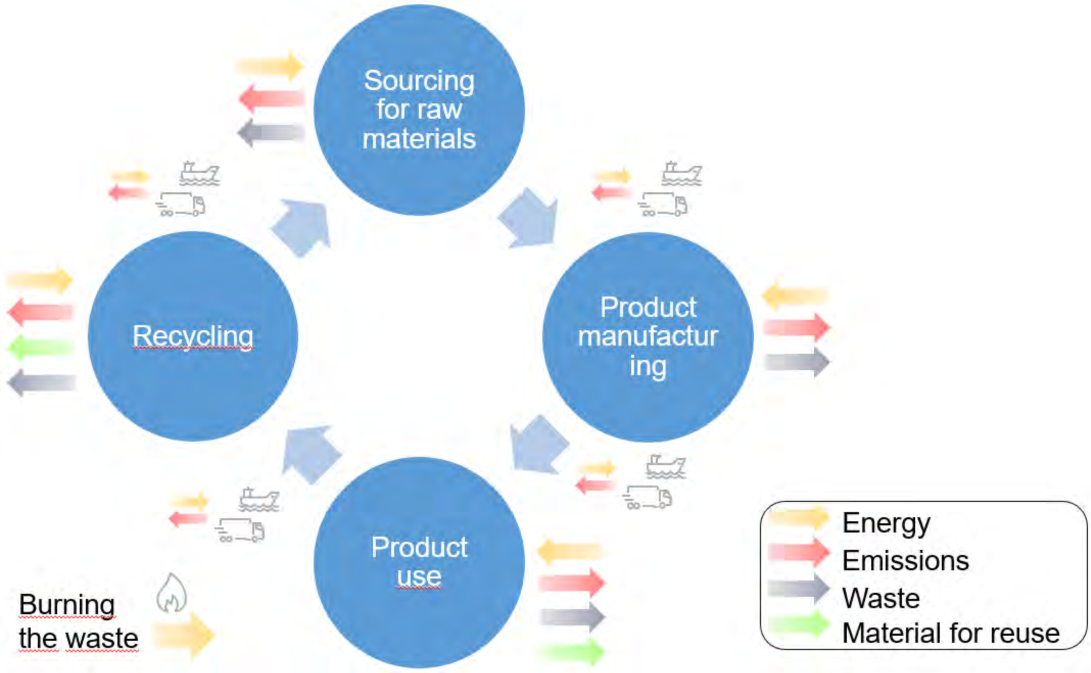


Figure 1.15. Main features of life cycle thinking

A LCA study consists of four stages:

1. defining the objectives and scope of life cycle assessment,
2. Life Cycle Inventory (LCI) analysis,
3. Life Cycle Impact Assessment (LCIA), and
4. interpretation of results.

A life cycle assessment starts by defining the objective and scope of the assessment, followed by a clear definition of the boundaries of the system under consideration. The system boundaries are defined to indicate which sub-processes are included and which are excluded. The subject and purpose of the study to be carried out will influence the level of detail in which the system boundaries are defined. The precision and scope of the life cycle assessment are also determined at the beginning of the assessment and can vary widely depending on the objectives of the study (ISO 14040, 2006; ISO 14044, 2006).

The inventory analysis is the second step of the life cycle assessment. It involves the collection and quantification of the inputs and outputs of the system under assessment. Data collection is also carried out at this stage. Typical inputs are energy and material flows, such as electricity or raw materials. Outputs can be, for example, material goods, services, or semi-finished products. The accuracy of the inventory analysis determines the accuracy of the final assessment, so it is important to collect as accurate information as possible about the system under consideration. Descriptions of unit processes are also saved using process diagrams. A detailed description of the unit processes, a listing of the units used, and a description of the calculation methods will facilitate a uniform and consistent treatment of the product systems under consideration. In addition, the inventory analysis determines emissions to air, water and soil and other relevant environmental aspects (ISO 14040, 2006; ISO 14044, 2006).

The purpose of the impact assessment, based on the information gathered in the inventory analysis, is to assess the potential environmental impacts over the life cycle of the product under consideration. This is done by placing the results of the inventory analysis into a specific impact category. Examples of environmental impact categories are eutrophication, acidification, or climate change. To translate environmental impacts into numerical results, characterization models and factors must be used. For example, the characterization model for climate change is the 100-year reference model defined by the IPCC and the characterization factor is the global warming potential (GWP100) specific to each greenhouse gas. The characterization model describes the environmental impact of each impact category (ISO 14040, 2006; ISO 14044, 2006).

The results of the inventory analysis are not valid for the characterization model as such, but must be multiplied by a characterization factor, which transforms the results into a characterization model. For example, when considering climate change, all life-cycle greenhouse gas emissions are converted into carbon dioxide equivalents, which are summed to give the climate change potential (GWP) of the system under consideration. Characterization factors are used for this purpose, an example of characterization factors for greenhouse gases is given in the following Table 1.4.

Table 1.4. Global warming potential factors

Carbon dioxide	1
Methane	28
Nitrous oxide	298

Interpreting the results is the final stage of the evaluation. Its aim is to draw conclusions and make recommendations in relation to the objective and scope defined at the beginning of the LCA, using both the results of the inventory analysis and the results of the environmental impact assessment (ISO 14040, 2006) The whole LCA process must be transparent and comprehensive, and the interpretation of the results as unambiguous as possible.

The results of a life cycle assessment can be used in many ways, for example in product development, policymaking, strategic planning, and marketing. It is also used to calculate and communicate carbon and water footprints, for example. Life cycle costing can also utilise the results of life cycle assessment (ISO 14040, 2006; ISO 14044, 2006).

While many companies strive to reduce their own footprint, more and more companies are developing products or processes that aim to reduce the footprint of their customers' products or services, thereby also creating a positive environmental impact, or handprint. Handprint calculation is also based on life cycle assessment. VTT and LUT University have developed a carbon handprint method for assessing and communicating positive environmental impacts (Pajula et al., 2018). A carbon handprint can be created in many ways, such as using less material and energy, reducing emissions and waste, or increasing product performance and lifetime compared to baseline.

Key lessons

Performance measures and key performance indicators (KPIs) are necessary to maintain and improve the performance of products and systems in the most efficient way throughout their life cycle.

- Overall efficiency (OEE) describes the efficiency of the system's operation relative to the theoretical or planned operation.
- Life cycle costs (LCC, WLC, TCO) consist of all direct and indirect costs incurred during the life cycle of a product or system.
- Life cycle costing looks at future costs and operating scenarios, so considering uncertainty and risk is an essential part of the process.
- Life Cycle Assessment (LCA) is the study of the environmental impacts of a product, service or activity using an ISO standardized methodology.
- A life cycle assessment focuses on the environmental aspects and potential environmental impacts (e.g., climate change) throughout the product life cycle.
- Footprints describe the life cycle environmental burden, while handprints describe the positive environmental benefits.
- The results of life cycle assessment and life cycle cost assessment can be used for example for product development, decision support, strategic planning, and marketing.

1.6. RISK MANAGEMENT

Teuvo Uusitalo

Introduction

Uncertainty is an inherent part of all organisational activities. Recognising and managing uncertainty is a key part of running a successful organisation. Systematic risk management is the key to operating in an uncertain environment. Well implemented risk management adds value.

The importance of risk management has increased recently for several reasons. The 2020 coronavirus pandemic has posed new challenges at all levels of society. In addition, businesses are constantly changing as the business environment and products change and new technologies enable new services and products. Business models are also changing, which changes the distribution of benefits, risks, and responsibilities between parties. Environmental requirements for sustainable development are driving the development of new technologies and new actors are entering the market. Production systems, value chains and networks are becoming more complex and harder to manage, and market reactions are swift. Increased uncertainty in the global economy is the new norm.

There are usually several factors that contribute to the risks. Those who have studied major accidents and significant realised risks have observed that aspects related to organisations' decision-making and management often affect the realisation of risks. The investigation into the 2008 international banking crisis revealed that some companies' board and senior management failed to define and measure an acceptable level of risk. There was insufficient technological infrastructure to effectively identify and measure risk (Senior Supervisors Group, 2009). The Deepwater Horizon oil rig accident investigation concluded that the accident could have been prevented if existing guidelines and practices had been followed. The organisation's operations focused on achieving financial results, with almost no attention paid to risk assessment and management. The culture encouraged risk-taking at the expense of systematic risk management (Deepwater Horizon Study Group, 2011). The investigation of the Fukushima nuclear accident also concluded that the accident could have been prevented if risk management had been at a sufficiently high level. For example, the nuclear power plant operator and the regulatory authorities had not assessed the likelihood of damage and were not sufficiently prepared for accident scenarios (The National Diet of Japan, 2012).

Risk management is a key part of an organisation's strategic management. Risk management involves a systematic process of identifying, assessing, and managing risks. The goal of risk management is to answer four basic questions:

1. What can happen?
2. How likely is this?
3. If an event occurs, what are the consequences?
4. How can the likelihood and/or consequences be reduced or managed?

Risk is understood differently depending on the context and the language used. Risk usually means something undesirable. On the other hand, risk also refers to opportunity and uncertainty. The risk management standard ISO 31000 (2018) defines risk as:

- *risk is the effect of uncertainty on objectives*

The effect is a deviation from the expected. It can be positive, negative or both, and can address, create, or generate opportunities and threats. Objectives can have different aspects and categories and can be applied at different levels. Risk is usually expressed as a combination of sources of risk, potential events, their consequences, and their probability. (ISO 31000, 2018)

In risk management, risks can be examined, and risk management methods can be applied at different levels. At the component level, the focus is on reliability. In machinery systems, key issues are machine safety, reliability, and accident prevention. Risk management in production systems must consider environmental risks, process and system safety, and risks to external stakeholders. At the business level, business, economic, financial, and strategic risks are under examination. At the global level, risks such as climate change, water availability, population growth and geopolitics are considered.

Risks can be classified in different ways. Kaplan & Mikes (2012) present the following classification:

- Preventable risks: accidents at work, interruptions in operational processes, wrong or incorrect actions.
- Strategic risks: voluntarily accepted risks aimed at achieving excellent strategic results.
- External risks: risks arising from events outside the organisation, which are beyond the organisation’s influence and control.

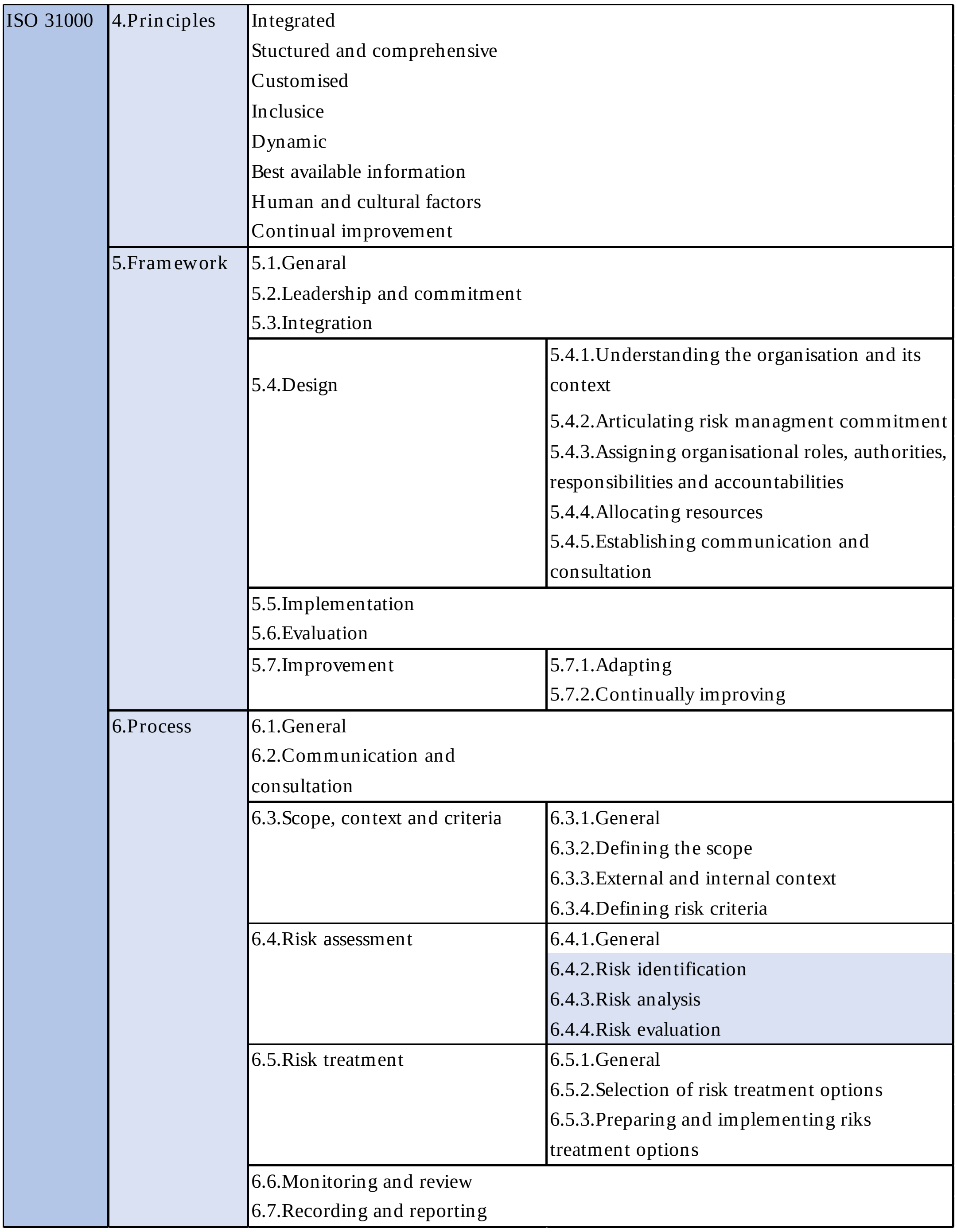
The aim of managing preventable risks is to avoid or eliminate risk factors cost-effectively. In managing strategic risks, the focus is on reducing the probability of events and the severity of their consequences. For external risks, the aim is to reduce the severity of the consequences if the risk materialises.

Risk management standard ISO 31000

The risk management standard ISO 31000 (2018) describes the principles, framework, and process for risk management (Figure 1.16). The standard presents a general approach that can be used in all industries and applied to manage all types of risks. It may be necessary to modify or develop the approach to fit the organisation's operations to ensure efficient, effective, and consistent risk management.

Risk management principles guide the operation. Risk management should be included in the organisation's management system, and structured operation and coverage help to ensure that results are comparable. Risk management should be tailored to the organisation's operations and operating environment. Key stakeholders should be considered and involved in an appropriate manner. Changes in the internal and external operating environment affect risks and should be considered in risk management. Historical data, information on the current situation and estimates of future developments are key inputs to risk management. Human and cultural factors have a significant impact on operations and risk management. Risk management must be continuously developed.

The risk management framework describes how risk management is incorporated into the organisation's core operations and tasks. Developing a risk management framework includes the integration of risk management into the organisation's management system and the planning, implementing, evaluating, and developing risk management.



ISO 31000	4.Principles	Integrated Stuctured and comprehensive Customised Inclusice Dynamic Best available information Human and cultural factors Continual improvement	
	5.Framework	5.1.Genaral 5.2.Leadership and commitment 5.3.Integration	
		5.4.Design	5.4.1.Understanding the organisation and its context 5.4.2.Articulating risk managment commitment 5.4.3.Assigning organisational roles, authorities, responsibilities and accountabilities 5.4.4.Allocating resources 5.4.5.Establishing communication and consultation
		5.5.Implementation 5.6.Evaluation	
		5.7.Improvement	5.7.1.Adapting 5.7.2.Continually improving
	6.Process	6.1.General 6.2.Communication and consultation	
		6.3.Scope, context and criteria	6.3.1.General 6.3.2.Defining the scope 6.3.3.External and internal context 6.3.4.Defining risk criteria
		6.4.Risk assessment	6.4.1.General 6.4.2.Risk identification 6.4.3.Risk analysis 6.4.4.Risk evaluation
		6.5.Risk treatment	6.5.1.General 6.5.2.Selection of risk treatment options 6.5.3.Preparing and implementing riks treatment options
		6.6.Monitoring and review 6.7.Recording and reporting	

Figure 1.16. Structure of the risk management principles, framework, and process elements of ISO 31000 (2018)

The risk management process includes communication and exchange of information with stakeholders, defining the operating environment and risk criteria, risk assessment, risk treatment, monitoring, review, recording and reporting (Figure 1.17).

Risk assessment is a key part of the risk management process. Risk assessment includes risk identification, risk analysis and evaluation of risk significance. The objective of risk identification is to find, detect and describe risks that could prevent the achievement of the objectives of the activity under review or help achieve the objectives. Risk analysis considers the potential consequences of the identified risks and the factors influencing those consequences, assesses the likelihood of the risks and evaluates the effectiveness of existing management measures. Several methods have been developed for risk analysis and are described in ISO/IEC 31010 (2019). In evaluating the significance of the risk, the results of risk analysis are compared with defined risk criteria. Based on this evaluation, decisions regarding risk handling or acceptance can be made, considering the operating environment, different external and internal requirements and consequences for stakeholders.

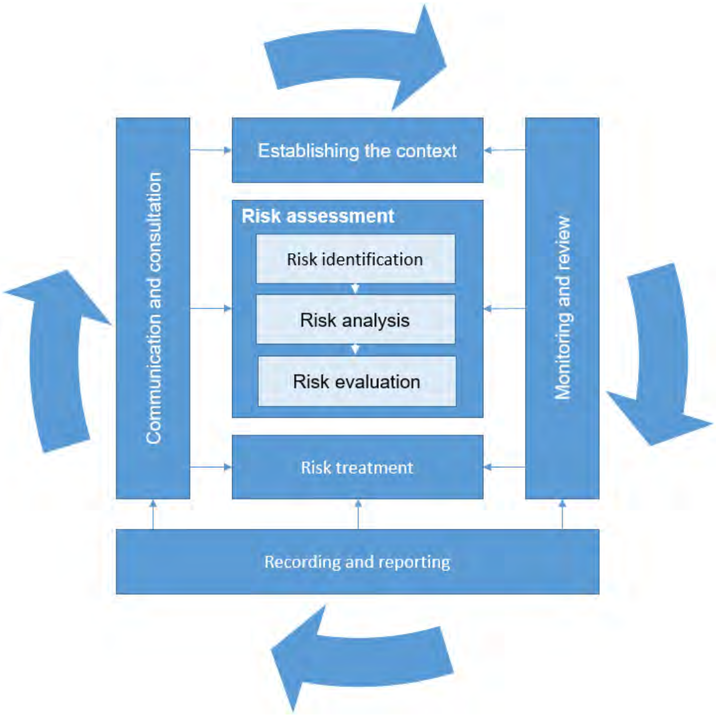


Figure 1.17. Risk management process (ISO 31000, 2018)

Key lessons

- Risk management is a central part of an organisation's strategic management. Well-executed risk management adds value.
- Risk management can involve examining risks and applying risk management methods at different levels.
- ISO 31000 presents a general risk management approach that can be used in all industries and applied to all types of risks. The standard describes the principles, framework, and process of risk management.
- Risk management is a systematic and managed activity.

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PART 2
MANAGEMENT OF PRODUCTION ASSETS

2.1. WHAT IS PRODUCTION ASSET MANAGEMENT

Kari Komonen

Introduction

The management of productive assets is not a new topic. In this chapter[1], physical assets and productive assets are used synonymously. Investors and management have been managing assets for hundreds, if not thousands of years. However, changes in our living and business environments mean that high quality physical asset management is more important now than ever before.

In manufacturing, the *Strategic Asset Management Plan (SAMP)* is based on the company's business strategy and aims to support the achievement of the company's business objectives. In addition to the technology used by the company, the strategy - and the choices made based on that strategy - is influenced by the evolution of the market for the company and the products or services it produces, its position in the market and the demands of the surrounding society.

In the early 2000s, VTT defined physical asset management as "the business principles and technologies for maintaining and improving the productivity, performance, safety, security and value of physical assets". The assets considered are processes, machinery, equipment and real estate in capital-intensive industries and services, as well as infrastructure networks such as energy grids.

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[1] This chapter with modifications is based on the chapter published by Kari Komonen in the Maintenance Yearbook 2019

The 2010s saw the launch of several standardisation projects related to asset management. These resulted in the publication in 2014 of the ISO 55000, 55001 and 55002 series of standards and EN 16646. The preamble, ISO 55000 (2014), defines asset management as "the coordinated action of an organisation to realise the value of its assets". The exploitation of value usually involves weighing up costs, risks, opportunities, and the level of activity (performance).

EN 16646 (2014) Maintenance *within physical asset management* defines physical asset management in equally simple terms: the coordinated action of an organisation to exploit the value of a physical asset. EFNMS (*European Federation of National Maintenance Societies*) defined physical asset management in more concrete terms: 'Physical asset management is the optimal lifecycle management of physical assets with the aim of achieving business objectives in a sustainable manner'.

The management of physical assets is strongly linked to an organisation's strategic business planning:

- It is a question of creating and maintaining production capacity and developing it in the product and market areas defined by the strategy, whether it is a question of physical products or services that require physical assets to produce them.
- The management of physical assets covers all stages of the life cycle, from feasibility study, conceptual design and technology selection, detailed design through to operation, maintenance (including corrective maintenance, replacement investments and modernisation) and decommissioning.
- The management of physical assets also includes the organisation's policies and principles that ensure effective performance towards common goals.
- Advanced decision-making, planning and accounting methods are an essential part of quality asset management.

Asset management includes all the life cycle management measures that the owner takes to achieve the best possible long-term and sustainable financial result. Industrial asset management therefore goes beyond the maintenance of equipment and covers all stages of the life cycle of a production system, from pre-investment profitability assessment (feasibility study), the solution chosen and its design, through to decommissioning.

The content of production asset management can be illustrated by the diagram below (Figure 2.1). In the middle of the circle are the stages in the life cycle of the equipment, and on the next circle are the elements that support and enable asset management. The outer circle describes the general principles of operation and its development. Asset management is not an isolated activity, but interacts with many environmental factors, such as input-providing organisations, markets, stakeholders, financial institutions, regulators, standard developers, and technology suppliers.

The physical asset management of an organisation is carried out through an asset management system. It covers the entire field shown in Figure 2.1.

ISO 55001 (2014) is a requirements standard that sets out the requirements for a management system. For the ISO 55001 requirement standard, the more familiar quality and environmental management systems (e.g.: EN ISO 9000, 2015; EN ISO 14001, 2015) and to some extent the British PAS 55-1 (2008), which was the first standard to address asset management in a holistic way, could be considered as a reference.

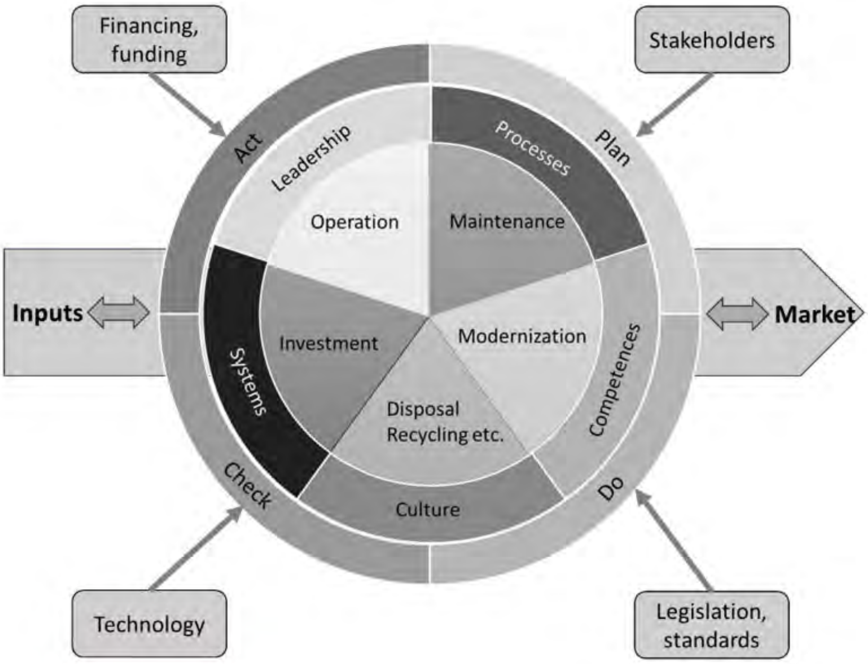


Figure 2.1. The field of physical asset management (Kortelainen & Komonen, 2016: modified from EFNMS model 2012).

Why managing production assets is important right now?

Capital-intensive industry plays a major role in Finland's economy. There are several reasons for this. The amount of production and exports of capital-intensive industries in the short and long term is significant. Energy production, paper and pulp, chemicals and metal processing are typical capital-intensive industries. Sectors comparable to capital-intensive industries include the infrastructure of society, such as electricity distribution networks, waterworks, railways, and ports. Production systems and infrastructures commit significant capital during the construction phase, and ensuring their lifetime profitability requires timely replacement investments, modernisation, and ongoing maintenance.

For example, much of the infrastructure networks globally were built at roughly the same time. Assets age accordingly. Equally, we no longer accept the same level of service for electricity and water networks that we accepted in the mid-20th century, for example. In addition to these trends, production asset systems in most industries are becoming more integrated and complex. Aging, integration, complexity, and increased quality requirements combine to pose a growing risk to society. This growing risk can have very serious consequences if it materialises, as we have recently heard in the news. … In Europe, manufacturing assets have been ageing, partly due to a shift of new investment from Europe to Asia. On the other hand, the prolonged weak economic cycle slowed down the start of replacement and modernisation investments in Europe for a long time. The number of internal and external pressures are increasing the need for higher productivity and operational reliability of production assets. At the same time, the quarterly economy leads to solutions for productive assets that are not efficient in the longer term, but in fact generate increasing costs related to production assets. Similarly, such an undesirable approach can lead to inefficient use of capital, low rates of turnover of physical assets. In the industrial sector, risks have increased due to the combined effect of several factors and trends mentioned above. Pressures for ever-higher returns on capital and strong and inappropriate incentives can lead to serious business, safety, and environmental risks.

Rapid and continuous changes in demand, technology and competition create turbulence in the business environment, which, combined with the low flexibility of production assets, creates challenging decision-making situations. The ever-increasing competition resulting from globalisation increases the pressure for ever-improving efficiency and productivity of production equipment. This forces organisations to bring forward replacement investments, improve production OEE levels, equipment availability and reliability. Safety and environmental requirements are having similar consequences. Production assets that were efficient and imagined to be productive for another 20 to 30 years are suddenly no longer capable of producing saleable products.

A fairly common global problem in capital-intensive industries is overcapacity and low return on capital. Returns on capital can be improved by lowering production costs or by a better rate of physical capital turnover. From a physical asset perspective, these requirements mean dynamic and continuous lifecycle management of production assets, optimal capacity building, improved overall equipment effectiveness (OEE), reliability and flexibility, and lower maintenance costs.

The importance of the capital committed to production systems and its impact on the system's profitability and the achievement of the firm's business objectives varies from one industry to another, depending on the industry's earnings logic, industry critical success factors, technological developments, and market behaviour. Improving the productivity of firms' development investment decisions, the efficient use of fixed asset options, optimising the overall efficiency of production equipment and the cost-effectiveness of equipment uptime, and the efficient use of services require an understanding of the implications of industry-specific business situations.

Internal organisational reasons for the timeliness of physical asset management are also easy to find. A major problem experienced by organisations over the last couple of decades has been siloed behaviour. The different functions of an organisation act according to their own objectives, while forgetting the needs of the whole. These challenges, despite the efforts of many companies, have not gone away. Therefore, one of the main objectives of developing asset management is to reduce silo behaviour. It is fair to say that there is a clear need for systematic, consistent, and methodologically sound physical asset management. This need is evident in both society and business. Certification of asset management has started slowly but surely, first in the infrastructure sector (mainly electricity grids).

In summary, we can list the following reasons to justify the timeliness of physical asset management (EN 16646, 2014):

- globalisation and increased competition,
- growing economic, safety and environmental risks,
- a major shift in business strategies - long term vs. short term,
- attitudes towards the management of physical assets have changed - increasingly, the length of ownership does not correspond to the overall lifetime of the asset (equipment),
- increased capital intensity in some industrial sectors,
- growing turbulence in the market,
- pressure to improve profitability and return on capital,
- the ageing of physical assets,
- increasing pressure to improve the added value of maintenance,
- an increasingly complex and uncertain decision-making environment,
- increased safety and environmental requirements, and
- "silo" behaviour in organisations, which keeps maintenance and other life cycle processes as separate activities.

Typical issues related to the management of production assets

The development of a production asset management and asset management system will bring benefits to the organisation. These benefits are listed in standards such as ISO 5500x and EN 16646 (2014). According to METSTA's EN 16646 training material (Komonen, 2016), for example, improved physical asset management provides better return on physical assets, better short and long-term profitability, better satisfaction among different stakeholders (e.g., customer satisfaction), stronger trust in the organisation's management, lower safety and environmental risk, higher quality products and services, more verifiable organisational capability, and improved performance and efficiency. The benefits are achieved through better management and control of all aspects of physical asset management. Typical issues that need to be considered in the management of physical assets include:

- analysing the organisation's operating environment and developing strategic plans,
- defining and developing management systems,
- identifying and managing critical success factors,
- defining requirements for physical assets,
- effective management of physical assets at all stages of their life cycle,
- defining and developing physical asset management processes (including maintenance),
- dependability management (including maintenance), and
- definition, implementation, and development of a performance measurement system.

Effective management of these issues requires effective uncertainty management, modelling of the production system as a basis for decision-making, and the definition and development of the necessary competences. The standard ISO 55001 (Asset management. Management systems. Requirements) covers following issues:

- context of the organisation,
- leadership
- planning
- support
- operation
- performance evaluation, and
- improvement.

The structure follows the content defined for all ISO management system standards. The ISO 5500x series of standards can be illustrated by the figure below (Figure 2.2).

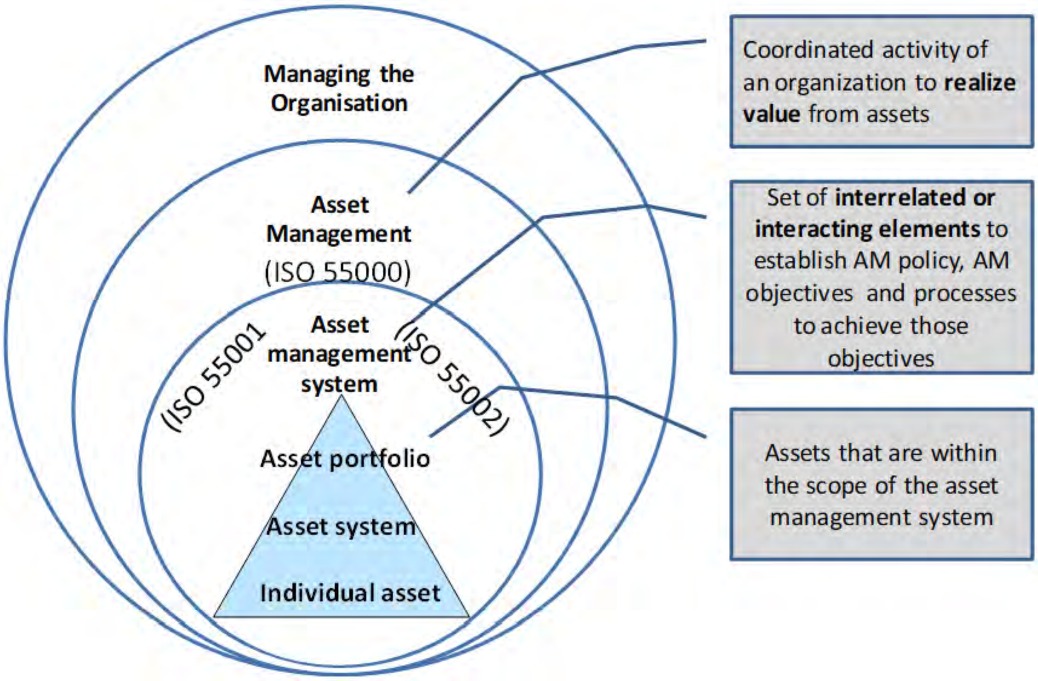


Figure 2.2. Structure of the ISO 55001, 55001 and 55002 series (METSTA training material/Komonen, 2016).

According to the standards, there are three main levels of asset management: asset portfolio, asset system and single asset. A single asset can be a single piece of equipment such as a pump, gearbox, or valve. An asset system can be a larger set of equipment consisting of several individual pieces of equipment, such as a sub-process, production line, etc. An asset portfolio contains several asset systems, such as a factory or a production plant with several production lines. The definition that prevails in each organisation depends on the technology in use and the specific needs of the organisation. EN 17485 (2021) defines the different levels of hierarchy for asset management as shown in Table 2.1. The detailed levels used in the standard are in accordance with PSK 7102. 2008 (Plant hierarchy).

Table 2.1. Asset management levels according to EN 17485 (2021)

	HIERARCHY LEVEL	ASSET PORTFOLIO	ASSET SYSTEMS	ASSET / SINGLE ASSET
1	A complex of several plants / factories	▨		
2	Plant / factory	▨	▨	
3	Production unit	▨	▨	
4	Production line		▨	
5	Process		▨	
6	Sub- process		▨	
7	Function			▨
8	Sub-function			▨
9	Equipment			▨
10	Component			▨
11	Part of			▨

Responsibilities for the management of productive assets in organisations

The management of physical assets requires a wide range and high level of skills. A common assumption is that the management of production assets is the responsibility of the asset manager of the organisation. In some organisations, such a person has been appointed. The role of the 'asset manager' is then to develop policies, procedures, and methods for the management of physical assets and to act as the owner of the asset management process. However, a very common international perception is that the 'asset manager' is a function of the organisation rather than a designated person. An asset manager function can be a person, a team or a collaborative practice or procedure. An asset manager as a function may be part of a maintenance, production, planning, finance, or even general management functions, depending on the specificities of the industry and technology, the characteristics of the company and its development plans. The EFNMS carried out a survey in 2011 to find out how physical asset management was organised in companies. The results are indicative and show the importance of technology and the business environment (Figure 2.3).

The study found that the maintenance function was often financially responsible for the management of physical assets. It was also common for the main responsibility to be taken by production management. Almost one fifth of the respondents had appointed an asset management team and one sixth an asset manager. Respondents came from a wide range of technology and business environments: from infrastructure to process industries. Similarly, the typical life span of assets varied widely.

The survey also sought to find out how the maintenance function is involved in the different stages of asset management. When asked about the technical *design* stage of an investment, maintenance was most often involved in the design either as a temporary team member or as a permanent member. The third most typical case was when the opinion of maintenance was asked (Figure 2.4).

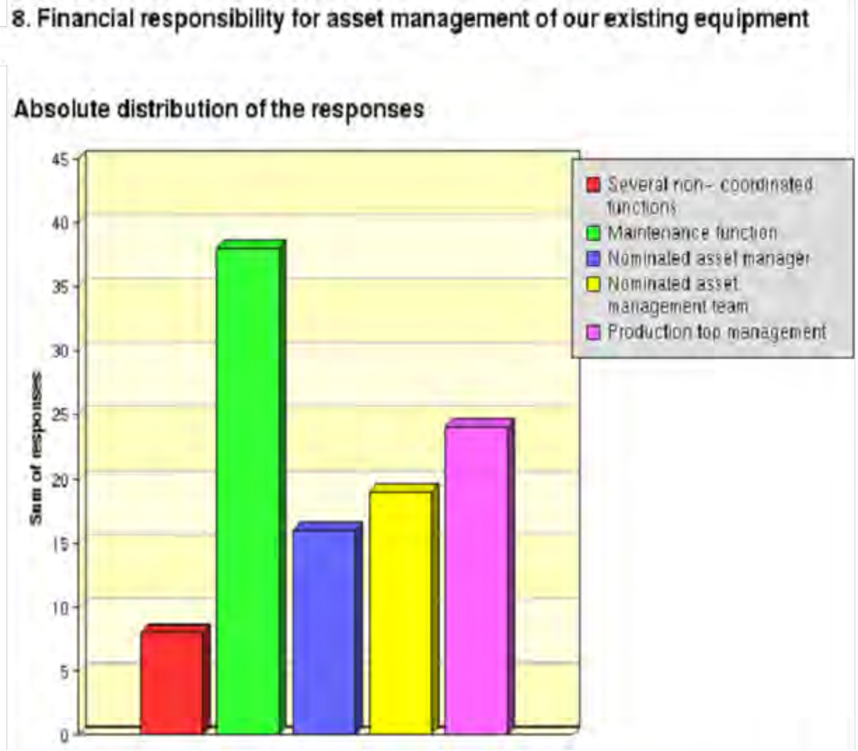


Figure 2.3. Organisation of physical asset management (EFNMS2012)

High-quality production asset management requires the seamless interaction of several organisational functions. It is a planned and organised interplay between production, maintenance, technical and business planning, investment planning, finance, and general management. It is important to remember that the management of productive assets is not only a matter for the managerial and supervisory levels but is the concern of every person working in the organisation. It is therefore important that personnel understand the requirements for the physical assets and the objectives and principles of asset management. Collaboration between different functions and the reduction of siloed behaviour requires not only common objectives but also common processes, with each function having its own role, linked to other roles in an understandable way.

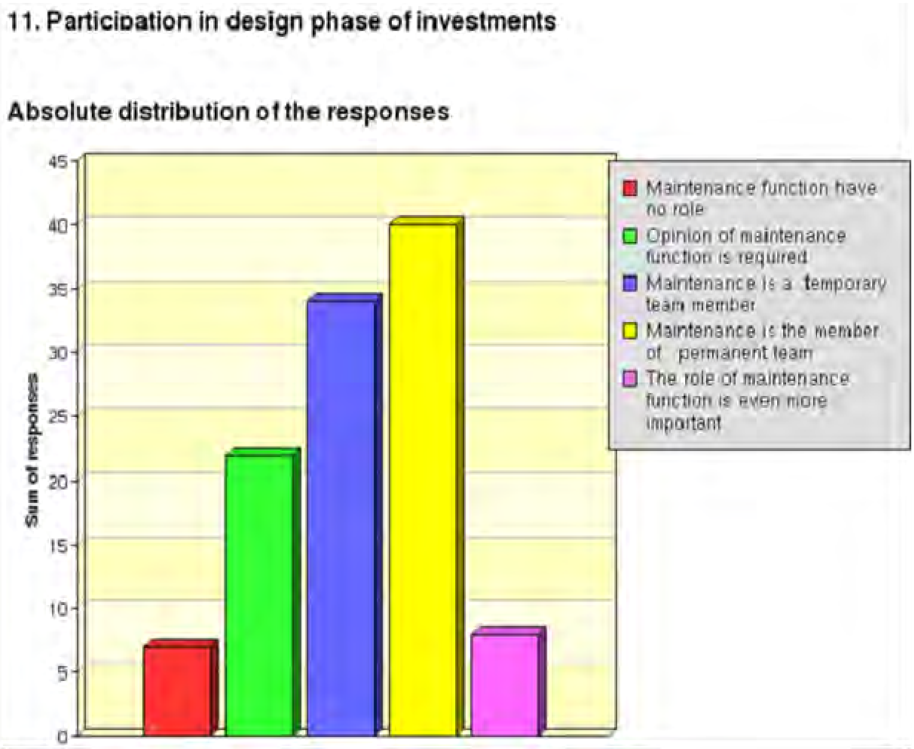


Figure 2.4. The role of maintenance in the design stage of an investment (EFNMS2012)

When asset and life cycle management is particularly important

The content and priorities of a quality asset management and asset management system depend on the technological and operational environment of the organisation. While the choices made by management regarding the management system will depend on the operating and technological environment of the individual organisation, the strategic plan of the organisation and the views of management, some general frameworks, guidelines, and choices can be identified.

Asset management is, of course, very important in those organisations, where value creation is particularly linked to productive assets and their efficient use. Several infrastructure sectors and the process industries are good examples of such industries. The way in which asset management is organised and what is its importance, are also influenced by the other factors determining the operating environment.

In a situation where technological and environmental (market) changes are large and rapid the management of production assets relies more on management decisions and direct control than in a situation where technological and environmental changes are slow. In the latter situation, physical assets are more often managed through management systems, guidelines, and processes (EFNMS asset management survey 2012, Komonen 2012). The above simplified classification is shown in Figure 2.5. The situation can be compared, for example, to the differences between crisis management and normal situation management.

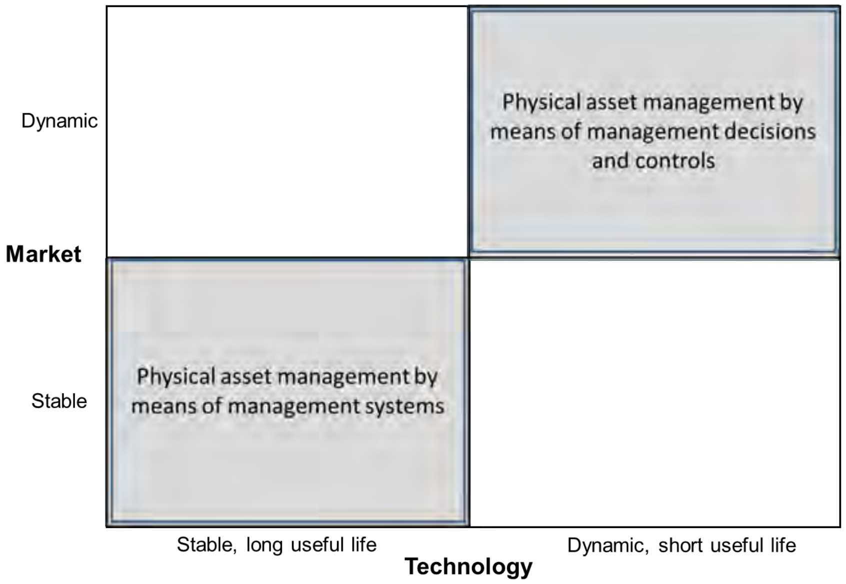


Figure 2.5. Impact of the operating environment and technology on the physical asset management system according to the EFNMS survey (EFNMS, 2012; Komonen, 2012).

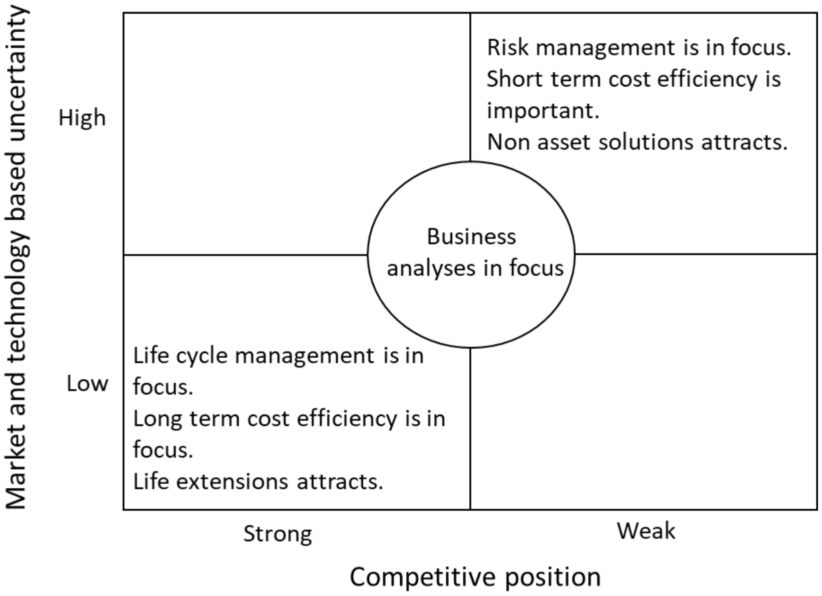


Figure 2.6. The impact of environmental uncertainty and competitive position on the management of physical assets.

Uncertainty related to the operating and technological environments also has an essential impact on the key element of asset management i.e., life cycle management and its attractiveness for companies. When the uncertainty associated with the operational and technological environment is high and the competitive position of the organisation is weak, risk management and short-term cost-effectiveness are highlighted. In a context of low uncertainty and strong competitive position, life cycle management is attractive and long-term cost-effectiveness is important. For organisations in the middle of the scale, high quality situation analysis and accurate conclusions are particularly important (Figure 2.6).

General objectives of production asset management

Generally speaking, the aim of physical asset management is to help organisations succeed better in the face of growing challenges. Thus, it aims to help organisations to define the requirements for production assets in an ever-changing environment and update them in line with the changing challenges. Furthermore, asset management helps organisations to find the best solutions for the acquisition, operation, and maintenance of their production assets. Carefully defined requirements for physical assets will ensure context-appropriate solutions, asset management strategies and plans that further:

- bring better profitability,
- better competitiveness,
- sustainable development and
- the right timing of development measures.

To achieve the above objectives, organisations must define and implement an asset management system and, where necessary, evolve it in line with changing business and technology requirements.

When an organisation faces challenges or problems in managing its assets, the focus often turns to technical issues and the people responsible for them. Often the root cause of the challenges is not technical but lies elsewhere. The root cause of the challenges may be, for example:

Technical reasons: e.g., new or old technology, wrong specification, choice of equipment not following specification, poor maintenance, etc.

- Changes in the business environment after the acquisition of equipment.
- Weak decision-making processes and methods.
- Poorly understood market requirements.
- Lack of competence,
- Poorly defined and/or unsuccessfully implemented asset management system.

Often the root cause of problems is the last on the list - the management system - even if, on a quick glance, the problem seems to lie elsewhere.

One of the main objectives of the asset management system is to ensure planned, systematic, and long-term asset management supported by management and designated managers, to reduce "silo behaviour" in the organisation and to ensure continuous improvement based on performance evaluation.

The specific objectives of physical asset management can be considered in terms of the procedures and methods by which the management of an asset is carried out. High quality asset management in an increasingly competitive environment requires better asset management methods. Successful organisations use analytically developed and tested methods. At the very least, their management understands the challenges involved in decision-making. Here are some considerations and approaches that can help ensure quality asset management:

- Identification of external and internal influencing factors that are relevant to the management of physical assets and maintenance management.
- Taking these impacts into account in decision-making and planning,
- Integration of production asset management and maintenance management.
- Promoting life cycle management as a normal practice and part of sustainable development.
- Reducing silo behaviour in asset management and developing cooperation (this includes cases of outsourcing).
- Promoting transparency throughout the organisation.
- Promoting visualisation as an effective tool for asset management.
- Promoting uncertainty management and simulation to assess the impact of different options and decisions.

Key lessons

- Physical asset management is the management of the life cycle of production assets and the development of supporting management systems and organisation.
- Organisational environments are becoming more demanding, unpredictable and the speed of change is increasing.
- The organisational and technological environment influences the basic choices of management systems. A stable environment and good competitiveness require a different management approach than a dynamic environment and poor competitiveness.

2.2. STRATEGIC ASSET MANAGEMENT METHODS

Kari Komonen

Flexibility and uncertainty

An organisation can compensate for uncertainty with flexibility. The more flexible an organisation is, the better it can cope with changes in the organisational environment that are difficult to predict. Unfortunately, high uncertainty and good flexibility do not always go hand in hand. The flexibility of a production system can be, for example:

- upward volume flexibility (increasing production capacity at low cost),
- downward volume adjustment (reducing production at low cost),
- product flexibility (low-cost product substitution),
- adapting to fluctuations in demand at low cost,
- adapting to change in critical success factors at low cost,
- material flexibility (the ability to adapt to variations in raw materials),
- technical robustness ("fault information", e.g., redundancy), and
- promoting visualisation as an effective tool for asset management.

A high degree of flexibility compensates for uncertainty on market, technology, and competitiveness grounds. Conversely, low flexibility can amplify the effect of uncertainty by increasing the need to upgrade, modify or modernise production assets in the case of future undesirable developments, which in turn implies unanticipated costs (Figure 2.7).

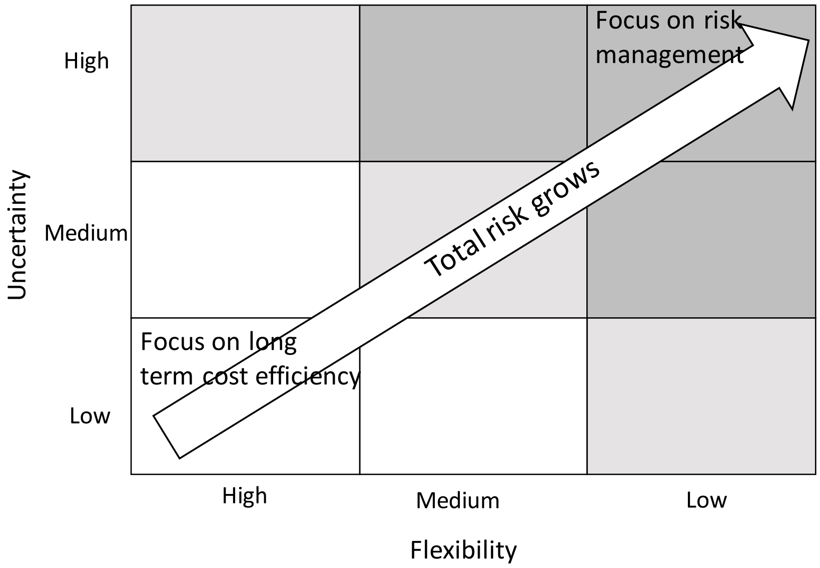


Figure 2.7. The impact of uncertainty and flexibility in the operating environment on the management of physical assets.

If a change in the business environment causes a significant change in demand for the product or a significant change in critical success factors, financial losses are likely since the initial investment has not yet been repaid or that new investments may be required to respond to the new market situation. Flexibility in the production system, such as volume flexibility, product flexibility or raw material flexibility, may compensate for possible losses. For example, the minimum efficient scale or an investment in expansion will have a significant impact on the volume flexibility of a production unit. The lower the minimum efficient scale or the lower the minimum efficient investment in expansion, the higher the volume flexibility. In this context, the possibility to sell old production equipment is also an important issue. The easier and more profitable it is to resell the equipment, the more flexible the production unit will be (we will come back to this later).

This approach differs from the traditional risk management framework in that it is not based on a risk assessment of specific events, their probabilities, and the severity of their consequences, but on a determination of the level of risk in the overall organisational environment to understand its implications for the management of the organisation's assets and asset solutions.

Factors affecting uncertainty

Many external influencing factors are at least partly beyond the control of organisations. Such factors may include, for example:

- legislation,
- environmental and safety requirements,
- general economic situation,
- political conditions,
- exceptional events,
- technological development, and
- market changes.

Defining and understanding uncertainty in markets and technological developments are key tasks for the management of an organisation. Market turbulence is, for example, a function of factors such as:

- barriers to entry,
- changing consumer preferences,
- changes in investor behaviour,
- changes in the different market areas,
- changes in industrial activity,
- price changes for product substitutes, and
- the life cycle stage of the product in question.

The speed of technological change is influenced by factors such as:

- changes in the number of innovations,
- economic barriers to market entry,
- technological barriers to market entry,
- know-how gaps between different actors,

- economic friction (e.g., capital intensity), and
- minimum effective scale or expansion investment.

Although these factors are largely beyond the control of management, companies are not passive actors, but can actively seek to influence society, markets, and technological developments. Naturally, the greater the influence of the firm, the less uncertainty there is in the business environment.

Factors affecting flexibility

Factors affecting flexibility can be related to the strategic plan of the organisation, business logic or technological factors. Resilience factors related to an organisation's strategic planning can mean choosing a strategy that is as robust as possible to environmental change (more on this later in Chapter 2.6) and developing a high-quality recovery plan. Business logic factors can mean, for example, investment practices within the firm, such as the use of real options, flexible practices that change according to environmental characteristics, or factors related to technological choices.

Flexibility measures the strength of the impact of uncertainty. The organisation in question has two main strategies to choose from: 1) mitigate the consequences, for example by reducing investment in production assets (e.g., by improving maintenance instead of investment) or 2) improve adaptability, for example by real options, lowering the asset specificity of productive assets or investing in technological leadership. Flexibility relates to factors such as:

- the length of the useful life of the equipment,
- investment propensity (e.g., replacements, expansions, and modification investments),
- investment criteria (calculation methods),
- effective maintenance strategies (corrective maintenance, condition monitoring investments and major repairs),
- replace or maintain decisions, and
- outsourcing decisions.

Real options

Real options are investments that are made now, even though they are not needed now, because using a real option reduces costs and increases the flexibility of the solution when the real option is used. However, when a real option is invested, it increases the investment cost, but if the real option is used in the appropriate time window, it reduces the overall cost. The use of a real option is therefore closely linked to the management of uncertainty. For example, in the construction of a 2-lane road, a bridge is built with a width of 4 lanes because there are plans to widen the road to 4 lanes in the future. This creates a real option that makes economic sense if the road is widened later and if, in addition, the widening is done in an economically efficient time window. On the other hand, the real option reduces flexibility, because if the real option cannot be used, for example because of a change in demand, the additional investment is useless.

Annual and cumulative costs											
	Investment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Alternative 1	**100**						**100**				
Alternative 1 Annual costs		10	10	10	10	10	10	12	12	12	12
Alternative 1 Cumulative cost		110	120	130	140	150	260	272	284	296	298
Alternative 2	**100**										
Alternative 2 Real option	**50**										
Alternative 2 Annual cost		12	12	12	12	12	12	12	12	12	12
Interest rate for real option	5,0 %	2,50	2,63	2,76	2,89	3,04	3,19	3,35	3,52	3,69	3,88
Alternative 2 Cumulative cost		164,5	179,1	193,9	208,8	223,8	239,0	254,4	269,9	285,6	301,4
Probability of the deployment of the real option	0-1						**1**				

Table 2.2. Example of a real option.

Table 2.2 shows an example of a simplified real option calculation. Option 1 is an investment without a real option. The investment and the annual costs in the next row are shown without discounting to the present and without any possible changes in monetary value. The investor has estimated that the need for an expansion investment, for example, is in year 6. In this case, the additional investment would cost 100 euros. In option 2, the basic investment is also 100 euros, but the possible future need for expansion investment has been considered and the cost of this investment is 50 euros in this case. The annual cost is slightly higher than in Option 1 due to the larger asset mass. The interest cost for the real option is calculated at % in the example, as the real option is a cost that would not be needed, now. When comparing the total cumulative costs of the two options, it can be concluded that if the real option is introduced in year 6, the real option is profitable. The longer the real option is postponed, the less profitable it becomes. The profitability of using the real option depends, of course, on the interest rate used, the liquidity situation of the organisation concerned, the uncertainty surrounding the need for the real option and the alternative investment targets.

Investments and flexibility

In a situation of high uncertainty in the organisational environment and technological developments, an attempt to increase flexibility can be made by avoiding investments in inflexible technologies and adopting *non-asset solutions*. Such alternatives may include subcontracting production, leasing equipment, investing only in alternatives with a payback period that fits within a less uncertain time horizon, postponing a decision to a later date or changing a new product strategy. In the case of an ongoing plant, the life of the old equipment can be extended instead of a replacement investment.

Technological product flexibility

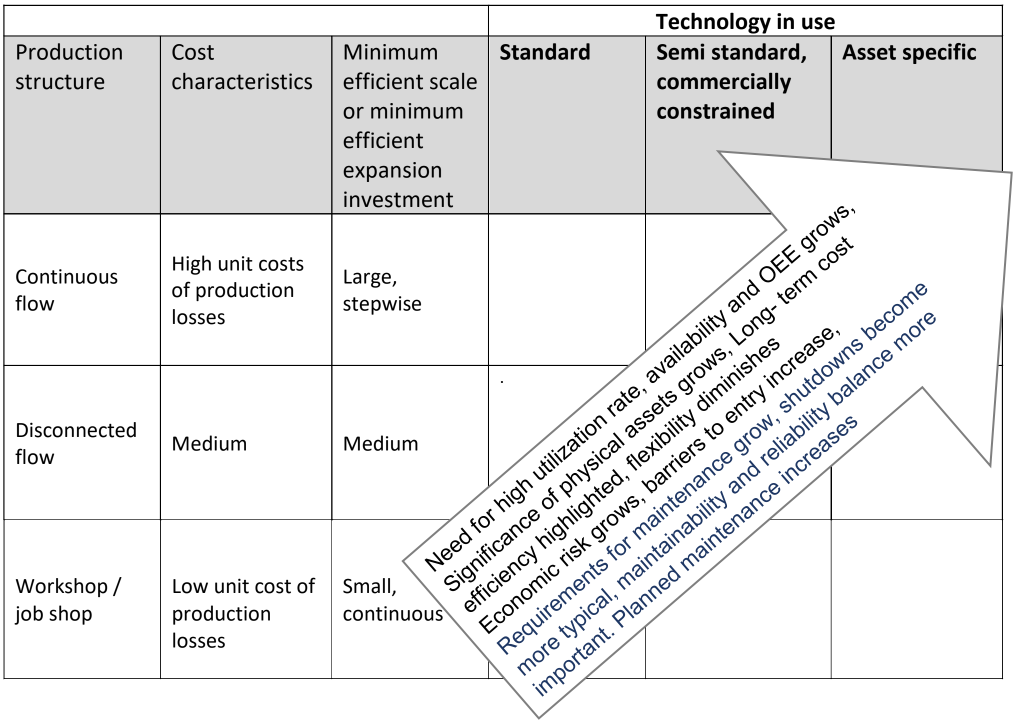
The technology in place can be multi-purpose, making changes to the product range technically easy and cheap. The technology may also allow the production of a wide range of products. These two sources of flexibility reduce the impact of uncertainty faced by the organisation. Production equipment consists of asset systems of varying specificity/standardisation. On the other hand, the contribution of these assets to the production of the company's product also varies. A product transformation may require a complete renewal of the production process or the replacement of a critical set of assets with new equipment. The adaptability of production equipment creates flexibility for physical assets in the case of small or medium product improvements or changes. The adaptability of physical assets is the result of the following factors:

- asset specificity,
- the replacement value of the present asset system (ARP), and
- the value of the investment required.

Together, these factors indicate the cost of the investment required for the change and the cost of abandoning the old equipment. The asset specificity of a production asset indicates how standard and saleable the asset in question is. The value of the investment required indicates how achievable economically the change is. Together, the asset specificity and the value of the investment provide an indication of how achievable the acquisition is and what its cost is. High specificity and high acquisition cost imply low transformability.

Volume flexibility

Figure 2.8 provides a simplified description of the impact of some technological factors on physical asset management strategies and practices. On the other hand, these factors have an essential impact on the volume flexibility of the production process in question. These factors are, on the vertical axis, the structure of production (degree of integration), the cost per unit time of production loss, the minimum efficient plant size and/or the minimum efficient expansion investment, and, on the horizontal axis, the standardisation of production technology and possibility to sell assets to raise cash.



			Technology in use		
Production structure	Cost characteristics	Minimum efficient scale or minimum efficient expansion investment	**Standard**	**Semi standard, commercially constrained**	**Asset specific**
Continuous flow	High unit costs of production losses	Large, stepwise			
Disconnected flow	Medium	Medium			
Workshop / job shop	Low unit cost of production losses	Small, continuous			

Need for high utilization rate, availability and OEE grows,
Significance of physical assets grows, Long- term cost
efficiency highlighted, flexibility diminishes
Economic risk grows, barriers to entry increase,
Requirements for maintenance grow, shutdowns become
more typical, maintainability and reliability balance more
important. Planned maintenance increases

Figure 2.8. Impact of the production system on asset management (Komonen, 2019).

The limited possibility to sell the assets of a semi-standard technology in the figure means that, although the technology in question is available on the market, its adaptability to the needs of a new owner is limited and, on the other hand, for reasons of competitive strategy, it may not be sold but rather scrapped in order to reduce capacity on the market.

Moving from workshop-type production to flow-type production, in most cases the possibility of volume increases changes at the same time. Flow-type production involves a large stepwise minimum efficient expansion investment, which implies weak/low volume flexibility. On the other hand, process adaptability is also costly and demanding. At the other end of the spectrum, stepless scalability is typical, implying good and cheap volume flexibility. On the other hand, process adaptability (product flexibility) can also be cheap and easy. In addition to the above, there are of course other technological factors that influence the priorities and approaches chosen, such as the reliability characteristics of the production system.

Table 2.3 shows a simplified version of Figure 2.8. This framework allows a rough analysis of when an investment solution is better than an efficiency improvement. It can also be applied to a simplified analysis of outsourcing decisions. In the case of high minimum investment and stepwise expansion, the production system is often integrated, while in the opposite case it is labour-intensive. In the case of an integrated plant, it is often profitable to increase capacity through improved OEE, improved maintenance or process modifications.

Table 2.3. Impact of the production system on investment decisions, a framework (Komonen et al. 2012; Komonen 2019)

		TECHNOLOGY	
		Standard	Asset spesific
MINIMUM EFFECTIVE SIZE OR MINIMUM EFFECTIVE EXPANSION INVESTMENT	Large, stepwise	Standard process. Subcontracting available. Subcontracting may be a good solution, especially if the capacity requirement is lower than the minimum investment will deliver. The sale of production assets is possible. High OEE levels and process modifications are important if subcontracting is not profitable.	A company-specific process. Difficult to sell assets. Subcontracting difficult. Expansion investments can involve risks. The stage in the life cycle of a product or equipment affects the decision. High OEE and process improvements are **very** important.
	Small, continuous	Standard hardware. Possibility to sell the equipment. Subcontracting or investment possible The cost of the OEE improvement or additional capacity invested determines the solution.	Company-specific equipment. Selling the equipment can be difficult. Subcontracting can be difficult. Increasing capacity through investment is low risk.

Uncertainty, time horizon and risk tolerance

If a change in the business environment causes a substantial reduction in demand or significant changes in the required characteristics or critical success factors of a product, financial losses are obvious because investments in production assets may not yet have paid off or new investments are required to manufacture new products or to meet the requirements of the critical success factors. The flexibility of the production system (volume flexibility, product flexibility or material flexibility) can compensate for the losses caused by the change. The minimum efficient scale is a significant indicator of the volume flexibility of a production plant. The smaller the minimum effective scale, the more flexible the production unit. Further, the easier and more profitable it is to resell old equipment, the more flexible the production unit.

An essential dimension of uncertainty in the business environment is time span and uncertainty as a function of time span. In this context, the concept of 'the portion of an investment that has not been repaid before a turbulent time horizon' is also introduced. Uncertainty can be viewed in relation to critical success factors. Similarly, uncertainty depends on the time span and the rate of change. At a general level, it is possible to distinguish three different time zones with different implications for asset management and investment decisions. These time zones in terms of critical loss factors and product demand are (Stacey, 1990 with modifications):

1. a known zone (e.g., recurring transactions, known order book, no new licences issued to the other operators),
2. a predictable, probable future time zone (e.g.: time-related barriers to entry are known, time requirements for product development are known, demand trends are known), and
3. discontinuous, turbulent zone (not predictable)

The length of the time zones depends on the needs that the service or product satisfies. For example, the supply of products that satisfy basic needs such as food, housing, and energy consumption does not change as quickly as information generation, training needs, or fashion markets. These changes may be driven by changes in demand for products, and in this case, they are indications of changes in consumer preferences or changes in business opportunities (pulling impact). It may also be driven by new products and services offered by technological developments or by more efficient production and logistical processes (pushing impact). The length of the first two time zones may be increased by financial inertias due to competitors' difficulties in obtaining financing for projects, too high a risk for the investment relative to the estimated payback period or too high a risk relative to the competitor's risk tolerance. Therefore, the length of the three time zones mentioned above will differ depending on the product, the market and the technology used. Figure 2.9 illustrates the combined effect of the flexibility of the production system and the above time zones on the level of risk of an organisation's investment.

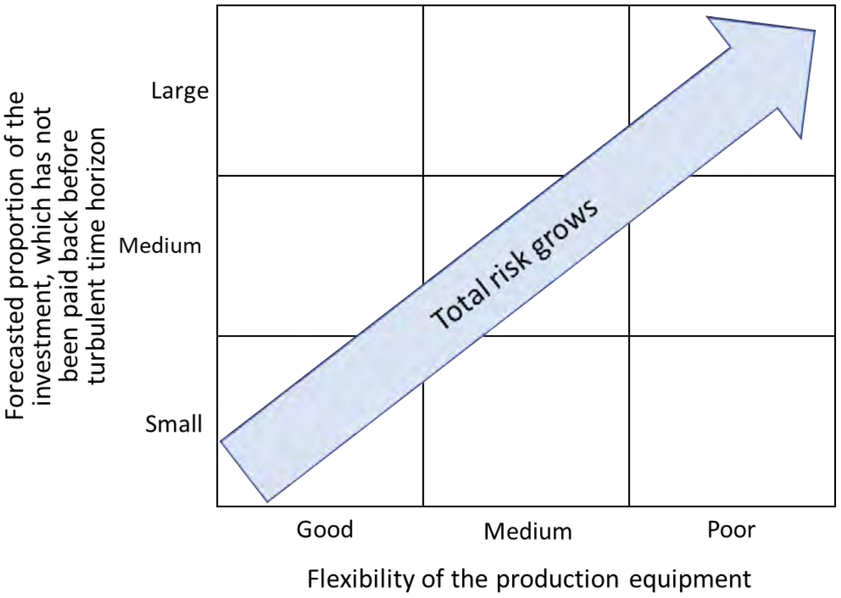


Figure 2.9. Interaction between flexibility and different uncertainty time zones.

Based on the above framework, it is also possible to define indicators that measure the risk associated with investments:

- Predicted share of investment not repaid within a known time zone (EUR)/organisation's risk tolerance (EUR).
- Projected share of investments not repaid before the turbulent period (EUR)/risk tolerance of the organisation (EUR).

The above frameworks have important implications for companies' production asset solutions, production asset management and asset management systems. These impacts include:

- the need to assess the flexibility requirements of production asset solutions,
- the need to define a management approach, a management philosophy (e.g., life cycle management) appropriate to the business situation of the organisation,
- the need to assess and define the useful life of the assets,
- a motivation to extend the remaining life of the assets,
- the need to carefully define the decision criteria and appropriate calculation methods for investments,
- the need to systematically assess the factors affecting the profitability of modifications,
- the need to systematically assess the factors affecting the profitability of replacement investments, and
- the need to systematically define effective maintenance strategies (e.g.: corrective maintenance, investment in maintenance control, major repairs).

Introduction[2] to the definition of the requirements

Organisations develop a strategic plan, of which the product and market portfolio is an essential part: for example: which products are included in the range, and in which markets they are sold. The products define the required production technology and market requirements for the products and possible production locations. The organisation's products also influence the economic structure of the firm: capital-intensive, labour-intensive or something in between. The surrounding society places demands and opportunities on the organisation through legislation, culture, infrastructure, etc. An organisation's decisions are also influenced by its economic position and the goals it has set for itself. Taken together, these factors influence the requirements for and the solutions to be adopted for production assets. Thus, an organisation's strategic plan for the management of its physical assets (ISO 5500x uses the acronym SAMP) is an essential part of the organisation's strategic plan.

The links between the management of production assets and an organisation's strategy and strategic plan are illustrated in Figures 2.10 and 2.11. In short, the technology used by the organisation, the market, the surrounding society and the goals, visions, long-term objectives, and other organisational characteristics of the company itself determine the requirements for the physical assets and further the solutions chosen for production assets. The identified requirements for the production assets are based on the critical success factors identified from the above factors. On the other hand, an important part of physical asset management and maintenance is to take a position on the different asset options identified by the organisation and to examine the impact of the different options on asset management, dependability, and maintenance.

Once the requirements for production assets are clearly defined, it is possible to decide on solutions that best meet these requirements in a cost-effective way. Defined requirements provide the basis for the formulation of asset management objectives, strategy, and plans. Further, the asset management objectives, principles and plans define the maintenance objectives, strategies, and plans.

The process described above can be called the strategic process of physical asset management. The success and development needs of this process need to be monitored and managed and improved as necessary. Although the use of KPIs is well developed, organisations need to review how well the three levels of the strategic process of physical asset management requiring KPIs are covered (Figure 2.11).

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[2] The introduction is based on the text of the 2019 Maintenance Yearbook (Komonen, 2019).

Figure 2.10. Managing physical assets as part of the strategic management of an organisation.

The successful implementation of an organisation's strategic asset management process needs a methodological framework. EN 17485 (2021), which is in the final ballot, provides the tools for the implementation of asset management processes.

Definition of the requirements

The methodology is based on the identification of critical success factors by business segment (Figure 2.11). As outlined above, the critical success factors within a segment are determined by the organisation's products and four influencing factors (market, society, technology, and the organisation itself). The critical success factors define the means, by which the organisation can achieve its business objectives and succeed in competition with competitors and substitute services/products. Critical success factors may relate to, for example:

- service levels (e.g., user experience, reliability, speed, punctuality),
- safety (e.g., personal, material, environmental, cyber),
- environmental friendliness (e.g., low emissions, low life cycle costs),
- performance (e.g., speed, volume, high input-output ratio),
- cost-effectiveness (e.g., price-quality ratio, input-output ratio), and
- low capital use (e.g., low life cycle costs, low acquisition costs, good performance).

The requirements for productive assets depend on the products or services produced by the organisation and the internal and external influencing factors (market, society, technology, and the organisation itself) described earlier, as well as the organisation's objectives, strategies and critical success factors defined on this basis. Defining requirements is not necessarily a simple and straightforward process, but a multi-dimensional and analytically demanding task. To facilitate this task, different business and technology environments can be reduced to a few main categories with clearly definable generic requirements for physical assets (EN 17485, 2021). Requirements may include, for example, capacity scalability, capacity, and flexibility:

- flexibility to meet changing customer needs,
- reliability, durability,
- environment and safety,
- product quality,
- efficiency,
- cost-effectiveness,
- the availability of the equipment,
- the future market value of productive assets,
- use of the latest technology in equipment selection,
- standardisation of production assets within the organisation,
- production assets based on staff qualifications.

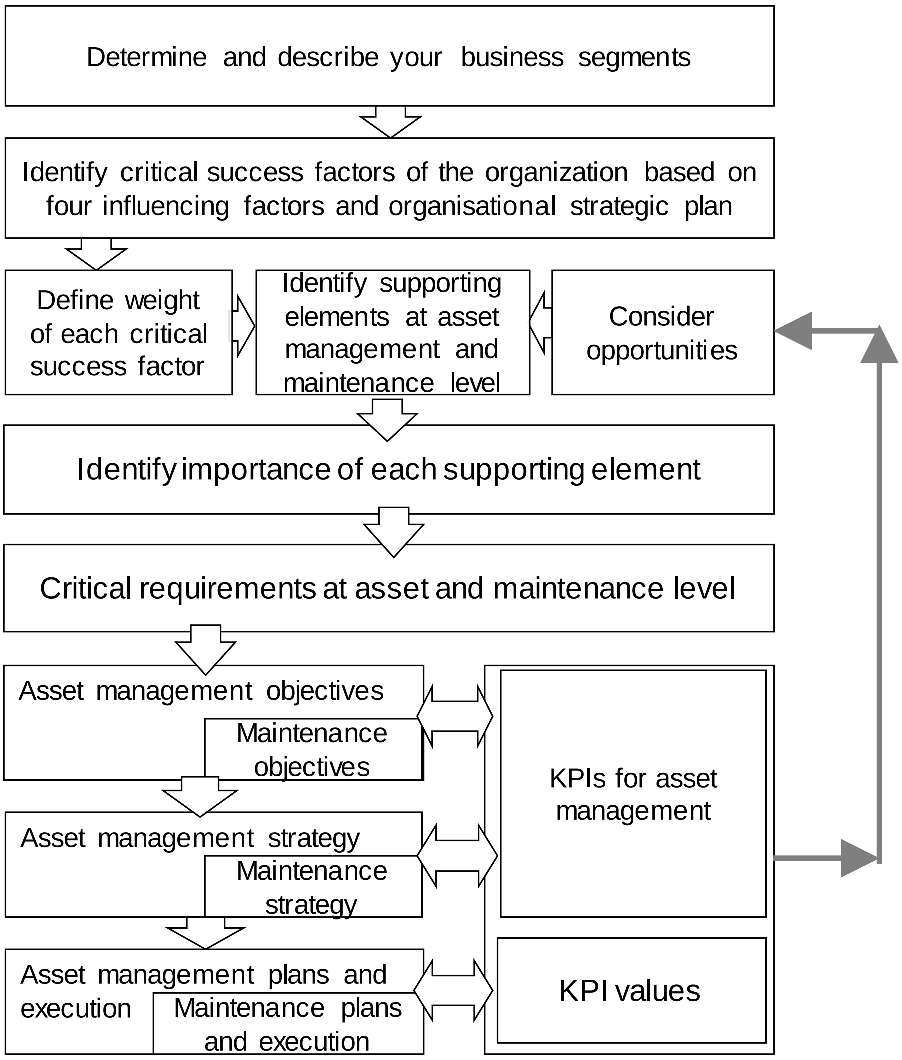


Figure 2.11. Managing physical assets as part of the strategic management of an organisation.

Requirements-related potential refers to the potential available to contribute to the achievement of critical success factors and set requirements:

- in some situations, there is little, limited or no potential,
- in some situations, the potential is high and therefore the requirements can be high,
- examples of limited potential: the potential of condition monitoring has already been exploited, there is no data available for periodic maintenance, etc., and
- examples of high potential: low use of condition monitoring, high maintenance debt, high but unused data, etc.

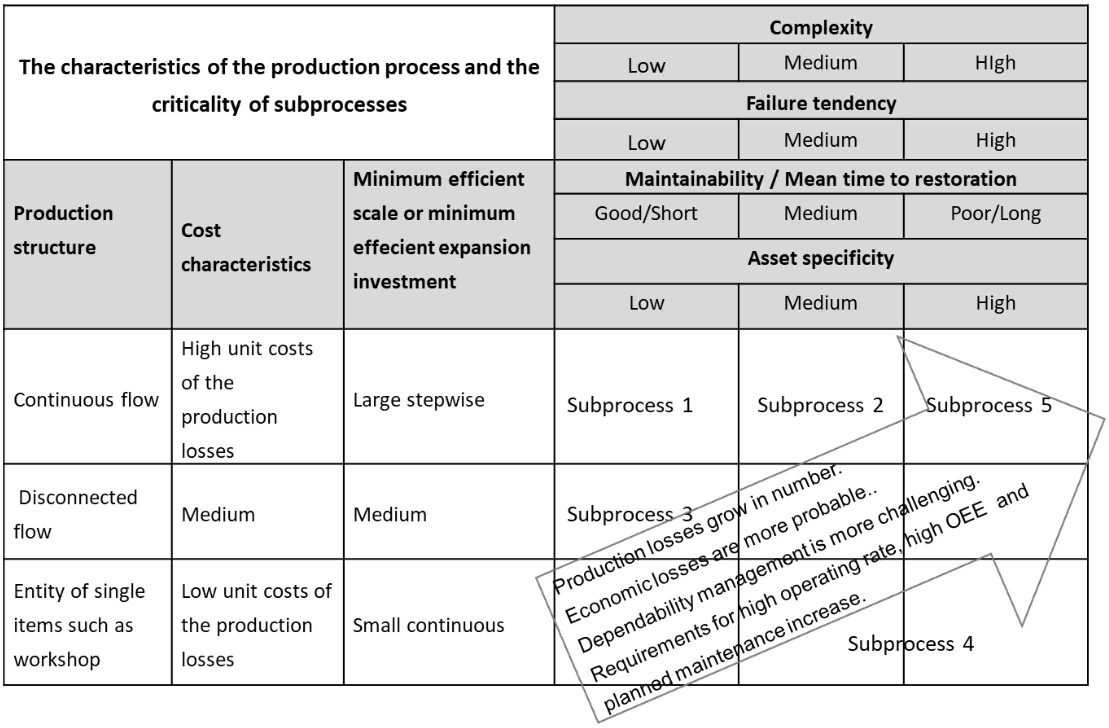
Once the requirements for the physical asset have been identified it is possible to define the objectives to be set for it and further define the asset management strategies to achieve them. Maintenance requirements, objectives and strategies are determined as part of physical asset management. An important element of the process is the monitoring of the need for change and achievement of success factors, requirements, and targets. This further requires the definition of key performance indicators for each of the above levels. Monitoring the relevance of the success factors identified and the need for change is the responsibility of the management and should be carried out on an ongoing basis. The monitoring of the relevance and need for change of the requirements defined on the basis of the success factors is the joint responsibility of the management and the organisation responsible for the management of the physical assets, as is the monitoring and updating of the strategies for the achievement of the asset management objectives.

Technological perspective

As mentioned earlier, the business and technology environment of a company has a significant impact on the management of its physical assets. Figure 2.12 (modified from Figure 2.8) provides a simplified description of the impact of some of the technological l factors on physical asset management strategies and practices. In the illustration, the factors are, on the vertical axis, the structure of production (degree of integration), the cost per unit time of production loss, the minimum efficient plant size and/or the minimum efficient expansion investment, and, on the horizontal axis, the complexity, failure tendency, maintainability, and asset specificity maintenance of the production equipment.

In the example in Figure 2.12, as we move from a workshop-type low unit cost of output loss to a high unit cost of continuous flow and high output loss, and from the less demanding dependability characteristics towards more demanding ones and from the standard technology to the asset specific one the significance of physical assets in value creation increases. Long-term cost efficiency is emphasised, and flexibility is reduced. Economic risk and barriers to entry will increase. The need for high operating rate, availability and OEE will increase. Maintenance requirements will increase and the need for high maintainability, reliability and planned maintenance will grow.

The medium asset specificity means (as explained earlier) a semi-standard technology which indicates the limited ability to sell the assets at the disposal stage. Although the technology in question is available on the market, its adaptability to the needs of a new owner is limited and, on the other hand, for reasons of competitive strategy, it may not be sold but rather scrapped to reduce capacity on the market. In addition to the above, there are of course other technological factors that influence the priorities and policies chosen, such as the reliability characteristics of the production system.



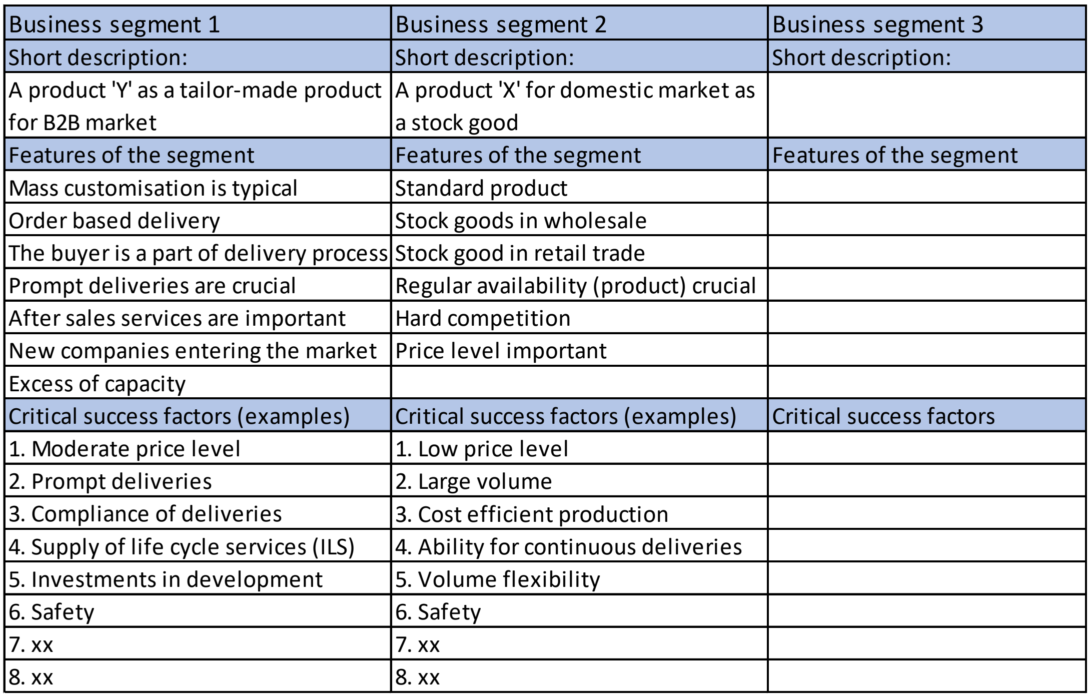
The characteristics of the production process and the criticality of subprocesses			Complexity		
			Low	Medium	HIgh
			Failure tendency		
			Low	Medium	High
Production structure	Cost characteristics	Minimum efficient scale or minimum effecient expansion investment	Maintainability / Mean time to restoration		
			Good/Short	Medium	Poor/Long
			Asset specificity		
			Low	Medium	High
Continuous flow	High unit costs of the production losses	Large stepwise	Subprocess 1	Subprocess 2	Subprocess 5
Disconnected flow	Medium	Medium	Subprocess 3		
Entity of single items such as workshop	Low unit costs of the production losses	Small continuous			Subprocess 4

Figure 2.12. Impact of production system (technology environment) on asset management: examples (Komonen, 2019).

A simplified approach to define the requirements for the assets

This chapter presents a framework for defining requirements based on critical success factors. Technically, depending on the specific needs of the organisation, this framework can use well-known methods such as QFD (*Quality Function Deployment*) (Cohen, 1997) or AHP (*Analytic Hierarchy Process*) or the KEPNER-TREGOE method. Only the basic process model and mindset is presented here (Figures 13-16). The figures are only examples of what is meant by each stage of the process and do not have any indicative content.

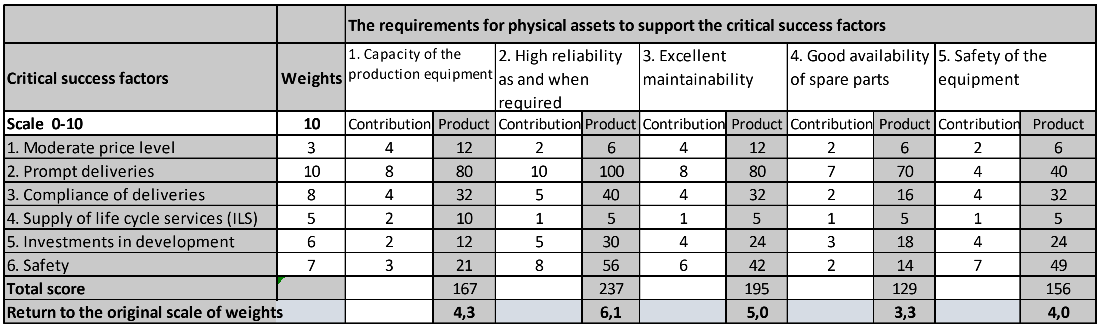
Figure 2.13 shows a framework for defining critical success factors. First, the organisation is divided into business segments, which differ in terms of the factors that affect them. Next, the characteristics of the segments are described. Finally, identify the critical success factors that meet the segment's requirements and deliver profitable long-term performance.



Business segment 1	Business segment 2	Business segment 3
Short description:	Short description:	Short description:
A product 'Y' as a tailor-made product for B2B market	A product 'X' for domestic market as a stock good	
Features of the segment	Features of the segment	Features of the segment
Mass customisation is typical	Standard product	
Order based delivery	Stock goods in wholesale	
The buyer is a part of delivery process	Stock good in retail trade	
Prompt deliveries are crucial	Regular availability (product) crucial	
After sales services are important	Hard competition	
New companies entering the market	Price level important	
Excess of capacity		
Critical success factors (examples)	Critical success factors (examples)	Critical success factors
1. Moderate price level	1. Low price level	
2. Prompt deliveries	2. Large volume	
3. Compliance of deliveries	3. Cost efficient production	
4. Supply of life cycle services (ILS)	4. Ability for continuous deliveries	
5. Investments in development	5. Volume flexibility	
6. Safety	6. Safety	
7. xx	7. xx	
8. xx	8. xx	

Figure 2.13. Identifying critical success factors.

In the next step, the critical loss factors are weighted on a scale chosen by the organisation, for example 1-5 or 1-10 (Figure 2.14). At the same time, the aim is to identify the physical asset requirements that contribute to the achievement of the critical success factors. Next, the strength of this impact is also weighed on a scale chosen by the organisation (e.g., 1-5 or 1-10). The significance of the critical success factor and the impact of the requirement on the critical success factor is multiplied by each other. This is done for each critical success factor and the products are summed for each requirement. In the example in Figure 2.15, the most influential requirement for a production asset is "performance" and the least influential requirement is "logistical optimisation of the production process". Finally, to illustrate the results of the process, the raw scores are rescaled to the original scale.



		The requirements for physical assets to support the critical success factors									
Critical success factors	**Weights**	1. Capacity of the production equipment		2. High reliability as and when required		3. Excellent maintainability		4. Good availability of spare parts		5. Safety of the equipment	
Scale 0-10	**10**	Contribution	Product	Contribution	Product	Contribution	Product	Contribution	Product	Contribution	Product
1. Moderate price level	3	4	12	2	6	4	12	2	6	2	6
2. Prompt deliveries	10	8	80	10	100	8	80	7	70	4	40
3. Compliance of deliveries	8	4	32	5	40	4	32	2	16	4	32
4. Supply of life cycle services (ILS)	5	2	10	1	5	1	5	1	5	1	5
5. Investments in development	6	2	12	5	30	4	24	3	18	4	24
6. Safety	7	3	21	8	56	6	42	2	14	7	49
Total score			167		237		195		129		156
Return to the original scale of weights			**4,3**		**6,1**		**5,0**		**3,3**		**4,0**

Figure 2.14. Definition of the requirements for the physical assets supporting the critical success factors.

The next step in the definition process is to assess how the sub-processes (assets) of the organisation's production process contribute to the fulfilment of the physical asset requirements. The methodology is like the previous step (Figure 2.15). The requirements shown in the figure and their weights come from the table in Figure 3.14. The impact of, for example, asset system 1 on the fulfilment of the requirements is then assessed. The scale is the same as in the previous steps and in the column "input" the weight of the requirement is multiplied by the strength of the impact. Finally, the inputs are summed up. Based on these result totals, it can be concluded that in this illustrative example, the most significant asset with respect to the requirements is the requirement number 2 and the least significant asset is requirement number 4.

The bottom row shows the share of each asset or sub-process in the total investment. This analysis provides information on which sub-process has the best input-output ratio in terms of requirements. A summary of this comparison is shown in Figure 2.16.

In terms of the input-output ratio, assets 2, 3 and 5 seem the most attractive. To identify the assets that have the greatest potential to influence the achievement of individual requirements, we need to look at the scores shaded in light red in the table in Figure 2.15. For example, the greatest improvement in performance in terms of compliance is achieved by asset system 1 (70.9). The second sub-process affecting performance is number 2. Figure 2.16 illustrates the organisation's estimate of the cost of the effectiveness of the asset systems measured by the share of the total investment.

		The impact of the various asset systems on the requirements for the physical assets									
Requirements	**Weights**	Asset system 1		Asset system 2		Asset system 3		Asset system 4		Asset system 5	
Scale 0-10	**10**	Contributi	Product	Contribution	Product	Contributi	Product	Contributi	Product	Contributi	Product
1. Capacity of the production equipment	4,3	5	21,4	7	30,0	3	12,8	2	8,6	2	8,6
2. High reliability as and when required	6,1	6	36,5	10	60,8	7	42,5	2	12,2	9	54,7
3. Excellent maintainability	5,0	7	35,0	9	45,0	5	25,0	1	5,0	4	20,0
4. Good availability of spare parts	3,3	5	16,5	7	23,2	3	9,9	2	6,6	6	19,8
5. Safety of the equipment	4,0	3	12,0	7	28,0	3	12,0	3	12,0	3	12,0
Safety can taken into account also as a separate process		**Low risk**		**Medium risk**		**Low risk**		**Low risk**		**Low risk**	
Total score			**121,4**		**186,9**		**102,3**		**44,3**		**115,1**
Estimate of the share of the different asset systems of the total investment (%)			**35**		**25**		**10**		**5**		**25**

Figure 2.15. Impact of the different asset classes on the physical asset requirements.

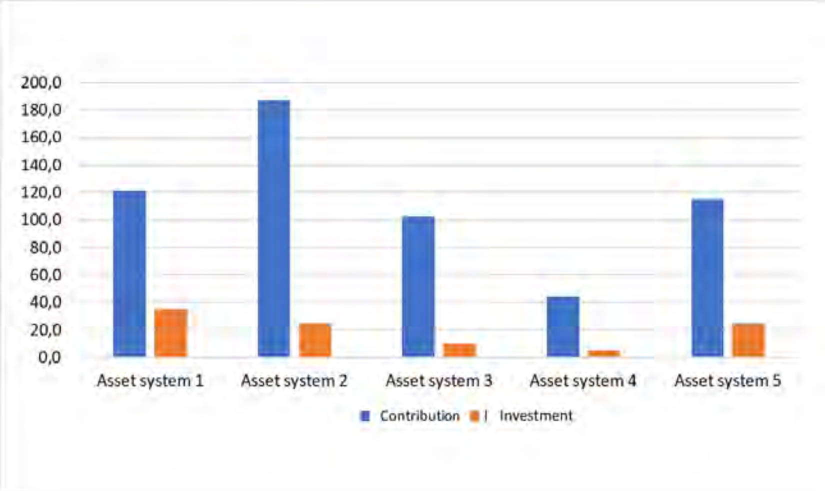


Figure 2.16. Comparison of the impact and contribution by the asset class.

The above approach can be used in the following situations:

- the preparation of a SAMP (Strategic Asset Management Plan) for the implementation of the organisation's strategic plan during the greenfield investment stage,
- updating the SAMP for the O&M (operation and maintenance) stage of the life cycle management of production assets,
- in the O&M stage of production assets to support decision-making on replacement investments, corrective maintenance, and modifications.

This approach allows development measures and requirements management to focus on those critical success factors that are seen as most important from a competitiveness perspective. On the other hand, it allows the identification of those requirements for production assets that have the greatest impact on the achievement of the critical success factors. Thirdly, it allows the identification of those assets that have a high impact on the achievement of each success factor. Fourth, the methodology can be used to identify those assets that have the greatest impact on the achievement of all the critical success factors. The frameworks in Figures 2.15 and 2.16 can also be used to analyse which development portfolio is most effective within the financial resources available, assuming if the organisation has some idea of the input-output relationship between the development activities associated with the different assets. Given the constantly changing business environment, technology and competitive situation, the company will need to update the above analyses, either regularly, for example as part of strategic planning, or within specific timeframes.

Activities during the deployment stage

When making decisions on the acquisition of production assets, lifetime returns and costs are often considered as a valid criterion for comparing investment options. In practice, life-cycle costs are used in investment decisions to a much lesser extent than publicly stated. In a survey published by EFNMS in 2012, around 45% of respondents reported using life cycle costs or returns as a criterion for investment decisions (Figure 2.17). Despite the high number of respondents from organisations responsible for infrastructure investments, this figure seems high. Based on the hand polls conducted during conferences and training sessions, the use of life cycle costs and returns as an investment criterion is significantly lower, especially in industry.

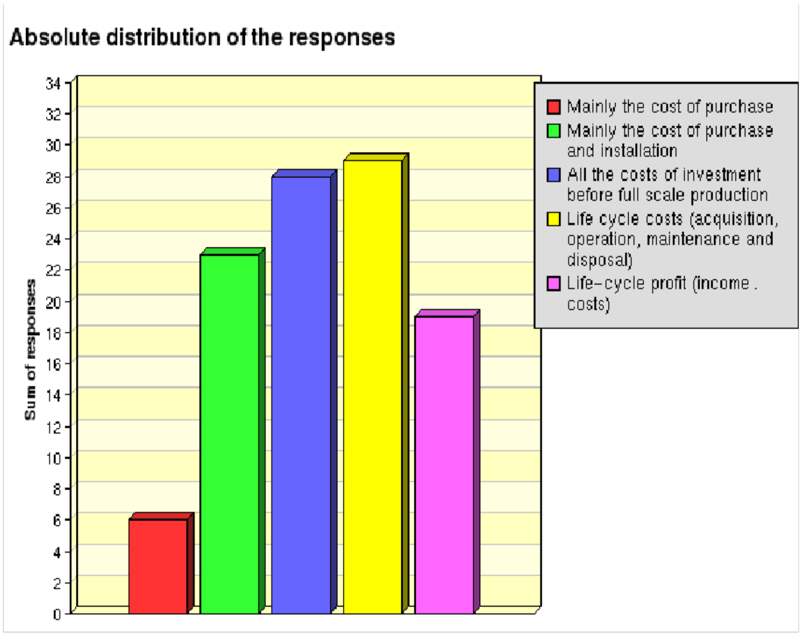


Figure 2.17. Use of different investment criteria in investment decisions (EFNMS, 2012).

If the economic lifetime of investments is long, the absence of life-cycle costs in decision-making may lead to a cumulative loss of cost competitiveness in the future. Since a short payback period is a common requirement for replacement or development investments, the use of a criterion such as the internal rate of return (IRR) may lead to a result where events after a few years of operation (e.g. 5 years) have no impact on the calculation of the profitability of the investment in the site and therefore an option that is more profitable in terms of life cycle costs over a 10-year time horizon is not selected. In this case, it is likely that the pressure against maintenance will increase, but at the same time, as better performance is required, lower maintenance costs are likely to be required. These two requirements in a bad case work against each other and further weaken the outcome (Komonen, 2019).

Whether life cycle costing or life cycle returns is the best method to choose between different investment options depends on the nature of the technology and business environment in which the organisation operates and the flexibility of the technology the organisation uses. These factors provide an indication, in general terms, of the expected economic life of a physical asset by assessing the uncertainty that an organisation faces. If an organisation's technology and business environment is dynamic, rapidly changing, it generally contains a high degree of uncertainty. If this situation is combined with the weak competitiveness of the organisation, the uncertainty of the business environment can be said to be high. High uncertainty about long economic lifetime does not motivate the use of lifetime returns or costs as a decision criterion. On the other hand, a stable environment and a long technical lifetime of the equipment combined with strong competitiveness encourages the use of life cycle cost or return calculations in investment decisions (Figure 2.18) (Komonen, 2019).

In life cycle management, it is of course important that the requirements for production assets are defined from the beginning to match as closely as possible the requirements of the operational and technological environment. On the other hand, especially in the case of an investment with a long-time lag between the decision and utilization, the situation based on which the investment was defined is likely to have already changed somewhat by the time of utilization. After utilization, the technological and business environment will continue to change and, consequently, the organisation will need to reassess the requirements for the production assets after a specified period. A special case of this situation is when the organisation considers it reasonable to extend the life of the asset, due to the changed business environment (Komonen, 2019).

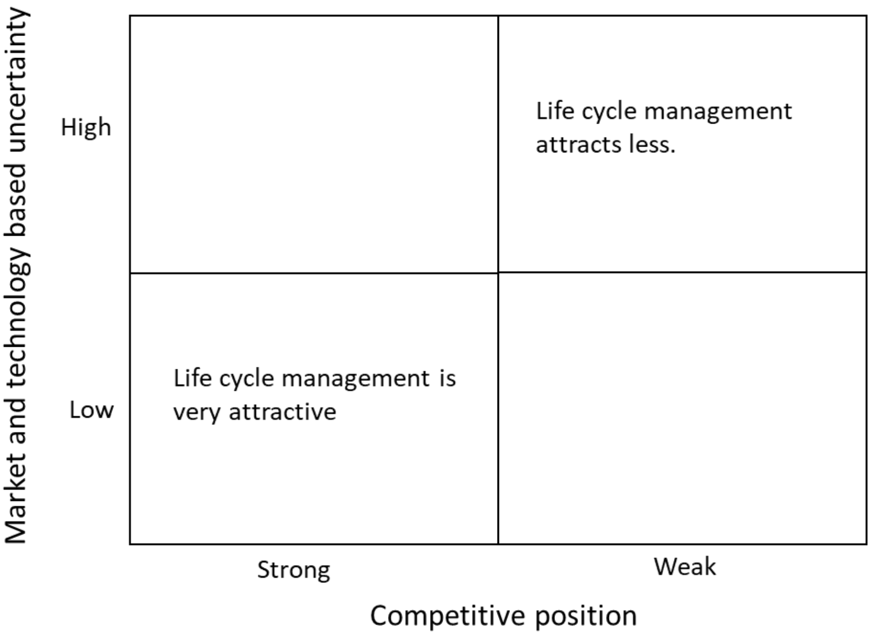


Figure 2.18. The interest of life cycle management in the management of production assets (Komonen, 2019).

On the other hand, an external change is not the only source of the necessary revision, as it is possible that the equipment has not met its original requirements. In this case, the requirements do not change, but the equipment must be improved to meet the original requirements. In the third situation, the need for revision is already predetermined because the production asset consists of several sub-processes that wear out or age at different rates. In this case, life cycle management includes a timed replacement investment or repair plan for the entire planned life cycle of the asset. Life cycle management therefore includes at least the following five cases, the five triggers for action:

- Normal maintenance.
- At the time of investment, commissioning or operation, a replacement investment or repair plan is drawn up to ensure that the whole installation will meet the specified requirements over its intended useful life, without changing the original requirements.
- Due to changes in the technology and business environment, the organisation's success factors and hence the requirements for physical assets change and therefore

the organisation needs to redefine the requirements and implement the necessary corrective maintenance, modifications, and modernisation (this may need to be done several times over the useful life of the asset).

- The necessary corrective maintenance measures and modifications may have to be carried out even if the requirements for the physical asset have not changed, in which case there is no need to modify the original requirements, but the required level of reliability, reliability of supply, quality or cost, for example, has not been achieved (it is also possible that the ageing and wear of the equipment has been estimated to be faster and therefore the original requirements could not be achieved).
- Extending the life of the equipment.

Utilizing lifecycle management requires an organisation to regularly analyse its business and technology environment and update its physical asset requirements. The requirements must continue to be allocated to the different components of the physical asset (production). It is therefore necessary to identify how different parts of the production process contribute to the achievement of the different requirements. "The 'regular updating' depends on the technology and business environment and is therefore mostly an organisation-specific issue. It is also important to prioritise the requirements, i.e., to define a weighting for each requirement and to update the weighting when the requirements are updated. Allocating requirements to different parts of the production process and updating requirements and allocation sets the basis for the five lifecycle management scenarios described above.

Decisions on the management of production assets are often related to life cycle management and timing. When major repairs are necessary, when corrective maintenance is required, when modifications to the production process are necessary, when replacement investments are necessary, or when modernisation is necessary. The different functions in an organisation (engineering, production, maintenance, purchasing, finance, and management) may have very different views on what should be done and when. However, all functions should have the same reference framework against which decisions are assessed. This framework should include a list of the factors influencing the decision and their status at the time the decision is taken. Such factors include, for example, the important targets identified (Komonen, 2019) requirements for the equipment:

- criticality of equipment,
- impact on meeting requirements,
- technical performance and potential,
- cumulative actual lifetime costs relative to the forecast,
- remaining useful life,
- the relative economic importance of the site (JHA of the site in relation to the JHA of the whole installation),
- site specificity,
- minimum shutdown time, which causes production losses,
- production downtime costs per unit of time (e.g., per hour),
- reliability history and current level,
- alternative measures available and their costs, and
- risk analysis.

PSK 7903 (2011) (Verification of Availability in the Process Industries) also provides an excellent reference framework for goal setting and decision making. The standard builds on the challenges of manufacturing asset management by defining their root causes far beyond the equipment engineering perspective and targeting them to different functions, thus moving away from the traditional 'chicken-and-egg' situation and addressing the challenge where it has the best chance of being solved. Root causes are classified in the standard as follows:

- caused by maintenance,
- caused by changes in the production process,
- caused by initial investment,
- caused by production, and
- due to an external factor.

Life cycle monitoring

Too little attention has been paid to the management of the life cycle of production assets and what happens to them after acquisition. This includes ex-post calculations of investments, such as monitoring life cycle returns and costs, compliance performance, changing requirements as the business environment and technology changes, and exploiting potential development potential. The EN17485 standard provides several ways to implement monitoring. Table 2.4 shows a simplified way of implementing life cycle monitoring. The table suggests that an organisation should assess the life cycle status of each asset system against six criteria and develop action plans based on these criteria. The criteria to be assessed are:

- Criticality, which here refers to the impact of the asset system in meeting the requirements of the production assets, the unit cost of the loss of production caused by the asset system, and its contribution to the purchase price of the plant.
- Economic performance includes actual life-cycle costs, total integrity cost evolution and maintenance costs separately.
- Technical performance includes an assessment of structural integrity, reliability, remaining lifetime and current and evolving performance.
- Compliance with social requirements includes, for example, directives,
- obsolescence includes, for example, the availability of updates, technical support and spare parts.
- Staff competence includes the competence to operate and maintain the equipment in accordance with the requirements and the related development.

Table 2.4. Content of life cycle monitoring

		LIFE CYCLE MONITORING			
	Evaluation criteria	Asset system 1	Asset system 2	Asset system 3	Asset system 4
1	Criticality				
2	Economic performance				
3	Technical performance				
4	Compliance with social requirements				
5	Obsolescence (obsolescence)				
6	Staff competences				
7	Development Plan				
8	Measures				

Key lessons

- Low flexibility in the production system combined with high uncertainty increases the risk faced by the organisation and, conversely, flexibility can compensate for the effects of high uncertainty.
- The technology in use affects flexibility. The more integrated the production system, the higher the unit cost of lost production, the larger the minimum effective scale, and the more asset-specific the production asset, the less flexible the production asset.
- The link between business and asset management is established by defining the critical success factors by business segment and identifying the requirements for production assets based on the critical success factors for the asset sets (production sub-processes).
- Critical success factors are determined by the characteristics of the market, the demands of society, the technology available and the characteristics of the organisation.
- The influencing factors mentioned in section 4 will determine whether, for example, life cycle management is an attractive option.
- After acquisition, the activities (triggers) during the operational stage of the production asset are: a) normal maintenance, b) measures required by replacement investment and repair plans made at the time of acquisition and updated during operation, c) measures aimed at achieving the original requirements, measures taken to achieve the original requirements not yet achieved or to exploit the perceived potential for performance beyond the original requirements, (d) measures taken to respond to changes in the organisation's environment and new requirements, and (e) measures taken to extend the life of the equipment where this is techno-economically the best solution.
- The need for and content of life-cycle monitoring.

2.3. INVESTMENT CALCULATIONS: METHODS AND THEIR USE

Kari Komonen

Introduction

The economic aspect of decision making (investment calculations) in this chapter is mainly related to the calculation methods used for investments and therefore also to the economic criteria for decision making. The accounting methods used are defined on an organisational basis and are usually defined in terms of financial accounting. It is natural to look at the enterprise and its financial performance. However, the operational efficiency of a company may require different practices. For example, it is understandable that, for example, depreciation practices of spare parts inventories are treated in the bookkeeping of an enterprise on the same principles as other assets. In this case, the inventory value of some spare parts may be fully depreciated and may have a zero value in the inventory accounts. In terms of operational management, such a principle would give completely wrong signals for operational development and so there should be another replacement value-based accounting for operational development (Komonen, 2019).

Organisations define decision-making criteria and calculation models according to business management principles that consider the business environment in which they operate. Nevertheless, it is worth questioning whether the chosen principles lead to the best achievable result and whether they take sufficient account of the environment in which the company operates. Some methods for calculating the return on investment are presented in Table 2.5.

Table 2.5. Calculation methods to support investment decisions.

METHOD	CONTENT	CHARACTERISTICS
(Net) present value (NPV), the present value of estimated net cash flow	Future net cash flows are discounted to the present, making different options comparable, If NPV >0, the investment is profitable.	High interest rates emphasise short-term returns at the expense of long-term returns. If only costs are considered, the method may lead to absurd results and the use of probabilities in this context may further distort the results. Estimating the useful life of an asset is an important part of the calculation.
The annuity method (EAC)	The annuity method converts NPV into constant annual amounts. Annuity=NPV/Annuity factor	The annuity is suitable for economic comparisons of different options having different useful lives. The risk levels of the different options should be the same.
LCP (Life Cycle Profit)	The LCP includes all the net returns generated by the physical assets over its lifetime.	The savings generated by the investment can be considered as its returns. NVP is a useful calculation method in this case, as is LCM (life-cycle margin).
LCC (Life Cycle Cost)	LCC includes all direct and indirect costs incurred during the lifetime of the system, including the purchase price (see Chapter 2.1).	In the literature, present value calculations are recommended for calculating life-cycle costs. This recommendation should be treated with caution as the use of NVP may lead to misleading conclusions.
Cost-Benefit ratio (CBR)	Most often used as a tool for social decision making = discounted benefits versus discounted costs.	Often used in situations where it is difficult to estimate the benefits of an investment in monetary terms.
Payback time	The time over which the net returns are equal to the acquisition cost.	The calculation can be based on discounted or undiscounted returns. This method is well suited to an uncertain environment. Does not directly indicate the profitability of the investment.
Life Cycle Margin (LCM)	Expected useful life divided by the payback time	A short payback time and a long useful life indicate a profitable investment. If the payback time equals to the useful life of the asset, it indicates a high level of risk.
Internal rate of return (IRR)	Calculates the interest rate at which the (net) present value of the investment = 0. If the IRR is higher than the target return on capital, the investment is profitable.	The importance of a short payback period as a criterion for investment is often appreciated and emphasised by company management. In this case, the IRR places a strong emphasis on the short-term returns and the impact of the useful economic and technical life of the investment is substantially reduced in the calculations.
Return on capital	Annual return after depreciation as a percentage of the investment cost (%).	The calculation can be based on the total investment cost or on the average capital employed in the investment.
Purchase price, value of investment		Not recommended, but possible for sub-process/equipment replacement investments at the end of the plant's life cycle.

Organisations use several methods to make decisions, but the preferred one to use in each situation could be situation specific. As noted above, managing physical assets requires different approaches depending on the technology and business environment of the organisation (Komonen, 2019). Asset management starts with investment. Investment planning essentially determines the return on investment, the future life cycle profits, or life cycle costs of the investment. The discounted net present value (NPV) calculation is based on the idea that:

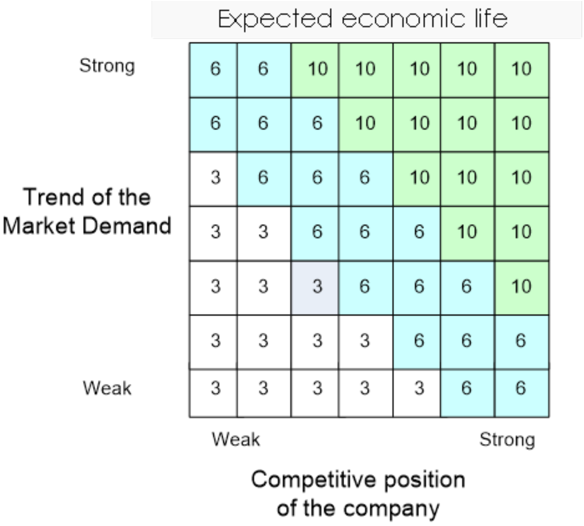
- organisations prefer to earn €10,000 today rather than €10,000 years from now; and
- the future cash flows generated by investments at different times must be made comparable by discounting them to their present values.

The almost standard-like net present value (NPV) is often used in the literature without considering the challenges involved. Those who use this calculation seem to apply NPV in investment calculations in a very rigid way. The following questions can be asked:

- what is the 'correct' interest rate to use for the calculation?
- what is the 'correct' remaining useful life to be used in the calculations?
- how is uncertainty considered in the calculation and in the different elements of the calculations?
- what is generally the appropriate formula for a company or department in each situation.

As noted above, in the case of a long projected useful life, the use of IRR as a decision criterion may lead to the selection of an option with a lower return potential. On the other hand, in the opposite situation, where the useful life is short, the use of LCC or LCP adds little value to the decision-making process, as risk management is the driver.

The remaining useful life of a production asset can be said to be a function of the uncertainty of the operating environment and competitiveness, unless the organisation can do something economically viable to reduce uncertainty or increase competitiveness, or unless the organisation is explicitly willing to take the risk because it believes the business area will be a significant source of future revenue. For example, high uncertainty and low competitiveness shorten the life expectancy (Figure 2.19).



Strong	6	6	10	10	10	10	10
	6	6	6	10	10	10	10
	3	6	6	6	10	10	10
	3	3	6	6	6	10	10
	3	3	3	6	6	6	10
	3	3	3	3	6	6	6
Weak	3	3	3	3	3	6	6
	Weak						Strong

Figure 2.19. Impact of uncertainty and competitive position on the lifetime used in the calculation (figures for expected lives are examples only) (Adapted from Heikkilä et al. 2012).

In view of the above, it would make sense, especially for a large organisation, to define an accounting policy map that considers the criteria and policies required by the different business areas, their different uncertainty environments, and competitive position. An example of such a map is shown in Figure 2.20 (Komonen, 2019).

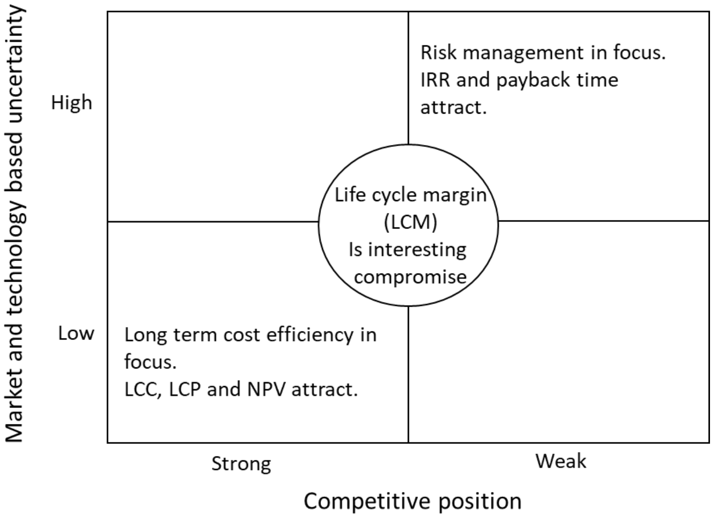


Figure 2.20. The attractiveness of different investment criteria in different business environments.

The choice of the appropriate investment calculation method also depends on the life cycle stage of the service or product produced by the organisation. The above proposed map of accounting principles could also consider the life cycle stage of the product. The EFNMS study (2011) also supported the above consideration (Figure 2.21). Based on the study, it seems that the prevailing tendency was to use life cycle costing or life cycle profit calculation in the early stages of the product life cycle (slow and fast-growing stages), while the acquisition cost of the investment was the criterion in the declining stage.

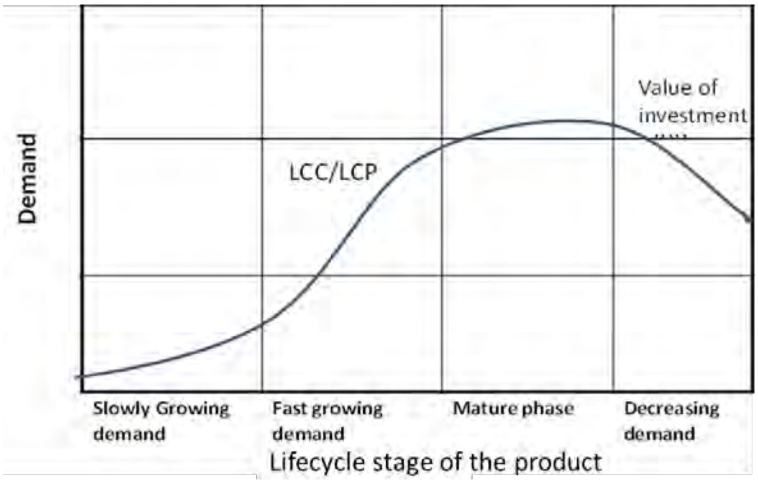


Figure 2.21. Use of investment criteria in investment decisions at different stages of the life cycle (EFNMS, 2012).

As mentioned above, it is useful to use more than one calculation method for investment calculations, and companies often do so (Figure 2.22). In the figure, the organisation has used two methods for calculating the return on investment: NPV and IRR. The example in the figure is clear because option 3 is the best when calculated based on both NPV and IRR. However, it is not always this easy.

It is also useful to link compliance with economic calculations. However, economic aspects can also be an essential part of the requirements definition. Figure 2.23 combines the compliance scores and estimated net present values for three alternative asset systems. This example illustrates the same simple situation as Figure 2.22, where the best option is the best in terms of both net present value and compliance. Conformity refers to the requirements for productive assets defined by the critical success factors and the ability of the alternative investment options to meet these requirements.

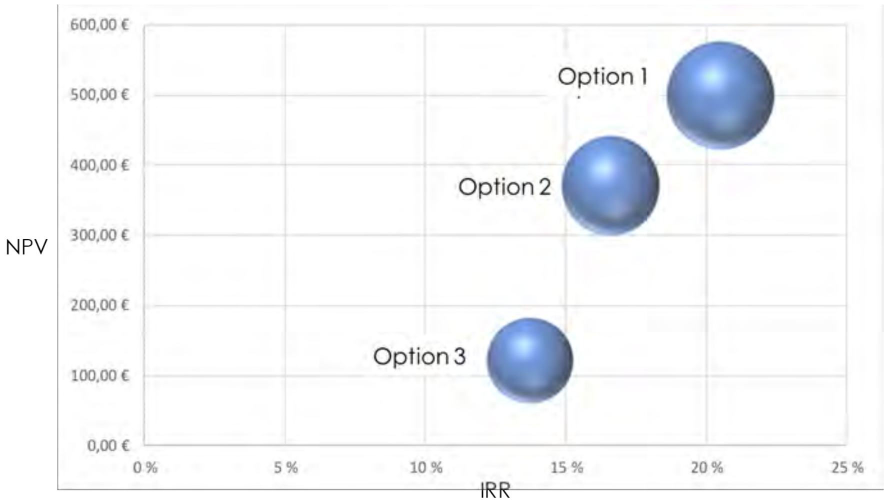


Figure 2.22. Use of multiple investment criteria in investment decisions.

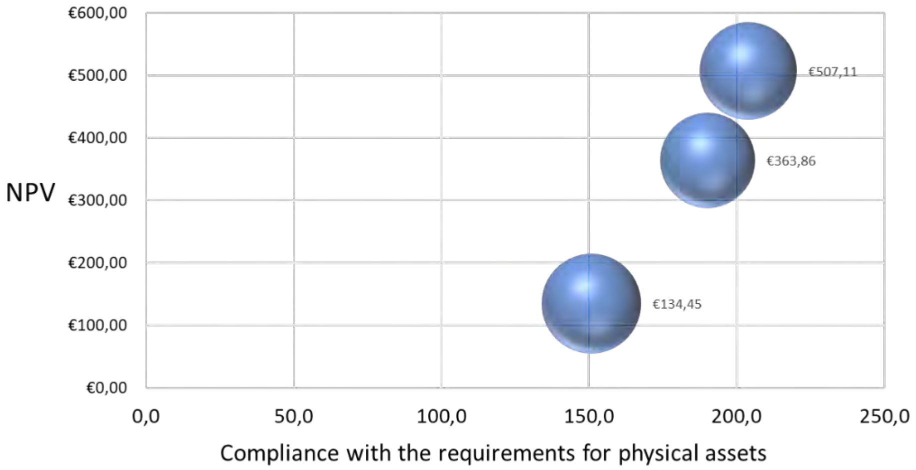


Figure 2.23. Joint review of economic calculations and compliance.

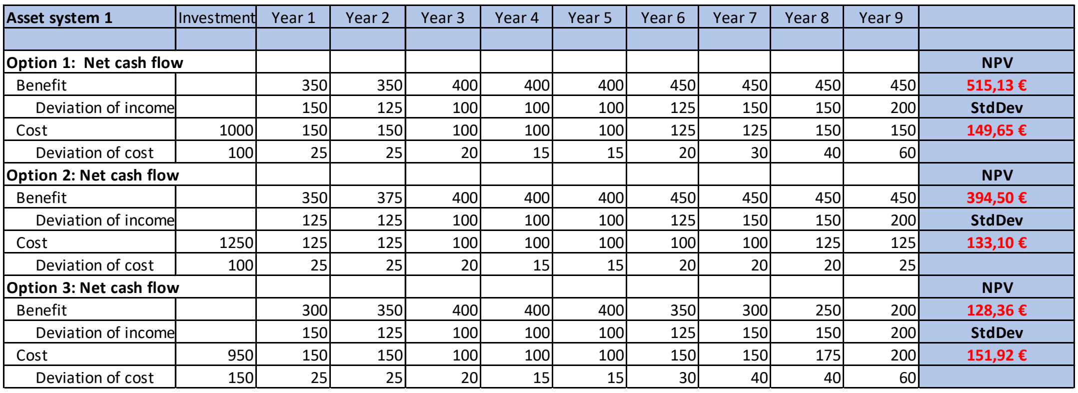
As outlined above, the choice of decision criteria and investment calculation models should consider the uncertainty that exists in the business environment of the organisation. Organisations often use scenario thinking in their decision-making, whereby they add or subtract, for example, 20% to the result of the calculations and see what impact these deviations have on the organisation's operations. However, this is often not an adequate level of uncertainty management. Decisions contain a few cost and revenue elements, and it would be useful to assess the level of uncertainty associated with these separately, to increase understanding of the strengths and weaknesses of different plans or different options.

A simple way to account for uncertainty is to estimate, for example, the variance associated with the estimated costs for each cost element, which can be, for example, a subjective expert assessment of the estimated range of costs (likely minimum and maximum). The variance may also be based on historical and benchmarking data. For example, ISO 15663. 2001: Life-cycle costing - Petroleum and natural gas industries - Parts 1-3 uses variance as a measure of uncertainty for each cost and revenue element (Table 2.6). EN 17485 recommends a similar practice.

Table 2.6. Calculation methods to support investment decisions.

Life cycle costs: **Cost elements**	**Option A**		
	Value (€)	**Deviation**	
		Absolute (€)	**Relative (%)**

Two indicators already give a reasonable idea of the impact of uncertainty: 1) the mean and 2) the deviation. If life-cycle costs in the form of NPV are estimated in a decision situation, for example by Monte Carlo simulation, a normal, log-normal, or triangular distribution requires the estimation of these two parameters. The normal distribution is not a good distribution for investment calculations because it ranges from minus infinity to plus infinity, which is not a reasonable assumption. The log-normal distribution does not have this challenge, and on the other hand, it describes a non-symmetric distribution, which is often a better assumption than the symmetric one. The triangular distribution is also useful. However, in the following example, the normal distribution has been used for simplicity. For each investment option, the example estimates the returns and costs for each year over a 9-year time horizon and the associated uncertainty in the form of deviation. The net cash flow for each year is therefore determined by the probability distribution of revenues and costs. The calculated net present values (expected value) and associated deviation for the three alternative investment scenarios have been calculated based on 300 simulation runs (Figure 2.24).



Asset system 1	Investment	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	
Option 1: Net cash flow											**NPV**
Benefit		350	350	400	400	400	450	450	450	450	**515,13 €**
Deviation of income		150	125	100	100	100	125	150	150	200	**StdDev**
Cost	1000	150	150	100	100	100	125	125	150	150	**149,65 €**
Deviation of cost	100	25	25	20	15	15	20	30	40	60	
Option 2: Net cash flow											**NPV**
Benefit		350	375	400	400	400	450	450	450	450	**394,50 €**
Deviation of income		125	125	100	100	100	125	150	150	200	**StdDev**
Cost	1250	125	125	100	100	100	100	100	125	125	**133,10 €**
Deviation of cost	100	25	25	20	15	15	20	20	20	25	
Option 3: Net cash flow											**NPV**
Benefit		300	350	400	400	400	350	300	250	200	**128,36 €**
Deviation of income		150	125	100	100	100	125	150	150	200	**StdDev**
Cost	950	150	150	100	100	100	150	150	175	200	**151,92 €**
Deviation of cost	150	25	25	20	15	15	30	40	40	60	

Figure 2.24. NPVs of investment options and associated uncertainty in the form of dispersion.

Which option is the best depends on the risk tolerance and risk behaviour of the decision-maker. The risk averse one will emphasise the small deviation and the risk taker will emphasise the expected value of the net present value. Visual inspection often facilitates decision making (Figure 2.25). In the figure, the horizontal axis shows the expected value of the net present value, and the vertical axis shows its deviation. However, the example in the figure is easy for both types of decision makers because the differences in the dispersion are small and the difference in the expected NPV is large.

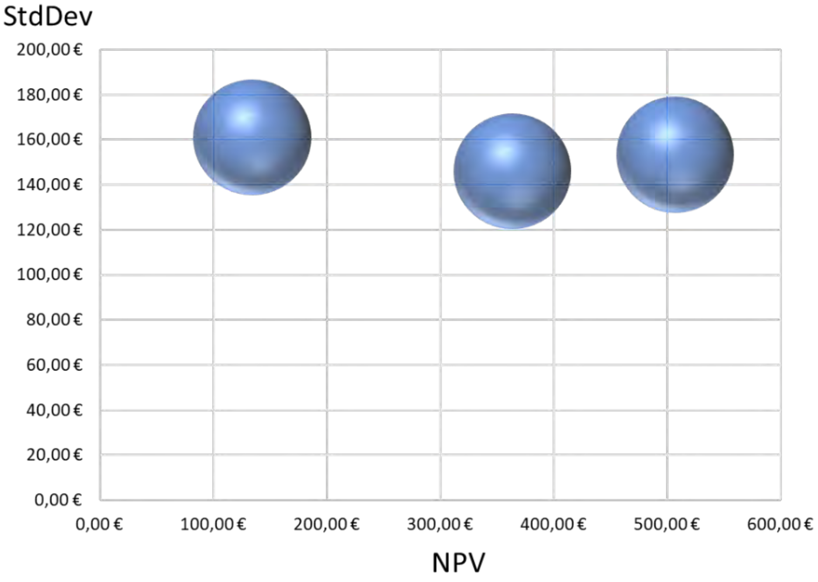


Figure 2.25. Investment decision *making using expected value and deviation.*

For tasks closer to maintenance, such as outage planning, improvement investments and replacement investments, timing is important. It is often a question of optimising the timing of a bundle of measures rather than the timing of a single event. There are uncertainties associated with the timing of measures for each item., which can be modelled using statistical methods or subjective probability distributions (Figure 2.26). The optimization of the timing of a bundle of measures based on probability distributions can be performed either by analytical methods or by simulation methods (e.g., Monte Carlo simulation) (Komonen, 2019).

The probabilistic method is often wrongly considered too specialised and scientific. However, it is in fact a natural human habit to take probabilities into account even in daily activities, albeit without realising it. On the other hand, there is no reason to fear that decision-making based on probabilities requires special knowledge of probability calculations or difficult-to-understand methods. For such purposes, easy-to-use computer-aided methods have been developed. On the other hand, it can be said that very few economists can calculate the internal rate of return on an investment without the help of our good friend Excel. To sum up, we can say that probabilistic decision making can be developed and used more effectively with the help of simulation, for example, because (Komonen, 2019):

- every decision-maker already uses at least subjective probabilities,
- in most normal decision-making situations, there are several influencing factors that should be taken into account,
- in general, a person cannot control the simultaneous effect of several variables without the aid of tools, especially if the variables are presented as probability distributions,
- it is possible to improve the quality of decision making with computer-aided tools that help to exploit either statistical or subjective probability, and
- it is possible to model a person's probabilistic judgements to better manage inferences from their subjective perceptions.

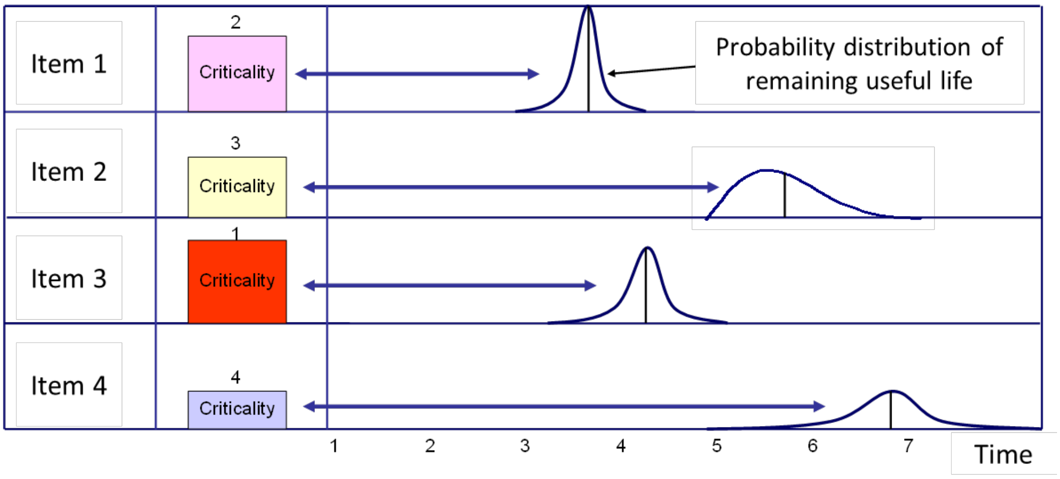


Figure 2.26. The challenge of optimal timing of multiple maintenance tasks (Komonen, 2019).

Key lessons

- The main content of investment calculation and appraisal methods.
- An uncertain organisational environment, weak competitiveness and risk aversion favour IRR and payback time for investment calculations, while a stable environment and good competitiveness favour the calculation of life cycle costs or profits. The life cycle margin is a good trade-off.
- Accounting for uncertainty by cost and income elements is important in the calculation, at least at the level of deviation.
- The estimated life cycle of the item is an important element in the calculation. The more competitive and less uncertain the business environment, the longer the life cycle used in the calculation can be.
- It is useful to use two or more variables in the calculation, for example: two calculation methods, mean and standard deviation, and the economic results and conformity of the alternatives.

2.4. MAINTENANCE AS PART OF ASSET MANAGEMENT

Kari Komonen

Maintenance during the procurement phase

Although maintenance is often perceived as an O&M activity, it starts at the acquisition stage of a production asset. Maintenance is not just an activity of the maintenance department but can be carried out by anyone in the organisation. In a small organisation, it can be the responsibility of, for example, the CEO. At the procurement stage, maintenance-oriented activities can be carried out by equipment designers, regardless of their position in the organisation. Reliability, maintainability, and security of maintenance are important maintenance-related issues already at the procurement stage. On the other hand, initial maintenance strategies and maintenance plans are or should be defined at the design stage. In general, it can be concluded that maintenance has not been and is not sufficiently involved in the acquisition stage and in the design stage of the equipment. There are numerous methods for analysing and planning at the acquisition stage of production assets. Their suitability for the different phases of an acquisition project obviously depends on the tasks and role of the phase itself and on the level of the asset hierarchy at which the acquisition is made. Several of these methods are also applicable to maintenance-related planning. Table 2.7 illustrates the range of maintenance-related methods available at the asset portfolio or asset system levels.

Table 2.7. Methodologies for the asset portfolio and asset system levels at the acquisition stage.

LIFE CYCLE STAGE	EXAMPLES OF METHODS	LOCAL PERFORMANCE FROM A MAINTENANCE PERSPECTIVE	OVERALL RESULT
Preliminary study (feasibility study)	Strategic analysis of an organisation, Analysis of critical success factors Risk analysis, LCP/LCC analysis	General maintenance impacts on the feasibility of the project	Compliance with the strategic plan of the organisation, Defining critical success factors
Concept	Critical Success Factor Analysis, Requirements Analysis, QFD (Quality *function deployment*) AHP (Analytic hierarchy process) LCP/LCC analysis	Evaluation of different equipment solutions in terms of reliability, maintainability, and safety of maintenance	Definition of requirements for production assets

Preliminary design	Allocation of reliability requirements to asset systems, Criticality assessment, QFD, RBD (*Reliability block diagram*), FTA,	Definition of maintenance requirements, Preliminary definition of maintenance strategy	Optimisation of life-cycle costs, Asset system-specific requirements
Detailed design	Allocation of reliability requirements to single equipment, Risk analyses, RBD, QFD, HAZOP FMEA/FMECA/RCM, FTA, ETA, Load-Strength-analysis, Replace, repair and discard analysis, Maintainability planning, CBM planning (Condition Based Maintenance)	Reliability forecasts, Reliability, and maintainability requirements, Allocation of requirements, Preliminary maintenance plan	Requirements and reference values for single assets
Manufacture of equipment	Application of relevant standards, conformity assessment and factory inspections,	Compliance with maintenance requirements	Factory inspection and approval, Compliance
Equipment installation	Conformity assessment, Definition of failure criteria, Failure mechanism studies, Definition of failure modes, Failure classifications, Application of relevant standards, POA, ETA, RCM, FMEA	Conformity, Inspection and testing of equipment, Detailed maintenance plans	Inclusion of equipment in the SAMP plan
Commissioning	Application of relevant standards, Determination of compliance,	Conformity and update of the above	Update of the above

Maintenance as part of the life cycle process

As has been pointed out on several occasions, one of the objectives of asset management is to reduce 'silo behaviour' in organisations, i.e., to improve collaboration between different functions. EN 16646 (2014) 'Maintenance within physical asset management' defines the role of maintenance in the different phases of the strategic development process of an organisation and, on the other hand, the contributions between different life cycle processes, i.e., the contributions to the success of other life cycle processes. A full description of both can be found in EN 16646, but extracts are described below. Figure 2.27 shows the process phase of the management system on the left and the desirable role of maintenance in each process phase on the right. The role of maintenance is defined using 4 different levels of involvement:

- responsible role,
- active participation,
- consultative role, and
- informative role.

Process stage	Role of maintenance
1. Organization's business strategy	Informative & consultative
2. Key success factors	Informative
3. Requirements for physical assets	Informative
4. Asset policy and strategy	Consultative
5. Allocation of the task roles to the asset systems	Consultative
6. Determination of physical asset solution	Consultative
7. Design of the asset systems within portfolio	Consultative
8. Creation of physical asset management system	Active participation
9. Creation of maintenance management system	Active participation
10. Planning of maintenance support resources	Active participation
11. Maintenance planning at the portfolio level	Responsible for task
12. Performance evaluation and improvement	Responsible for task
13. Disposal and acquisition of asset systems	Consultative

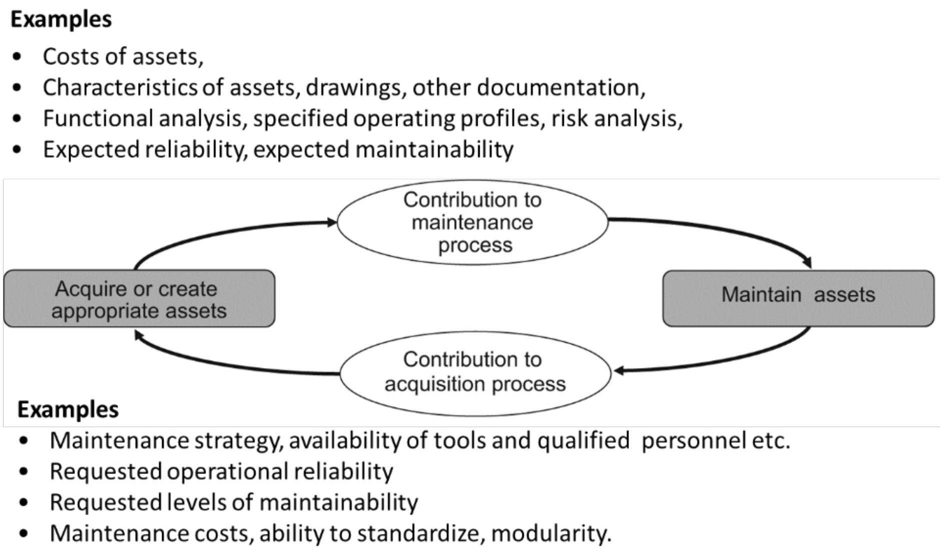
Figure 2.27. The role of maintenance at different stages of the management process: extract (MESTA Training Material, Komonen, 2016).

To reduce siloed behaviour, an organisation should define the roles of other functions at different stages of the governance system. Collaboration within the organisation can also be developed by defining the contributions between the different life cycle processes. In EN 16646 this has been done between maintenance and other life cycle processes.

The contributions between maintenance and other life cycle processes are presented in the standard as bilateral requirements. Below, these contributions are illustrated by two examples:

1. equipment procurement and maintenance (Figure 2.28), and
2. operation and maintenance (Figure 2.29). The attributes are presented by way of example only, so for a complete picture it is worthwhile to refer to the standard itself.

Interaction under the standard is two-way and iterative. It is often said that 75%-80% of the in-service costs are generated by the planning and decisions made at the procurement stage. Thus, for the sake of business profitability and future life cycle costs alone, the interactions and contributions illustrated in the figures below are essential.



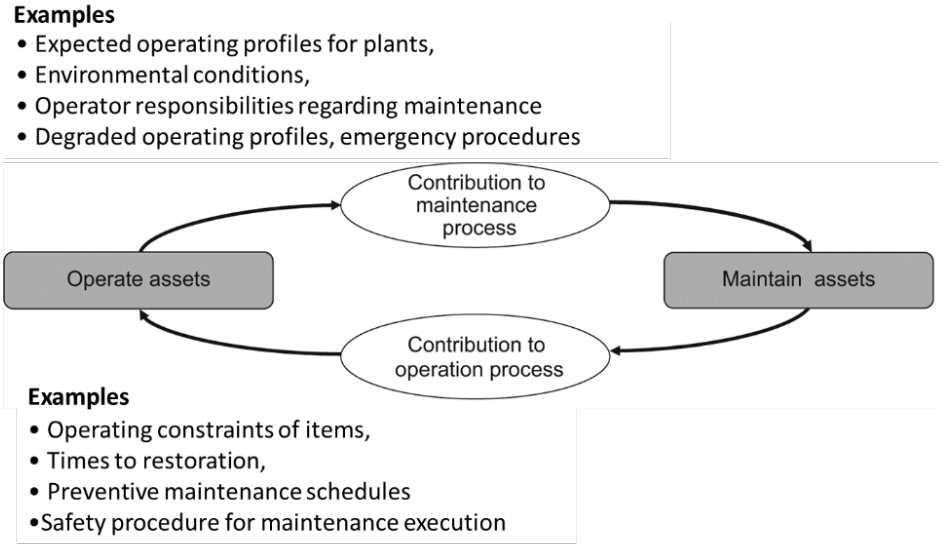
Examples

- Costs of assets,
- Characteristics of assets, drawings, other documentation,
- Functional analysis, specified operating profiles, risk analysis,
- Expected reliability, expected maintainability

Examples

- Maintenance strategy, availability of tools and qualified personnel etc.
- Requested operational reliability
- Requested levels of maintainability
- Maintenance costs, ability to standardize, modularity.

Figure 2.28. Contributions between acquisition of equipment pt and maintenance with examples (Komonen, 2016).



Examples

- Expected operating profiles for plants,
- Environmental conditions,
- Operator responsibilities regarding maintenance
- Degraded operating profiles, emergency procedures

Examples

- Operating constraints of items,
- Times to restoration,
- Preventive maintenance schedules
- Safety procedure for maintenance execution

Figure 2.29. Contributions between operation and maintenance with examples (Komonen, 2016).

In addition to the roles the governance process and the contributions between life cycle processes, the organisational perspective can be approached through the root causes of the asset management challenges (Table 2.8), which were presented at a rough level above. These root causes are also often located in different functions within the organisation, creating boundary barriers and blaming others. On the one hand, locating root causes is essential to solving problems and, on the other hand, problems are rarely attributable to a single source. The root cause list provides a new way of looking at the organisation of a company's activities that considers the requirements of technology and the business environment (PSK 7903, 2011). The objective of this approach is to solve problems and, on the other hand, to solve or exploit opportunities with the resources that have the best potential to do so. The PSK 7903 standard proposes a set of indicators to measure different customer issues and their success (Table 2.9). PSK 7903 looks at challenges from the perspective of the availability of production equipment, but this can equally well be extended to include reliability costs or safety and environmental costs. In the simplified example below, costs are also included.

Table 2.8. Possible root causes of the challenges of production asset management.

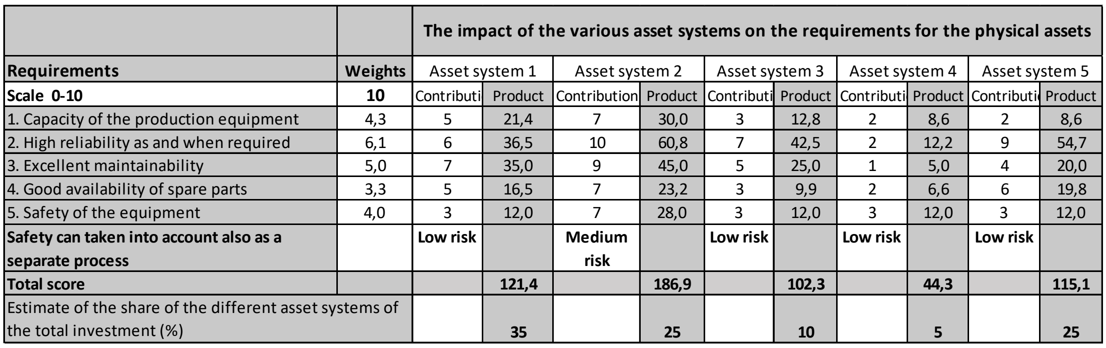
Due to maintenance: ● Not done ● Not done as planned ● The plan has been incorrect or incomplete	Due to a change in the production process: ● The performance of the item is not sufficient. ● Increased process stress ● Increased environmental load
Due to investment (from the original): ● Process characteristics ● Incorrect or incomplete instructions for operation and maintenance ● Wrongly selected equipment ● Improperly installed or commissioned equipment	Resulting from the operating of: ● Change to the operational plan. ● Error in maintenance and cleaning by the operator ● Incorrect use ● Inadequate process control
Due to external factors: ● Wrong raw material or commodity ● Installation and commissioning of the other process ● Manufacturing defects ● Natural phenomenon ● Scarcity	

Table 2.9. Root causes as a framework for production asset management PSK 7903 (2011) (Komonen, 2019).

ROOT CAUSES OF UNAVAILABILITY (INCLUDING COSTS AND SAFETY PROBLEMS)	**AVAILABILITY DUE TO MAINTENANCE OR THE COST OF MAINTAINING IT**	**TECHNICAL AVAILABILITY OR ITS COST**	**OEE OR ITS COST**	**OVERALL OPERATIONAL EFFECTIVENESS OR ITS COST**
Maintenance costs	X	X	X	X
Changes in the production process		X	X	X
Challenges resulting from the investment		X	X	X
Challenges resulting from operation (partly)			X	X
Due to external factors				X

Strategic basis for maintenance

The maintenance strategies are based on the framework presented in Chapter 2.2 (Figure 2.30). This framework provides the basis for a criticality analysis, which is one of the starting points for a maintenance strategy. It also provides an indication of the assets that require particular attention to meet or exceed all or some of the requirements.



		The impact of the various asset systems on the requirements for the physical assets									
Requirements	**Weights**	Asset system 1		Asset system 2		Asset system 3		Asset system 4		Asset system 5	
Scale 0-10	**10**	Contributi	Product	Contribution	Product	Contributi	Product	Contributi	Product	Contributi	Product
1. Capacity of the production equipment	4,3	5	21,4	7	30,0	3	12,8	2	8,6	2	8,6
2. High reliability as and when required	6,1	6	36,5	10	60,8	7	42,5	2	12,2	9	54,7
3. Excellent maintainability	5,0	7	35,0	9	45,0	5	25,0	1	5,0	4	20,0
4. Good availability of spare parts	3,3	5	16,5	7	23,2	3	9,9	2	6,6	6	19,8
5. Safety of the equipment	4,0	3	12,0	7	28,0	3	12,0	3	12,0	3	12,0
Safety can taken into account also as a separate process		**Low risk**		**Medium risk**		**Low risk**		**Low risk**		**Low risk**	
Total score			**121,4**		**186,9**		**102,3**		**44,3**		**115,1**
Estimate of the share of the different asset systems of the total investment (%)			**35**		**25**		**10**		**5**		**25**

Figure 2.30. Requirements as a framework for maintenance strategies.

The maintenance strategy and its underlying requirements are first defined at the acquisition stage and are continuously updated throughout the life cycle of the asset for a few reasons, already described in chapter 2.2. For example, if an important requirement for a production asset is high availability or uptime, it is necessary to consider which aspect of dependability will be addressed at the acquisition stage. Designers must therefore consider whether the required dependability can be achieved by investing in:

- reliability,
- maintainability,
- usability,
- supportability, or
- a combination of these.

In some reviews, two new factors have been added: misuse prevention and user skills, which should also be considered in the decision-making process (Figure 2.31). IEC 60050(192) also introduces recoverability as a factor of dependability. The following influencing factors will obviously have impact on the level of investment in these above elements of dependability, for example to achieve the availability requirements:

- operating conditions,
- operating constraints,
- technology in use,
- operational mode,
- the technical potential of each component as predicted at the time of acquisition or remaining potential during operating stage,
- the input-output ratio of development measures, and
- the general financial constraints of the organisation.

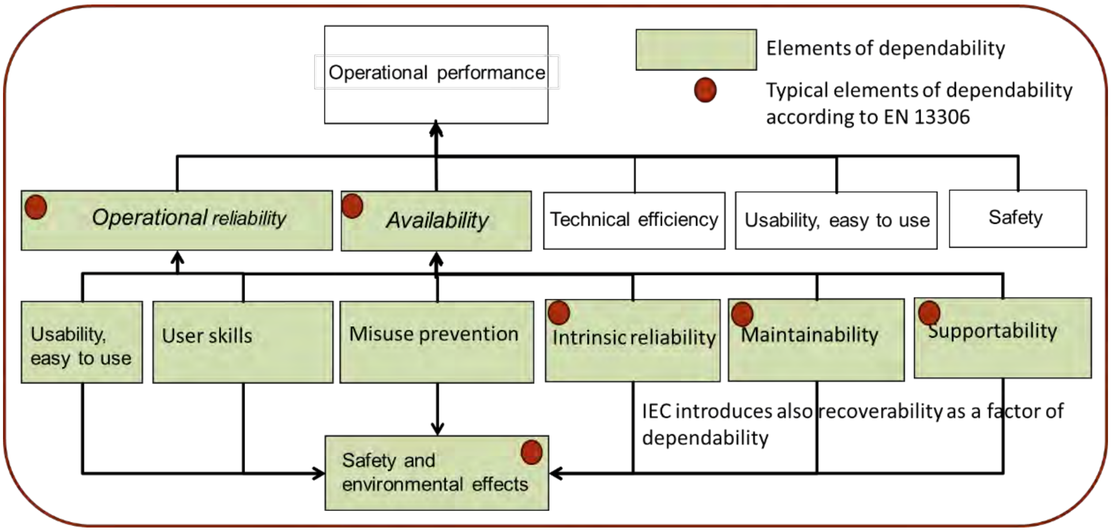
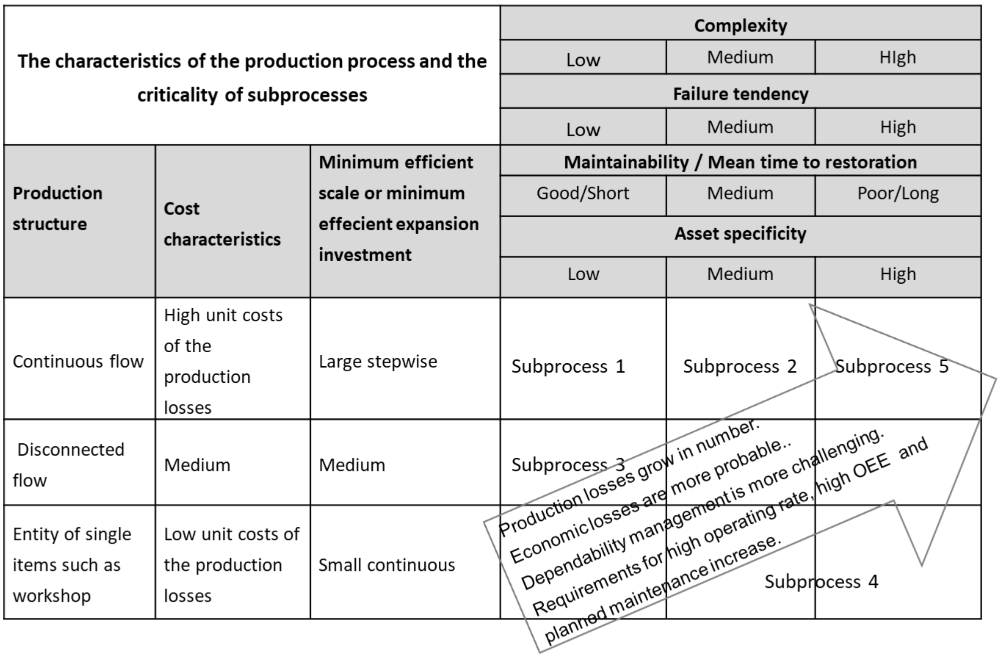


Figure 2.31. Components of reliability as a framework for a maintenance strategy



The characteristics of the production process and the criticality of subprocesses			**Complexity**		
			Low	Medium	HIgh
			Failure tendency		
			Low	Medium	High
Production structure	**Cost characteristics**	**Minimum efficient scale or minimum effecient expansion investment**	**Maintainability / Mean time to restoration**		
			Good/Short	Medium	Poor/Long
			Asset specificity		
			Low	Medium	High
Continuous flow	High unit costs of the production losses	Large stepwise	Subprocess 1	Subprocess 2	Subprocess 5
Disconnected flow	Medium	Medium	Subprocess 3		
Entity of single items such as workshop	Low unit costs of the production losses	Small continuous		Subprocess 4	

Production losses grow in number.
Economic losses are more probable..
Dependability management is more challenging.
Requirements for high operating rate, high OEE and
planned maintenance increase.

Figure 2.32. Impact of the production system (technology environment) on the maintenance strategy.

The impact of the technology in use on the functioning of an organisation has already been outlined above. In this context, they can be presented again, this time from the perspective of strategic planning for maintenance. In the example in Figure 2.32, as we move from a workshop-type unit cost to a unit cost of continuous flow, and from standard technology to company-specific production assets, and additionally from simple, low failure rate, and easily maintainable items to the complex, high failure-rate and not easily maintainable items, the importance of physical assets increases. Long-term cost efficiency is emphasised, and flexibility is reduced. Economic risk and barriers to entry will increase. The need for high levels of throughput, availability and OEE will increase. Maintenance requirements will increase and the need for high maintainability, reliability and planned maintenance will grow. The implications outlined above will largely determine the strategic approach to maintenance.

The technological aspect has been studied in several projects at VTT (Technical Research Centre of Finland Ltd.). A project carried out in 2008-2010 investigated the impact of production and maintenance environments on maintenance strategies and practices (Komonen et al., 2011). The study identified factors that had a significant impact on the shaping of maintenance practices. These factors were the following:

- criticality of the equipment/risk posed by the equipment,
- failure tendency,
- typical repair time or typical time to restoration
- maintenance needs (need for regular preventive maintenance),
- the possibility of maintenance (e.g., the existence of maintenance windows during operating time),
- human and environmental risks,
- skills need, and
- the need for maintenance investment.

Content of the maintenance strategy

There are different views in the literature on the content of maintenance strategies. Sometimes even dependability development methods are confused with strategies (RCM). In this chapter, maintenance strategies are treated as any other strategy: 'a strategy determines how the objectives set are to be achieved'. Thus, several different dimensions can be listed against which strategies can be defined.

1. what to aim for (goals, objectives),
2. the requirements for production assets to be invested in,
3. which specific assets to invest in,
4. what is being developed in the maintenance management system,
5. major repairs, replacement investments and improvement investments and development of maintenance process,
6. the desired portfolio of maintenance types,
7. strategy on time concepts,
8. condition monitoring and condition-based maintenance strategy,
9. developing maintenance resources (staff, spare parts, facilities, tools, documentation, systems),
10. organisational strategy, and
11. subcontracting strategy.

Maintenance management system

Questions 1 to 3 were already discussed above. The development of a maintenance management system is a very important part of the maintenance strategy. The development of the maintenance field and maintenance processes is a demanding and holistic aspect of the strategy. It is largely a question of where to strategically invest to meet the requirements and thus the demands of the critical success factors. The maintenance management system is illustrated in Figure 2.33. Realization maintenance processes refer to the way in which the organisation wants different tasks to be performed. Maintenance functions describe what maintenance is responsible for and what activities it is responsible for. In contrast, maintenance processes describe how the different activities are related to each other and what inputs they receive and what outputs they produce to other processes. Maintenance processes are described in EN 17007 (2018) standards. In the standard the following realization processes are described in detail:

- prevent undesirable events by avoiding failures and faults (PRV),
- restore the items in required state (COR),
- implement preventive and/or corrective actions on the item (ACT), and
- improve the items (IMP).

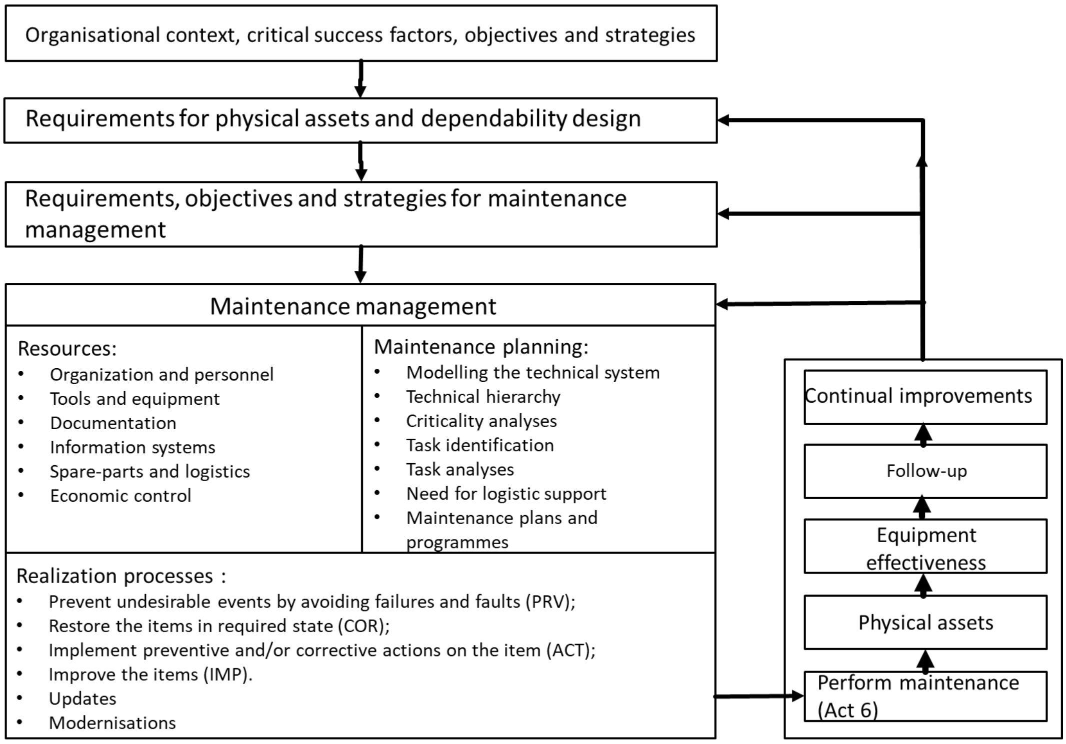


Figure 2.33. Maintenance management system.

Maintenance type strategy

The targeted portfolio of maintenance types depends on the maintenance requirements, the technology in use and its dependability characteristics, and the remaining potential. The reliability characteristics of the technology include failure models, failure mechanisms, failure frequencies and associated probability distributions (see also Figure 2.32). While some of the effects of these factors are optional, others are largely 'technically predetermined'. For example, whether a piece of equipment fails suddenly, gradually but quickly or slowly (ageing or wear and tear) influences the maintenance type strategy that can be chosen. The influence of dependability characteristics on the maintenance type strategy is illustrated as an elementary framework in Figure 2.34.

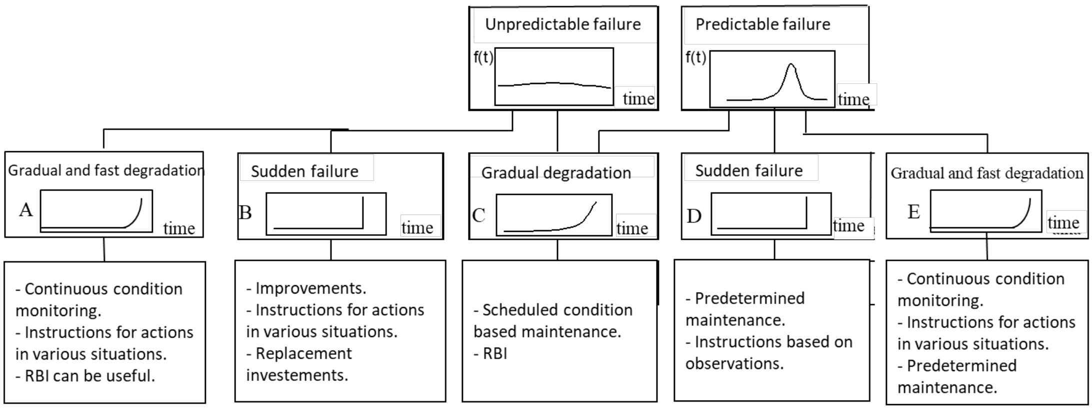


Figure 2.34. Technology-based selection of an efficient maintenance type.

However, the appropriate maintenance type depends also on the other factors such as the probability of undesired events or severity of the consequences. In the simplified situation we have four different cases present:

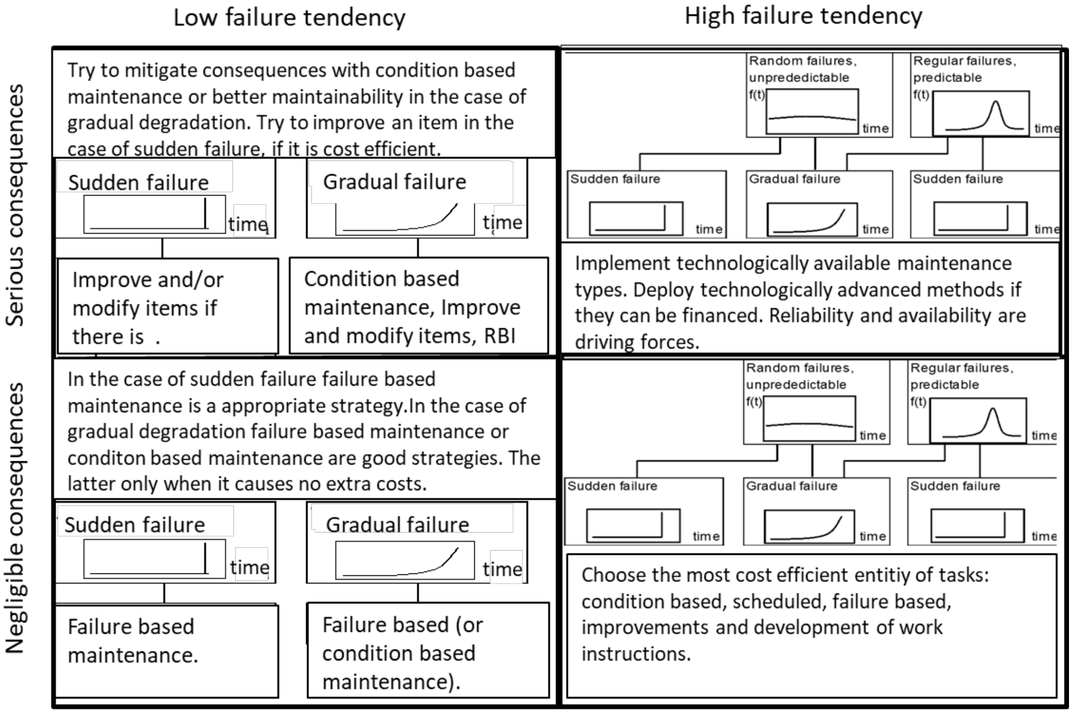
1. High probability and serious consequences.
2. High probability and negligible or acceptable consequences.
3. Low probability and serious consequences.
4. Low probability and negligible or acceptable consequences.

Combination of the above four situations and the technology-based selection criteria are presented in Figure 2.35. In the situation of number 1 (high probability and serious consequences) organisations should use the technologically efficient methods to manage the risks. In the situation of number 2 (high probability and negligible consequences) organisations should use the economically efficient methods to manage the maintenance events. In both the cases 1 and 2 there probably is a lot of data available about failure behaviour e.g., probabilistic distribution.

In the situation of number 3 (low probability and serious consequences) there is little experienced data about failure behaviour, or it is acquired by e.g., laboratory tests or expert judgements. Therefore, organisations should mitigate the severity of the consequences or try to improve the reliability of equipment especially in the case of sudden failure. In the case of gradual degradation, scheduled inspections (e.g., RBI) can be useful to prevent failures or mitigate consequences.

In the last situation of number 4 (low probability and negligible or acceptable consequences) failure-based maintenance is an attractive option. In the case gradual failure failure-based maintenance is a good option. However, condition-based maintenance can be possible option, if it does not require economic expenditures.

The above guidelines are suggestive only. Maintenance type strategies demand careful analyses and calculations. Reliability based maintenance (RCM) can be a good tool to help in analyses.



Try to mitigate consequences with condition based maintenance or better maintainability in the case of gradual degradation. Try to improve an item in the case of sudden failure, if it is cost efficient.

Improve and/or modify items if there is .

Condition based maintenance, Improve and modify items, RBI

Implement technologically available maintenance types. Deploy technologically advanced methods if they can be financed. Reliability and availability are driving forces.

In the case of sudden failure failure based maintenance is a appropriate strategy.In the case of gradual degradation failure based maintenance or conditon based maintenance are good strategies. The latter only when it causes no extra costs.

Failure based maintenance.

Failure based (or condition based maintenance).

Choose the most cost efficient entitiy of tasks: condition based, scheduled, failure based, improvements and development of work instructions.

Figure 2.35. A framework to define maintenance type strategy.

Strategy related to time concepts

The time strategy is intrinsically linked to maintenance types. An organisation needs to define which time-based activities it will seek to improve, such as:

- time to restoration (TTR)
- maintenance time (TTM)
- time between failures or time to failure (TTF)
- time between shutdowns (TBDT)
- preventive maintenance time, and
- the time required for major shutdowns.

For these time factors, efforts can be made to improve the mean (average) or deviation around the mean. Which of these is the more effective strategy depends on the critical success factors and the prevailing potential. Figure 2.36 shows the situation of the weekly variation and average of the demand and production capacity faced by a production organisation. The figure shows that the average capacity is sufficient compared to the average demand, but the weekly fluctuations mean that the demand exceeds the capacity at times. The figure shows that the production capacity of the firm's production facility is sufficient if the capacity variation can be reduced. It is assumed that the capacity variation depends on the measures (downtime) required for maintenance. If a firm wants to increase maximum capacity, it should increase average capacity and reduce deviation, but if it wants to increase its ability to meet current demand, reducing deviation might be sufficient.

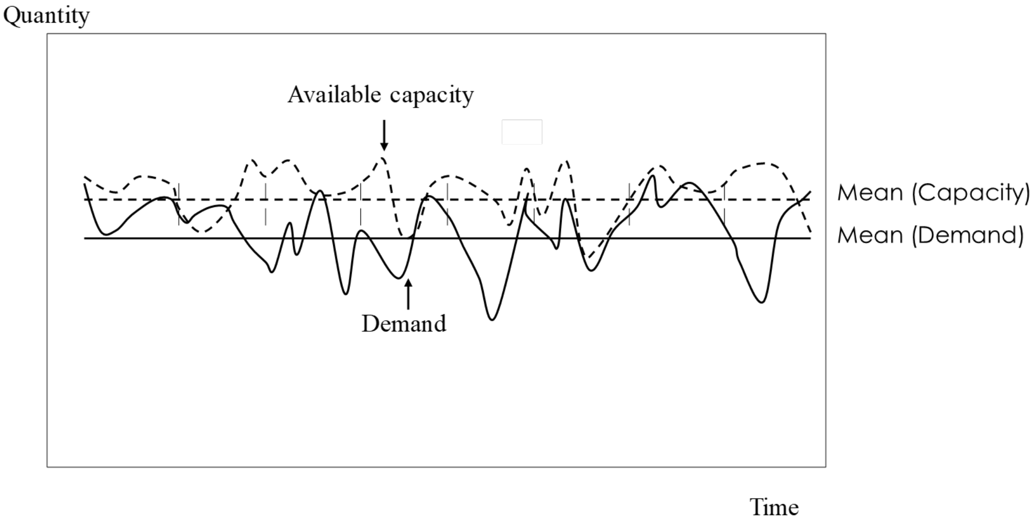


Figure 2.36. Impact of mean and variance on production capacity adequacy.

Figure 2,36 shows the impact of the means and variances on the firm's ability to meet weekly demand. The firm can influence the maintenance times and their deviation through the above mentioned TTR, TTM, TTF, etc. The following list describes the factors that can be used to improve averages or deviations.

The maintenance period can be reduced by, for example:

- by reducing the active maintenance time,
- by extending the mean time between failures,
- reducing waiting times,
- developing repair methods,
- developing the professional skills of maintenance staff,
- by increasing the proportion of planned maintenance,
- using condition-based maintenance,
- improving reliability and maintainability,
- by improving work organisation.

Maintenance time deviation can be reduced by, for example:

- standardising waiting times,
- developing standard repair methods for recurring faults,
- by improving predictability,
- improving the timing of measures (maintenance actions),
- improving the homogeneity of maintenance operators' professional skills,
- by increasing planned maintenance,
- using condition-based maintenance,
- by systematising the performance of condition assessments, and
- by improving work organisation.

The development of condition-based maintenance (CBM) is an effective way to improve the performance and cost-effectiveness of maintenance. CBM strategy, includes:

- targets with reference values,
- assessment of potential,
- where to invest (input-output analysis),
- schedules,
- the methods used,
- staff development needs.

Strategies for maintenance resources

Strategies related to maintenance resources in terms of staffing can be related to, for example, uniformity, multi-skilling, self-direction, IT skills, certification, basic training requirements, etc. For spare parts stocks and logistics, strategic issues include the value of stocks in relation to the size of production assets, prompt and reliable deliveries, co-stocking, number of suppliers, number of direct deliveries to the site, cost-effectiveness of spare parts activities, etc.

A strategy related to maintenance resources can also relate to the use of technologies utilised in maintenance. These may include digitalisation of maintenance (e.g., IOT), robotics, automated maintenance, mobile document and data management, augmented reality, use of different analysis and decision-making methods (e.g., FMEA, FMECA, RCM, FTA, RBD, RBM), etc.

Organisational and outsourcing strategy

The organisational strategy may include statements on the division of labour, roles, and the internal organisation of the maintenance function between operational and maintenance staff. The effectiveness and efficiency of the maintenance organisations depend on several influencing factors. Examples of influencing factors are, but not limited to:

- the size of the plant (economics of scale),
- complexity of the physical assets,
- diversity of technologies,
- required levels of maintenance,
- required lines of maintenance

- integration level of the equipment (see e.g., Figure 2.32),
- maintenance types of strategy,
- maintenance workload pattern, and
- location (e.g., remote location or high-density area).

Organisation strategy can contain, for example, following aspects:

1. to whom the maintenance function reports to,
2. should maintenance organisation be centralised or decentralised,
3. should maintenance function be outsourced and to what extent,
4. what should be the number maintenance experts,
5. what kind of maintenance teams should the organisation have, or
6. what should the responsibilities of operation and maintenance personnel?

The reference framework for this definition can be, for example, the maintenance levels (classification of maintenance according to its complexity/maintenance levels) or the maintenance hierarchy (the organisation in which maintenance is carried out). Maintenance levels are defined in EN 13306 (2017):

Level 1: simple tasks, low training needs,

Level 2: basic tasks requiring qualified staff and precise instructions,

Level 3: complex tasks requiring qualified technical staff and precise instructions,

Level 4: tasks requiring mastery of a method or technology and specialised technical staff,

Level 5: Tasks requiring the knowledge of the manufacturer of the item or a specialised supplier and specialised tools/equipment.

Maintenance echelon, line of maintenance can include options such as:

1. is carried out in the field (e.g., in the production process),
2. is carried out in a workshop,
3. is carried out by the equipment manufacturer.

The levels of maintenance as a strategic framework have a strong connection with the technological structure of the equipment. Some technologies require e.g., the higher maintenance levels than the others. In Table 2.10 an example of the maintenance levels for the various items of the production equipment are presented. The required levels of maintenance as a strategic issue are especially important at the acquisition stage of the assets.

Table 2.10. Example of maintenance levels for various items.

LEVEL OF MAINTENANCE (MODIFIED FROM EN 13306)	**PROPORTION MAINTENANCE LEVELS**			
	Case 1 %	*Case 2 %*	*Case 3 %*	*Case 4 %*
Level 1: simple actions, which require minimal training.	*80*	*65*	*40*	*10*
Level 2: basic actions which must be implemented using detailed procedures by qualified personnel	*15*	*20*	*30*	*20*
Level 3: complex actions carried out using detailed procedures by qualified technical personnel.	*5*	*10*	*25*	*25*
Level 4: actions which requires the good know-how of a technique or a technology and is implemented by specialized technical personnel.		*5*	*5*	*30*
Level 5: actions which requires a good knowledge held by a manufacturer or a specialized company				*15*

As stated earlier, the organisational strategy can further define the general principles of the organisation of maintenance, such as the level of decentralisation, specialisation in, for example, preventive maintenance, corrective maintenance, or basic maintenance tasks. The organisational strategy may include statements on the division of labour, roles, and the internal organisation of the maintenance function between operational and maintenance staff, and it may also include statements on the role of maintenance in other processes of the organisation. The organisational strategy may also include a position on the subcontracting of activities. Williamson's (1985) view of the form of effective governance as a function of business frequency and the specific nature of the investment or acquisition is described below. This model, based on transaction cost theory, is generally intended to explain subcontracting decisions, but is also applicable to maintenance.

For the purposes of this text, standard low asset-specificity maintenance services may include cleaning, scaffold services, lifting services, property maintenance, standard equipment maintenance for less critical items, etc. The services of technology provider companies can fall into several categories, but often they can be placed in the "intermediate" position, between a standard and an "asset-specific" service. Such services may include, for example, maintenance services provided by suppliers of paper machines, process cranes, electrical equipment, etc. for the core process. The "asset-specific" category may include maintenance services that focus on very company-specific technology in critical areas and require specialised knowledge of the company's production process. The development of maintenance strategies and the most critical aspects of maintenance planning may fall into this category.

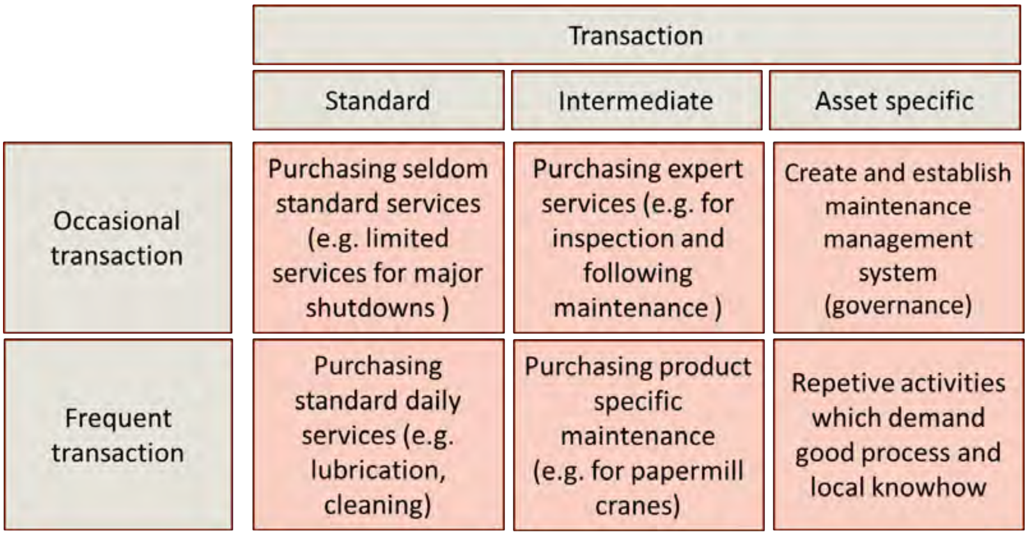
In Williamson's review, the vertical axis represents, in terms of frequency, the nature of the business, which can be occasional (occasional) or recurring (constant turnover). These two dimensions together with three categories of asset specificity can be used to describe 6 different combinations (see Figure 2.37), or different worlds (which Williamson reduces to 4):

1. A standard item can always be left to market forces (classical contract situation). It is the most efficient form of management in the situation in question.
2. When the object under consideration is placed in the category of "intermediate", two different situations arise: in the case of occasional transactions, the most efficient form of management is trilateral, i.e., the maintenance service can be

subcontracted and the management of the contractual relationship is based on the impartial decisions of a third party, the "judge" (arbitrator).

3. n the case of recurrent transactions, where the buyer retains control because of the repetition of transactions, long-term bilateral management can be used. In this case, control is based on mutual agreements.
4. For an "asset-specific" target and recurring transactions, the Williamson model recommends integrated ("do-it-yourself") control. In contrast, for occasional transactions, both integrated and triangular management are possible. Applied to maintenance, the Williamson model could mean, for example, the interpretation shown in Figure 2.37.

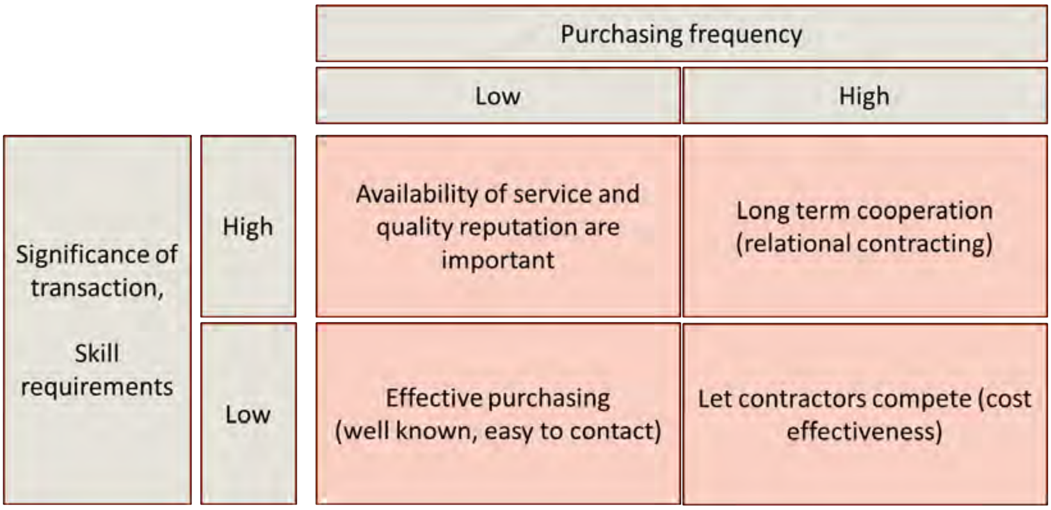
New professional service needs arising from digitalisation, IoT and other technological developments may undermine the Williamson model to some extent. Taking these developments into account, Williamson's theory of business costs is also quite valid for defining maintenance outsourcing strategies.



	Transaction		
	Standard	Intermediate	Asset specific
Occasional transaction	Purchasing seldom standard services (e.g. limited services for major shutdowns)	Purchasing expert services (e.g. for inspection and following maintenance)	Create and establish maintenance management system (governance)
Frequent transaction	Purchasing standard daily services (e.g. lubrication, cleaning)	Purchasing product specific maintenance (e.g. for papermill cranes)	Repetive activities which demand good process and local knowhow

Figure 2.37. Application of Williamson's theory to maintenance (example).

Purchase activities can also be viewed in different ways and from the point of view of the purchase transaction. This is done in Figure 2.38. In this figure, the effective purchasing strategy is assessed in terms of purchasing frequency and transaction importance. In a situation with low frequency and low importance, an effective sourcing strategy is efficient purchasing. This means that the purchase is carried out with the least possible effort and administrative cost. On the other hand, where the importance is high and the frequency is low, the availability of the service in general and the quality reputation of the service provider are important because the randomness of the procurement does not allow the possibility of correcting a possible wrong decision. When the frequency of procurement is high, and the importance of the transaction is high, long-term cooperation is an effective procurement strategy. In the last case, the frequency of acquisition is high, but the importance of the transaction is low. In this case, a procurement strategy based on price competition between service providers is efficient.



		Purchasing frequency	
		Low	High
Significance of transaction, Skill requirements	High	Availability of service and quality reputation are important	Long term cooperation (relational contracting)
	Low	Effective purchasing (well known, easy to contact)	Let contractors compete (cost effectiveness)

Figure 3.38. Acquisition "success factors" based on business frequency and its importance.

The above taxonomies were used to present the different organisational contexts that influence the type of subcontracting strategy that is effective. The rationality and effectiveness of subcontracting can also be approached through individual influencing factors. Table 2.11 shows the impact of 7 different factors on subcontracting tendency.

Table 2.11. Factors influencing an organisation's propensity to subcontract maintenance.

THE INFLUENCING FACTOR	**THE IMPACT**
Unit cost of loss of production	The high unit cost increases the criticality of the site, which places significant quality demands on subcontracting.
Structure of the production system	Highly integrated production increases the unit cost of lost production and the criticality of the target, which places high quality demands on subcontracting.
Criticality of the equipment	As above
Scale	The larger the target organisation, the more difficult it is for the subcontractor to achieve economies of scale vis-à-vis the buyer. This also applies to the diversity of skills.
Maturity of the maintenance market	For example: there are multiple service providers in the market (real competition), the market should be able to deliver the required requirements (e.g., economies of scale), there are real incentives to operate efficiently, service providers can face contractual penalties.
Complexity of the production system	A complex system may, for example, require very diverse and multi-level competences. Can the provider credibly offer these.
Qualification requirements	As above

Presentation and summary of the maintenance strategy

Model based on key performance indicators

The maintenance strategy can be expressed in simple terms using a KPI model, which also describes the basis for strategic choices. The model follows the business-driven process presented earlier in this chapter, but with the addition of two important elements: technological influencing factors and intermediate objectives (Figure 2.39):

- requirements for physical assets are based on segment-specific critical success factors,
- maintenance objectives meet these requirements,
- intermediate objectives are targets that cannot be simply decided, but which led to the achievement of maintenance objectives,
- maintenance means are planned and decided measures leading to intermediate objectives,
- the potential available tells us where we have the most room for improvement and finally,
- technological influencing variables help to interpret objectives and results to be achieved, help to understand the potential for development, and help to select measures appropriate to the technology.

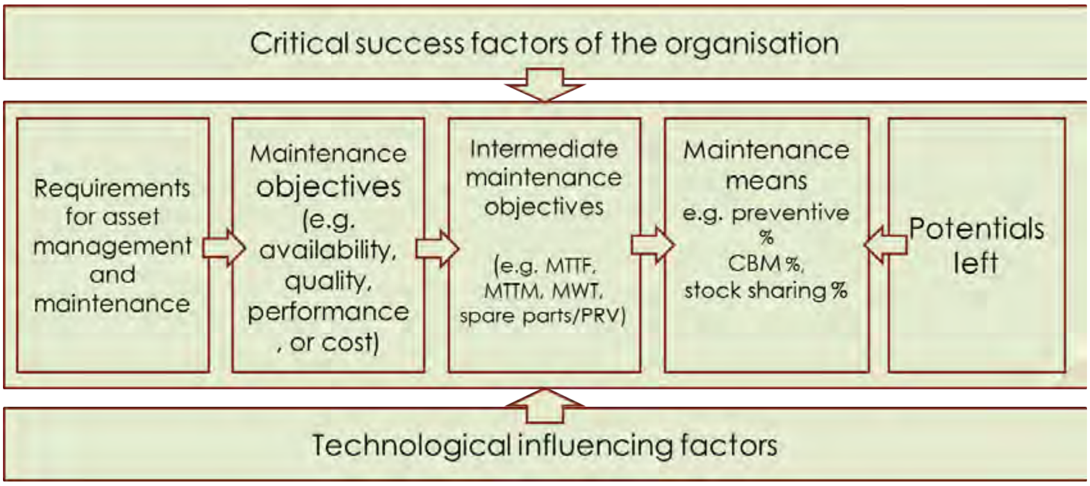
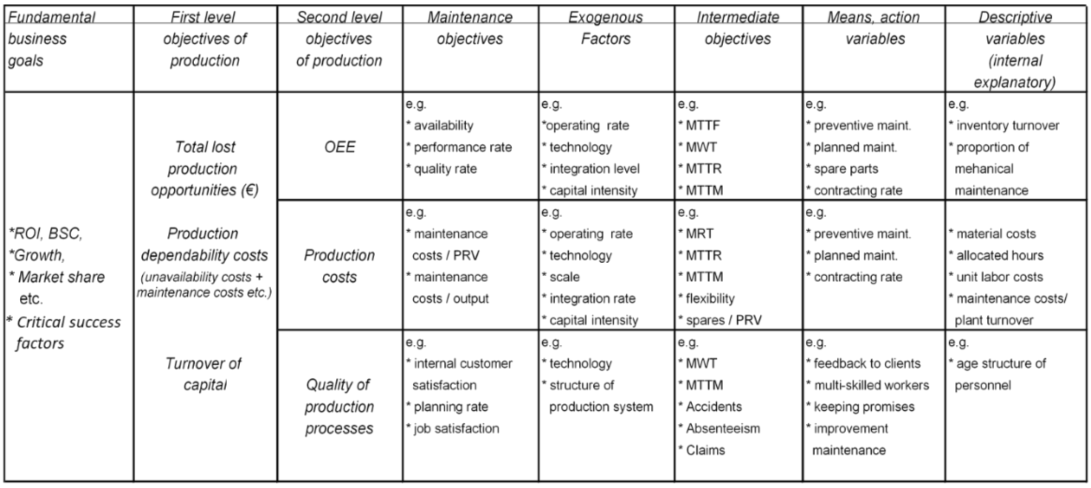


Figure 3.39. Key performance indicator summary of the maintenance strategy

Table 2.12. Extract from the strategic summary for the infrastructure sector

STAGE 1	**STAGE 2**	**STAGE3**	**STAGE 4**	**STAGE 5**	**STAGE 6**	**STAGE 7**
Define segments	Critical success factors	Weights	KPIs (Key performance indicators)	Maintenance KPIs	Requirements for the asset system	Activities
Segment I	Punctuality	5	Delays (pcs/year)	Delays due to maintenance	Short MTTR, small deviation, efficient condition monitoring	Standardisation of recurring works, ultrasonic inspections >x times/year

The framework described above can be adapted to the organisational context. Table 2.12 shows an approach implemented in the infrastructure sector and Figure 2.40 shows a model that fits into a traditional manufacturing environment. The application to a production organisation is an example of what can be in different columns and is not an example of which specific things lead to intermediate objectives and from there to targets.



Fundamental business goals	*First level objectives of production*	*Second level objectives of production*	*Maintenance objectives*	*Exogenous Factors*	*Intermediate objectives*	*Means, action variables*	*Descriptive variables (internal explanatory)*
**ROI, BSC, *Growth, * Market share etc. * Critical success factors*	*Total lost production opportunities (€)*	*OEE*	e.g. * availability * performance rate * quality rate	e.g. *operating rate * technology * integration level * capital intensity	e.g. * MTTF * MWT * MTTR * MTTM	e.g. * preventive maint. * planned maint. * spare parts * contracting rate	e.g. * inventory turnover * proportion of mehanical maintenance
	Production dependability costs (unavailability costs + maintenance costs etc.)	*Production costs*	e.g. * maintenance costs / PRV * maintenance costs / output	e.g. * operating rate * technology * scale * integration rate * capital intensity	e.g. * MRT * MTTR * MTTM * flexibility * spares / PRV	e.g. * preventive maint. * planned maint. * contracting rate	* material costs * allocated hours * unit labor costs * maintenance costs/ plant turnover
	Turnover of capital	*Quality of production processes*	e.g. * internal customer satisfaction * planning rate * job satisfaction	e.g. * technology * structure of production system	e.g. * MWT * MTTM * Accidents * Absenteeism * Claims	e.g. * feedback to clients * multi-skilled workers * keeping promises * improvement maintenance	e.g. * age structure of personnel

Figure 3.40. Example of a strategic summary in a manufacturing organisation.

Strategic efficient maintenance portfolio

As stated earlier in this chapter, a portfolio of maintenance operations must meet the requirements for production assets and at the same time be economically efficient. In this context, this means looking for the portfolio of measures that provides the best input-output ratio and can be implemented within the available budget (Figure 2.41).

A portfolio of measures can consist of, for example:

- replacement investments,
- technical solutions (modifications),
- improvement investments,
- condition monitoring investments,
- efforts on predetermined maintenance, or
- improving the effectiveness of corrective maintenance.

The definition of the strategic portfolio starts like the definition of the asset management strategy (Figure 2.41):

1. identify critical success factors,
2. define the requirements for physical assets,
3. define the contribution of assets to the requirements,
4. compare the current situation with the requirements,
5. identify the available potential,
6. identify and prioritise opportunities for improvement and the range of measures available,

7. a set of alternative measures is generated for each item,
8. form alternative portfolios,
9. estimate the input-output ratio (input-output ratio) of each portfolio,
10. compare alternative portfolios with the available budget, and
11. determine whether it is worthwhile to deviate from the indicative budget.

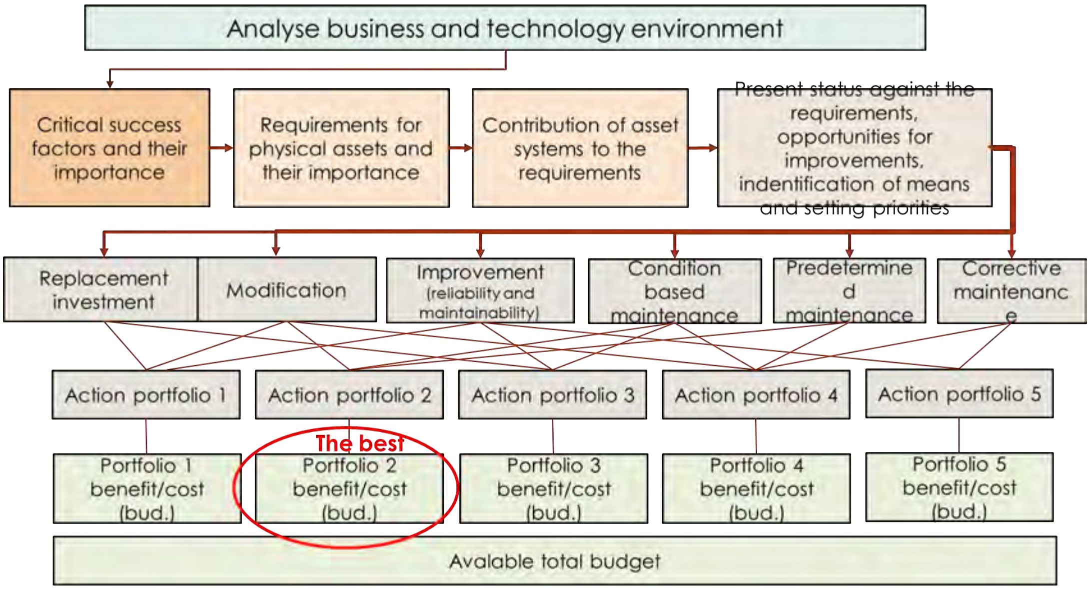


Figure 3.41. Defining a strategic portfolio for maintenance.

Key lessons

- The maintenance strategy depends to a large extent on the business environment of the organisation and the technology in use. This in turn is reflected in the requirements defined for the production assets that support the critical success factors of the organisation.
- The first steps in the maintenance strategy are taken at the equipment acquisition stage, during conceptual, preliminary, and detailed design. The plant's reliability planning serves as the basis for the maintenance strategy.
- The maintenance strategy is not based on a maintenance type strategy or an outsourcing strategy alone but covers all maintenance activities and technological dimensions based.
- A subcontracting and outsourcing strategy is determined by a few factors and is not just an on-off decision.
- A strategic portfolio of maintenance activities is a better starting point for development than a single measure.

2.5. CRITICALITY ANALYSES AS PART OF MAINTENANCE PLANNING

Pasi Valkokari

Introduction

As discussed in Chapter 2.4, decisions on productive asset management are often related to life cycle management and the timing of necessary measures. Different functions within an organisation (engineering, production, maintenance, purchasing, finance, and management) may have very different views on what should be done and when it should be done. However, all these functions should have the same reference framework against which decisions are assessed. This framework should include a common understanding of the significant factors to be considered in the context of decisions.

For production equipment, criticality analysis is a relatively quick way to identify the most significant items in production systems in terms of the risks that are central to the business. This should support the common understanding creation in the organisation, concerning the most significant items of production equipment. Criticality study is most often carried out in a working group using expert judgements. As a result of the criticality analysis, it is possible to develop an understanding of the more relevant risk and development areas of the production in terms of its components. This increased understanding can be used, for example, to achieve the following objectives:

- Rapid improvements in reliability and maintenance planning.
- Changes in the business environment, such as changing demand.
- Timing of replacement investments and identification productivity opportunities.
- Improving occupational and environmental safety.

Criticality analysis is a potential starting point for achieving these objectives, often complemented by other methods (Figure 2.42).

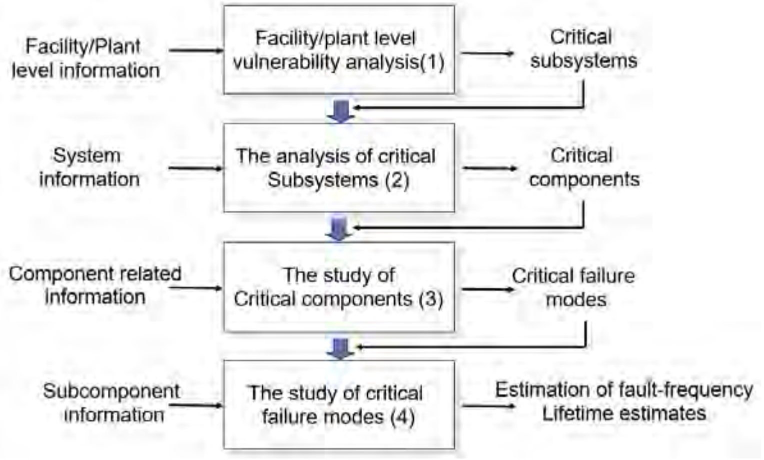


Figure 2.42. Hierarchical reliability analysis diagram.

If the criticality analysis does not provide sufficient information to support decision making to improve reliability, complementary approaches can be used. Complementary analyses to the criticality analysis include, for example, the following approaches:

- *Failure and Mode Effect Analysis (FMEA)* - a basic method for hazard identification and frequency analysis. The method makes it possible to identify the failure modes and their effects on the object under consideration. An extension of the method, Fault Modes, Effect and Criticality Analysis (FMECA) includes the assessment of the criticality of the identified faults.
- *Fault Tree Analysis (FTA)* is a hazard identification and frequency analysis technique that first identifies an unwanted event and determines all the event chains leading to it. The analysis is documented in a graphical, tree-like, format.
- *Event Tree Analysis (ETA)* is a horizontal tree diagram that uses inductive reasoning to identify possible consequences of various initial events,
- *Hazard and Operability Study (HAZOP)* is a basic method of hazard identification that systematically assesses each part of the object under consideration and examines how deviations from the design objectives can occur and whether they have adverse consequences.
- *Life Cycle Costing (LCC)* can be used for economic analyses of different development options to assess their viability.
- *Reliability Block Diagram (RBD)* is a frequency analysis technique that builds a model of the system and its redundancies to assess the overall reliability of the system.
- *Risk Based Inspection (RBI)* is an optimised structural system inspection programme based on structural risk analysis.
- *Risk Informed In-Service Inspection (RI-ISI)* is an optimised structural inspection programme based on structural risk analysis.
- *Probabilistic Risk/Safety Analysis (PRA/PSA)* is a risk analysis method applied in space technology and nuclear power plants, for example, which identifies the chains of events that make up accidents and estimates the frequency of occurrence and consequences of these chains of events.

However, this chapter will mainly focus on demonstrating the application and use of the criticality classification approach presented in PSK 6800 (2008). At its best, the approach supports establishing a common understanding at the organisational level of the criticality of production equipment.

Steps in the criticality review

According to PSK 6800, "*Criticality is a characteristic of an item describing the magnitude of the risk associated with the item.The item is critical if the associated risk (injury to persons, significant material damage, production losses or other unacceptable consequences) cannot be considered acceptable.*"

The criticality analysis includes the following steps. The presentation of the steps does not follow the full process outlined in the PSK 6800 standard, but includes insights gathered from practical cases on how to conduct the review.

Determining the scope of the study, the coefficients to be used and their qualitative descriptions.

- The scope of the study will be decided at this stage. The scope of the review can be limited, for example by starting with the activities identified as the most critical. In a broad sense, the review can cover all the activities of a large factory integrator and thus the entire production process.
- One of the first tasks of the analysis is also to determine the coefficients to be used in the criticality analysis and their qualitative descriptions. For example, how long production stoppage corresponds to a minor inconvenience to production.
- The scale of the criticality coefficients to be used should also be decided. In Table 11, scale values from 0 to 4 are used for the different criticality categories. Different scales can also be used. In this case, however, it is useful to assess the relationship between the categories and the weighting factors from the point of view of the weighting of the individual criticality factor.
- During the definition phase, it is also useful to identify the coefficients describing the probability of failure [p] and their qualitative descriptions. Typically, a scale of 0 to 5 has been used for this task, where a value of 0 usually means that failure is not considered likely during the lifetime of the equipment. Similarly, a value of 5 indicates a short (e.g., 0-2 months) failure/event interval.
- In addition to considering the criticality values, determine the cost factor for each criticality category. The cost factor can be defined for production and quality losses as well as repair and follow-up costs. This provides valuable additional information on the total follow-up costs of potential failures and thus supports the quantification of the scope of development measures.

The weight of output loss used in the analysis is W_P.

- The weighting coefficients describe the interdependence of the technical process functions of the plant. The PSK 6800 standard suggests that the weighting factor should be determined according to the hierarchy of the process under consideration and its overall capacity distribution. This approach is a good starting point when a set of several production processes is selected as the object of analysis. It helps to understand the importance of the different stages of the process for the magnitude of the potential production losses and hence the criticality factor. In practice, however, the analysis often focuses on a single production line, so that the weighting factor is often determined on other criteria than a hierarchical diagram to support the determination of the production impact factor.

Determine weighting factors for the other critical factors to be considered.

- In addition to production loss, typical critical factors include:
    - Factors related to occupational safety $[W]_S$
    - Factors related to environmental safety $[W]_e$
    - Factors associated with quality degradation $[W]_q$
    - Factors associated with the repair of failure/consequential costs $[W]_{.r}$
- Typically, the choice of the weighting factor is influenced by the strategic priorities of the company. The choice of a weighting factor allows the importance of a single criticality factor to be emphasised in the overall criticality index.
- Other factors can also be considered. For example, in the food and pharmaceutical industries, the potential hygiene risks from equipment failures may become relevant.

A practical example of the criticality factors to be used in a criticality assessment at the equipment level is given in the following table (Table 2.13).

Table 2.13. Example of criticality factors at the equipment level, the numerical values in this example are for reference.

	Object	Weighing factor [W]	Multiplier [M]	Cost Classification	Qualitative description / Selection criteria
Impacts to production efficiency	**Production loss**	**E.g. 100**	**0**	**For review, according to each selection criterion corresponding profit-losses (e.g. 3-10 h production stoppage corresponds to 3,000-10,000 € worth of lost revenue)**	Non-operation of equipment has no impact on the sub-process or department
			1		Non-operation of equipment stops the sub-process or department momentarily (eg, ≤3 h)
			2		Non-operation of equipment stops the sub-process or department for a short time (eg. ≤10 h)
			3		Non-operation of equipment stops the sub-process or department for a considerable time (eg. 10 to 24 h)
			4		Non-operation of equipment stops the sub-process or department for a long time (eg. >24 h)
	Quality loss	**E.g. 30**	**0**	**For review, according to each selection criterion corresponding quality costs (e.g. quality loss corresponds to 3-10 h production loss)**	Non-operation of equipment does not cause quality costs to the end product.
			1		Non-operation of equipment causes quality costs on the end product equivalent to a momentary production loss
			2		Non-operation of equipment causes quality costs on the end product equivalent to a short-term production loss
			3		Non-operation of equipment causes quality costs on the end product equivalent to a major production loss
			4		Non-operation of equipment causes quality costs on the end product equivalent to a long-term production loss
Safety and environmental impacts	**Safety Risks**	**E.g. 50**	**0**		No safety risk
			1		Minor safety risk
			2		Moderate safety risk
			3		Major safety risk
			4		Serious safety risk
			5		Fatal safety risk
	Environmental risks	**E.g. 50**	**0**		No environmental risk
			1		Minor environmental risk
			2		Moderate environmental risk
			3		Major environmental risk
			4		Serious environmental risk
			5		Extremely serious environmental risk
Repair or consequential costs	**Costs of repair or consequences**	**E.g. 30**	**0**	**No costs**	Repair or consequential costs are not significant in relation to other losses.
			1	**e.g. 0 - 2000 eur**	Minor repair or consequential costs equivalent to a momentary production loss
			2	**e.g. 2000 - 10 000 eur**	Medium repair or consequential costs equivalent to a short-term production loss
			3	**e.g. 10 000 - 20 000 eur**	High repair or consequential costs equivalent to a major production loss
			4	**e.g. 20 000 euroa**	High repair or consequential costs equivalent to a long-term production loss
Propability of the failure/event	**Failure/event interval [p]**	**1**	**0**		A failure is not likely during the lifetime of the facility (e.g. failure interval of more than 10 years)
			1		Long failure interval (e.g. failure interval 5 - 10 years)
			2		Moderate long failure interval (e.g. failure interval 2 years - 5 years)
			3		Rather short failure interval, for example (e.g. failure interval 1 year - 2 years)
			4		Short failure interval (e.g. failure interval 0.5 - 1 year)
			5		Very short failure interval (e.g. failure interval 0-6 months)

List the devices to be considered.

- For this task, it is advisable to use the equipment list, PI charts or similar data from the maintenance information system, which will provide a comprehensive collection of the equipment under consideration.
- A spreadsheet page is available as an annex to the PSK 6800 standard, which can be used as a basis for review and calculation of criticality indices. However, it is easy to build a spreadsheet page for this task yourself.

Determination of the criticality values of the equipment and calculation of the criticality index (C) and its sub-indices (Ms, Me, Mp, Mq and Mr) using the given parameters.

- Once the equipment under consideration has been listed, the criticality values for each of the elements are determined.
- Based on the determined weight coefficients, criticality values and failure probability categories, the total criticality [C] and the magnitude of the criticality sub-indices are calculated.
- The criticality index C of a device is calculated using the following formula:

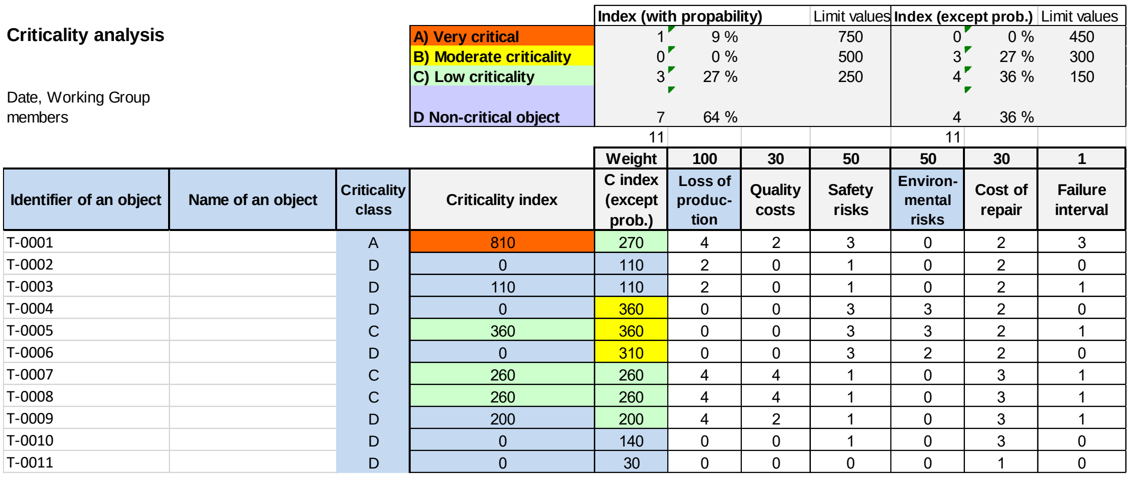
  $$C = p * \Sigma \ (Wx * Kx)$$

  where p = failure/event interval, Wx = weight for each criticality factor and Mx = estimated criticality class for each criticality factor.

Making a criticality classification.

- Criticality ranking guides the prioritisation of remedial measures. This task typically determines the value of the overall criticality index above which sites are identified as requiring immediate action. For example, in this context, the classification may be as follows:
  1. Very critical
  2. Moderate criticality
  3. Low criticality
  4. Not a critical item
- The value of a single sub-index may also be considered significant in the classification. For example, the failure of a component may pose a significant risk to personal or environmental safety, but due to the overall criticality of the object, it is not considered a very critical object. In this case, a single factor may trigger the initiation of development measures.
- It is also possible to look at criticality without the probability factor. If the assessment assigns a failure value of 0 to the equipment, this means a value of 0 for the calculation of the criticality value. However, it is possible that for objects that fail very rarely, the potential consequences and costs are significant. Even in these cases, it is useful to consider contingency measures in case of failure.

Figure 2.43 shows an example of a spreadsheet page used in a criticality analysis (note, this example does not directly include tracking the cost impact of failures).



Criticality analysis

Date, Working Group members

	Index (with propability)		Limit values	Index (except prob.)		Limit values
A) Very critical	1	9 %	750	0	0 %	450
B) Moderate criticality	0	0 %	500	3	27 %	300
C) Low criticality	3	27 %	250	4	36 %	150
D Non-critical object	7	64 %		4	36 %	
	11			11		

				Weight	**100**	**30**	**50**	**50**	**30**	**1**
Identifier of an object	**Name of an object**	**Criticality class**	**Criticality index**	**C index (except prob.)**	**Loss of produc-tion**	**Quality costs**	**Safety risks**	**Environ-mental risks**	**Cost of repair**	**Failure interval**
T-0001		A	810	270	4	2	3	0	2	3
T-0002		D	0	110	2	0	1	0	2	0
T-0003		D	110	110	2	0	1	0	2	1
T-0004		D	0	360	0	0	3	3	2	0
T-0005		C	360	360	0	0	3	3	2	1
T-0006		D	0	310	0	0	3	2	2	0
T-0007		C	260	260	4	4	1	0	3	1
T-0008		C	260	260	4	4	1	0	3	1
T-0009		D	200	200	4	2	1	0	3	1
T-0010		D	0	140	0	0	1	0	3	0
T-0011		D	0	30	0	0	0	0	1	0

Figure 2.43. Example of a form for a criticality analysis.

Key lessons

- Criticality analysis is a relatively quick approach to gain an understanding of the most critical functions/equipment/components of the production assets.
- In most cases, the criticality classification is based on expert judgement, but if reliable event data on the failure events at the site is available, this can be used to support the work.
- The review can be carried out at the system, subsystem, or device levels in accordance with the limitations imposed by the available human resources. If the review starts with a specific subsystem, with the intention of expanding the review later, it is good to ensure the comparability of the evaluation criteria.
- It is useful to look at the resulting overall criticality values for equipment from several angles. These include the elevated criticality of a single component, as well as the criticality without the failure probability.
- Valuable information can also be generated by considering the cost categories of potential cost drivers (production costs, quality costs, repair costs and consequential costs) in the analysis. This will support the determination of the magnitude of development measures.

2.6. PERSPECTIVES ON STRATEGIC ASSET MANAGEMENT

Jyri Hanski

Introduction

Strategy describes the long-term goals of the organisation. Among other things, it defines the scope of the organisation's activities and competitive advantages, its strategic fit with its environment, and its resources, competences, and values. Strategic management and strategic objectives provide guidelines for strategic asset management (ISO 55000, 2014). Strategic decisions are often complex and uncertain. Understanding the factors that influence decision-making, i.e., the decision environment, supports the setting of strategic objectives, the selection of decision criteria and the evaluation of alternative strategies. Strategic asset management decisions often involve complex systems composed of a large number of interacting components, whose history influences present-day activities, and which are affected by constantly changing environmental factors (Snowden & Boone, 2007).

Complex systems introduce uncertainty into decision-making. Uncertainty refers to the lack of information about an event, its consequences or probability (ISO, 2009). Strategic asset management decisions are often uncertain and have significant long-term implications for different actors and stakeholders. Complexity and uncertainty arise from many factors: long life cycles of physical assets, decisions based on incomplete information, different needs and requirements of stakeholders, hierarchical structure of systems, complex technologies, information systems and organisational structures, and the huge number of different types of assets to be managed. In addition, strategic asset management is influenced by many emerging trends and perspectives such as legislation, sustainability, circular economy, climate change, technological advances, ecosystem perspective, business models and risk management.

A SWOT analysis is a common way of outlining the pursuit of sustainable competitive advantage. It looks at how to exploit internal strengths and avoid weaknesses, and how to exploit opportunities and neutralise potential threats in the operating environment. The internal side of the SWOT analysis is based on a resource-based view of competitiveness, where internal differences within firms explain their success or failure. The external side is based on an environment-based view of competitive advantage, which emphasises the analysis of the environment and the identification of the features of the environment that lead to good performance. Figure 2.44 shows the perspectives that influence strategic asset management, divided into the external and internal aspects of the organisation.

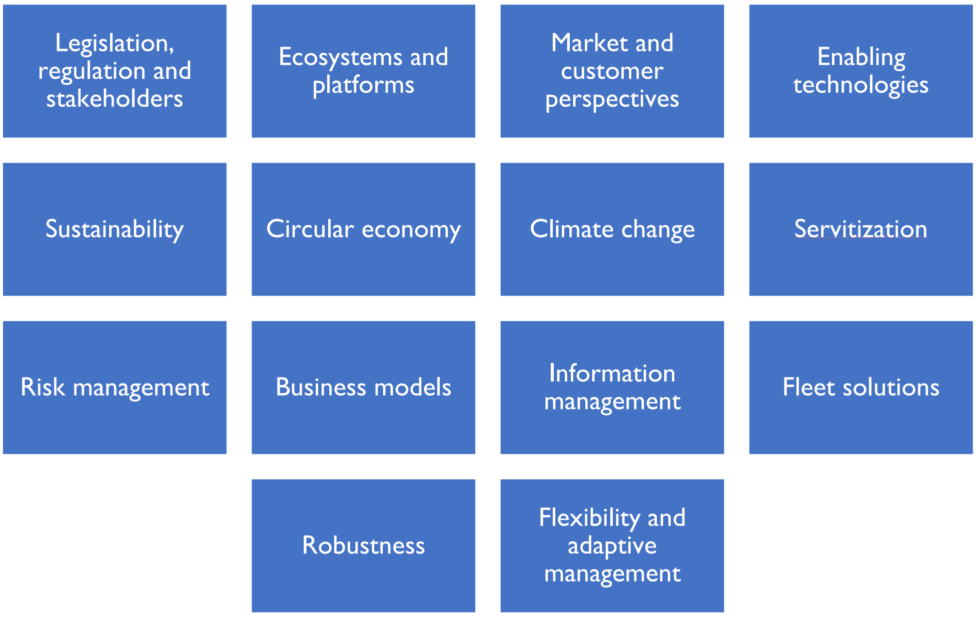


Figure 2.44. Perspectives on strategic asset management

These perspectives are changing asset management strategies and practices now and in the future. They add complexity and uncertainty to strategic asset management decision-making and the need for new tools to manage uncertainty. On the other hand, new perspectives will also create new business opportunities, for example to promote sustainability and adapt to climate change. In the following, the different perspectives and their impact on strategic asset management are presented in more detail.

The internal perspective of the organisation

The internal perspective consists of the company's culture, values, mission, and vision (ISO 55000, 2014). This perspective is complemented by key aspects that influence strategic asset management: risk management, business models, knowledge management, fleet solutions, robustness, flexibility, and adaptive management.

Risk management

Risk management is a key part of strategic asset management and includes the activities that control and manage risk in organisations. Risk is defined as the impact of uncertainty on objectives, where the impact can be either positive or negative (ISO 31000, 2018). Risk management is a continuous process with the objectives of transparency inside and outside the organisation, increasing risk awareness, reducing the likelihood of future losses, preparing for undesirable situations, and achieving organisational objectives. The role of risk management is highlighted in strategic decisions and in the management of complex systems such as infrastructures. Risk management as part of strategic asset management requires identifying all key risks, assessing their impact on the value of physical assets and optimising risk management activities.

Business models

The business model describes the logic with which a company creates and captures value. The business model should succeed in three areas: value creation, value proposition and value capture (Clauss, 2017). Value creation consists of the capabilities, technology, partnerships, and processes required by the business model. The value proposition describes the content of the service, including the offering, customers, markets, channels, and customer relationships. The revenue model and cost structure play a key role in capturing value. In strategic asset management, the business model has traditionally been considered, particularly in outsourcing decisions. Examples of business models for maintenance services include short-term price-driven, availability-driven, and long-term collaborative partnership contracts. New digital solutions enable new business models such as providing service platforms and technologies, analytics-based services for troubleshooting, predictive maintenance, and predictive performance management, and optimizing the performance of physical assets based on data, advanced analytics, and domain expertise (Ahonen et al. 2020).

Information management

Information management lays the foundation for successful strategic asset management. In this context, information management refers to the processes of information management, data management and data value, data processing and analysis, documentation and reporting, data integration, knowledge management related to physical assets and the information systems in which data is collected and stored. Data management typically consists of the following activities: data collection and pre-processing, descriptive data analysis, data modelling and the use of data to support decision-making or in other ways. Data related to physical assets is typically a huge, complex, and fragmented collection of data in various information systems and documents. In this context, including in support of strategic asset management, big data solutions have been developed that exploit volumes of data that cannot be handled by commonly used software solutions.

Fleet solutions

Fleet solutions and fleet management refers to the management of systems, subsystems, and components with similar characteristics. An example of fleet solutions is the evaluation of the performance of individual equipment and machines against the current or past performance of an entire fleet of similar machines (Lee, Bagheri & Kao, 2015). New digital solutions enable the collection and analysis of data regardless of the physical location of the equipment. For example, this allows global manufacturing companies to compare the performance of their machines across sites and conditions.

Robustness

The long life cycles of physical assets, operating in large networks, and the demands of multiple stakeholders and changes in the operating environment bring uncertainty to strategic asset management decision-making. In complex and uncertain decision situations, consensus is often reached on the time horizon to be considered, the number and content of scenarios, and the variables to be used to describe the performance of solution options. The main challenges are often related to the determination of the performance of the selected variables in different scenarios and the value of the selected solution options. Therefore, asset management decisions should consider the robustness of the selected solution options. A robust solution or strategy performs well under the largest number of plausible future scenarios compared to the alternatives (Lempert et al., 2006). Robust solutions and strategies are particularly profitable in uncertain long-term investments.

Flexibility and adaptive management

Adaptive management aims to increase the resilience of systems through flexibility, continuous learning, and experimentation (Fritsch, 2017). Its guiding idea is that the future will unfold in sometimes unexpected ways that cannot be fully anticipated. Adaptive management is therefore a complementary approach to robustness. Adaptive strategies are based on current knowledge and anticipated conditions but are also flexible to changes in the future. The guiding principle of adaptive strategies is therefore that strategies are not in place for decades, but for short periods of time and are adapted as needed. In strategic asset management, adaptive management should be considered at the planning stage, so that physical assets are flexible to change in response to changing requirements.

External aspects of the organisation

The external perspective of the organisation consists of the main trends and perspectives that influence the business environment and, through this, the strategic asset management.

Legislation and stakeholders

Legislation imposes requirements on strategic asset management and creates uncertainty for strategic decisions. For example, technological, institutional, and economic changes such as deregulation, privatisation, and changes in the price of materials and raw materials can have a significant impact on strategic asset management decisions. Strategic asset management decisions involve multiple stakeholders and complex networks that impose their own, sometimes conflicting, requirements on decision-making.

Ecosystems and platform solutions

Businesses operate in complex and dynamic networks, where several companies work together to deliver products and services, i.e., value to their customers. Such networks are called ecosystems. Products and services related to physical assets are based on data, knowledge, and other resources of multiple actors. Platform solutions aim to make the sharing of these resources more efficient, and their transition can reshape industry structures and bring entirely new players, such as platform and data solution providers, into industrial sectors.

Market and customer perspective

Market structure, characteristics and demand strongly influence strategic asset management decisions. Market characteristics include market sophistication, barriers to entry, uncertainty, and volatility, means of differentiation and legislation. New digital technologies are blurring and even removing the boundaries between markets, making market delineation challenging. The customer perspective and the decision-making environment are at the heart of strategic asset management. The organisation needs to understand the decision situations faced by customers and in which situations customers benefit from the products and services offered.

Enabling technologies

Technological development and new technological solutions have a significant impact on the effectiveness of strategic asset management. Strategic asset management is affected by advances in a wide range of technologies such as Cyber-Physical Systems (CPS), virtual technologies, Artificial Intelligence (AI), cloud computing, increased instrumentation, robotisation, nanomaterials, biotechnology, energy technology, digital platforms and blockchain technology. The development of digital technologies is seen as one of the main drivers of change affecting strategic asset management decisions.

Sustainable development

Sustainable development aims to meet society's current needs from an environmental, social, and economic perspective, without compromising the ability of future generations to live. Increasingly, companies are expected to apply the principles of sustainability and many companies have made it an integral part of their strategy. There are many perceived benefits to sustainability: avoiding fees and fines, the importance of community relations, higher revenues and lower costs through improved reputation and reduced other costs, and improved competitiveness. Strategic asset management plays an important role in promoting sustainability because production facilities, infrastructure and the products and services they produce account for a large share of global resource consumption and emissions, and a huge number of people depend on the labour they require. Adherence to the principles of sustainable development places new long-term economic, environmental, and social demands on strategic asset management.

Circular economy

Circular economy is an emerging trend that aims to promote sustainable development by minimising the use of waste, energy and raw materials in the systems under consideration. Currently, only 9% of materials are recycled back into production systems, so circular economy solutions are seen as having huge potential (Circularity Gap, 2019). The circular economy is seen to have positive environmental, social and economic impacts. A shift to circular economy approaches is estimated to reduce Europe's greenhouse gas emissions by up to 70%, increase the workforce by around 4% (Wijkman & Skånberg, 2015). Strategic asset management and the circular economy have many similarities - both aim to optimise the use of resources or the value of assets over their life cycle. However, the circular economy has a stronger focus on the reuse of materials and equipment and the use of renewable resources, while strategic asset management currently focuses on financial sustainability and risk management.

Climate change

Mitigation - reducing greenhouse emissions and increasing sinks - is a keyway to fight climate change. Efficient use of resources is one of the keyways to mitigate climate change, as the production and use of materials and products account for a large share of man-made greenhouse gas emissions. Strategic asset management therefore plays an important role in mitigating climate change. While mitigation has been a central part of European and international climate policy, the importance of adapting to the impacts of climate change has also been recognised. This is because even if mitigation targets are met, the impacts of climate change are likely to be faced (Swart et al., 2009). Mitigation and adaptation objectives should have a major impact on the management of assets at the strategic level. Asset management should adapt and respond to changing conditions and the potential for increased extreme weather events. These impacts will be strongly felt in the energy sector, for example, but also, at least indirectly, in other sectors.

Servitization

In recent decades, companies have added services to their previously product-centric offerings. This development is called servitization. Servitisation and the increased collection and analysis of data on products and services enables the extension of service offerings to different stages of the life cycle. One of the main objectives of strategic asset management is to guarantee a certain level of service to current and future customers, which can be supported by the servitization development. Service obsolescence is also seen as an enabler for many sustainable development and circular economy business models.

Key lessons

- Strategic asset management is influenced by many internal and external aspects of the organization.
- These perspectives will have a major impact on asset management strategies and practices now and in the future. They add complexity and uncertainty to strategic asset management decision-making and the need for new tools to manage uncertainty.
- Key emerging issues include sustainable development and the circular economy, new digital technologies, and climate change adaptation.

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PART 3

COLLECTING, ANALYSING AND EXPLOITING DATA

3.1. DATA AND DATA SOURCES IN LIFE CYCLE MANAGEMENT

Helena Kortelainen and Toni Ahonen

Introduction

Life cycle management is a very data-intensive activity that requires the collection, processing, and refinement of diverse data (e.g., IEC 60300-3-2, ISO 55002, EN 15341). Data diversity is a key challenge for data mining: in addition to data generated by measurement systems, there is manually collected event data stored in maintenance information systems or logbooks, master data presenting the configuration and design drawings of machines and equipment, work instructions, images, and videos, among others. Another challenge is the interfaces between information systems and organisational functions, which make it difficult to transfer data from one system to another. Exchange of data between different companies is characterised with complex technical and business issues.

Digitalisation is shifting the focus from data collection to data exploitation. The typical question is no longer "What data do we need?" but rather "How can this data be used?". Processing, enriching, and refining data helps to understand equipment failures or production bottlenecks, but predicting future failures or production bottlenecks requires the development of deeper knowledge and models.

This chapter discusses the different forms of data, the processing and enrichment of data into information that is relevant to the user and decision-maker. It also looks at the methods used to collect data and the various information management systems, and their exploitation to support decision making.

Data, information, knowledge, and wisdom

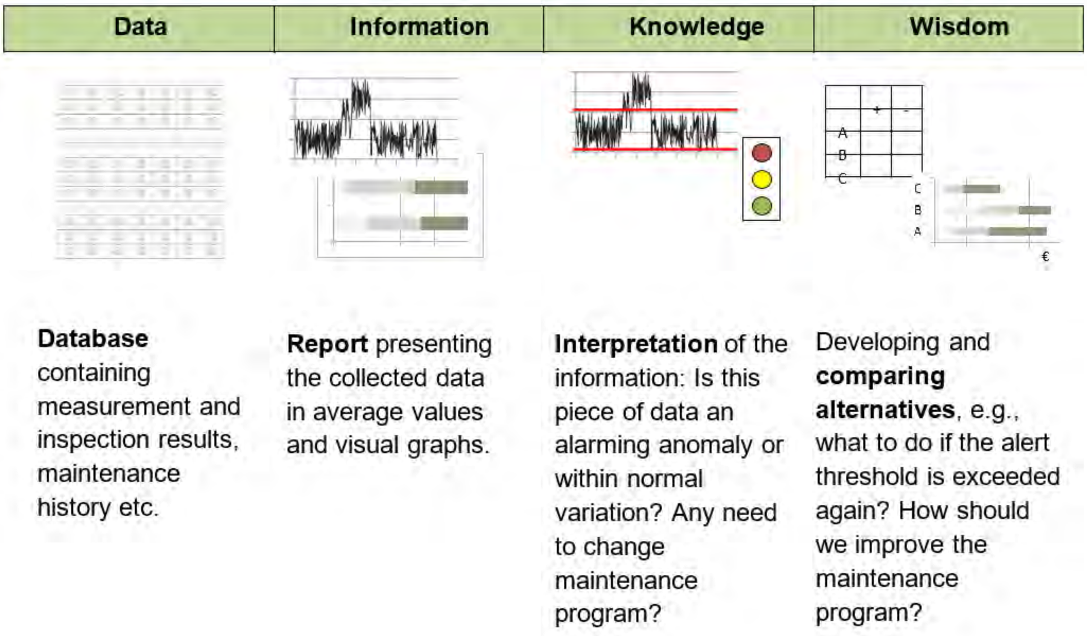
In everyday language, the word 'data' generally means information. Ackoff (1999) defines data and information as:

"Data are symbols that represent the properties of objects and events. Information consists of processed data, the processing directed at increasing its usefulness. Data are the products of observation. Data elements are of no use until they are in a useable (i.e., relevant) form."

Data is obtained through observations. Data appears in many different forms such as numbers, drawings, pictures, text, or sound. Data can be refined and enriched, for example by drawing on knowledge or expertise from a variety of sources.

A widely used typology for structuring the complexity of data is the *DIKW (Data - Information - Knowledge - Wisdom)* hierarchy, whose levels describe the degree of processing of data. The DIKW hierarchy was published by Ackoff in 1989 and since then has been extended and several variations have been proposed (e.g., Rowley, 2006). In the DIKW model, data is numerical and non-numerical information collected and stored about the subject under consideration. Data are often collected in databases. Information is created by processing the data into a form that is more understandable to the human brain, for example, into trend charts, averages or other meaningful metrics or graphs. The difference between data and information is therefore functional rather than structural. Information appears in descriptions and answers to questions that begin with the words who, what, when and where. Information systems produce, store, retrieve and process data. Knowledge is the ability to interpret information and identify actions that may be required. Knowledge can be acquired through human interaction through tacit knowledge transfer, instructions, or experience. The DIKW hierarchy also includes the concept of "wisdom". Wisdom is the ability to combine information from different sources and to identify alternative courses of action, drawing on knowledge gained from previous experience, and to compare and evaluate the pros and cons of the options available.

The levels of the DIKW hierarchy are illustrated by the condition monitoring example in the figure below (Figure 2.1). The raw data collected in the databases is seldom very useful as such. Processing the data into information in the form of indicators and graphs will help to understand the situation much better. Adding empirical or modelling data to this information allows to assess when the values of the condition monitoring measurements indicate that a component is aged and requires intervention, or when the process parameters indicate an abnormal situation. This knowledge can be further evaluated against other sources of information to determine whether the component should be completely replaced with another type, whether the maintenance program should be changed, or whether a recurring problem requires a redesign.



Data	Information	Knowledge	Wisdom
Database containing measurement and inspection results, maintenance history etc.	**Report** presenting the collected data in average values and visual graphs.	**Interpretation** of the information: Is this piece of data an alarming anomaly or within normal variation? Any need to change maintenance program?	Developing and **comparing alternatives**, e.g., what to do if the alert threshold is exceeded again? How should we improve the maintenance program?

Figure 3.1. Examples of different forms and processing of data (Kunttu et al., 2017).

Tacit knowledge

In addition to the information stored in databases and systems, an important part of the life cycle management related information is so-called *tacit knowledge*. Tacit knowledge refers to non-verbal insights, gut feeling, and knowledge that people acquire through experience.

The American scientist Michael Polanyi (1966) is often cited as the creator of the concept of tacit knowledge. He summed up the essence of tacit knowledge by saying that "*we know more than we can tell*". People cannot express all the knowledge that is reflected in their actions in the form of habits, routines, practices, and feelings. Given the importance of tacit knowledge, much research has been done on how to transfer, store and transform it into an explicit or visible form (e.g., Nonaka & Takeuchi 1995). Processing and enriching data helps to understand, for example, machine breakdowns or production bottlenecks, but predicting future breakdowns or production bottlenecks requires the development of deeper knowledge and models. It is precisely in creating this deeper understanding that tacit data is so important.

Explicit knowledge and tacit knowledge complement each other and help create new knowledge. Nonaka & Takeuchi (1995) described the creation and sharing of new knowledge in an organisation with their well-known SECI model (Figure 2.2). The transformation of tacit knowledge into explicit knowledge starts with the interaction between individuals (*socialisation*). In the next stage, tacit knowledge is transformed into an understandable and interpretable form using concepts and models (*externalisation*), and is combined into larger sets, organised, and analysed, so that it can also be combined with previously stored information (*combination*). The explicit knowledge is widely available to the organisation, at the same time as it is internalised into what is being done, it also becomes part of the personal knowledge base of individuals (*internalisation*), from where the cycle starts again.

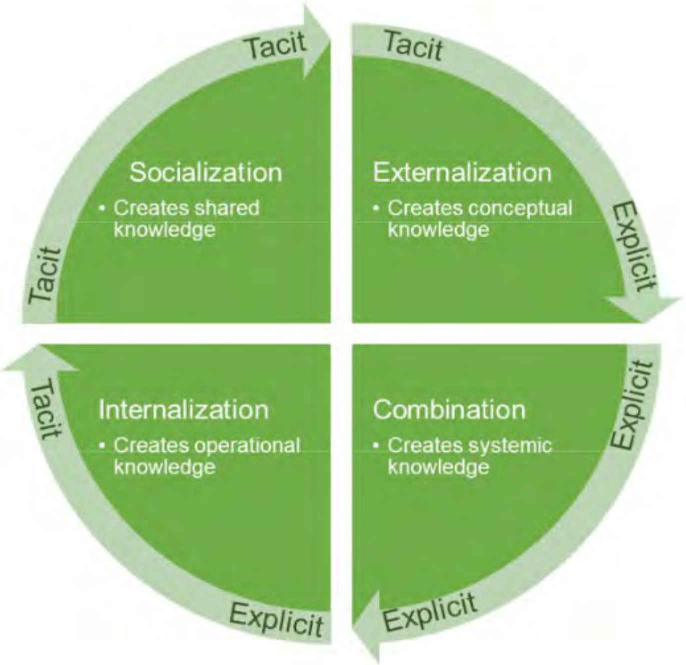


Figure 2.2. SECI model illustrating the creation and sharing of new knowledge in an organisation (Nonaka & Takeushi, 1995).

Tacit knowledge can be learned through experience and can be transferred and shared through a variety of methods. These methods include (Chennamaneni & Teng, 2011):

- observation,
- mentoring,
- apprentice- and craftsman-models,
- metaphors,
- analogies,
- storytelling,
- concept map,
- prototypes,
- best practices,
- learning from experience, lessons learned,
- expert interviews,
- brainstorming,
- case-based reasoning (CBR), and
- fishbone diagrams.

Sources of life cycle data

In the first life cycle stages (see Part 1, Figure 1.2), new data and information are created along with the progress of the item design and implementation. In the subsequent life cycle stages, data about product performance, reliability, maintenance and modifications, use, about conditions and loads applied on the product, and about several other issues is accumulated and can be captured. With the advent of digitalisation, the measurement and monitoring of various factors related to product performance and use is technically feasible and cost-effective. So, the amount of data that can be collected has exploded and is expected to continue to do so. For example, an autonomous passenger car is estimated to generate 4000 GB of data - every day (Meariam, 2017).

While more and more data are being produced, *big data*, artificial intelligence and data analytics are not new. For example, back in the 1990s, Shell Expro analysed the historical data generated by North Sea drilling systems over 20 years of operation. During this period, tens of millions of work orders had been created in the information systems. These work orders were transferred to one database, and it took two years to clean up the database. The data was then analysed. As a result, only four cases (about 3%) showed a statistically significant correlation, rather than non-randomness. However, even one identified problem was worth the effort (Woodhouse, 2018).

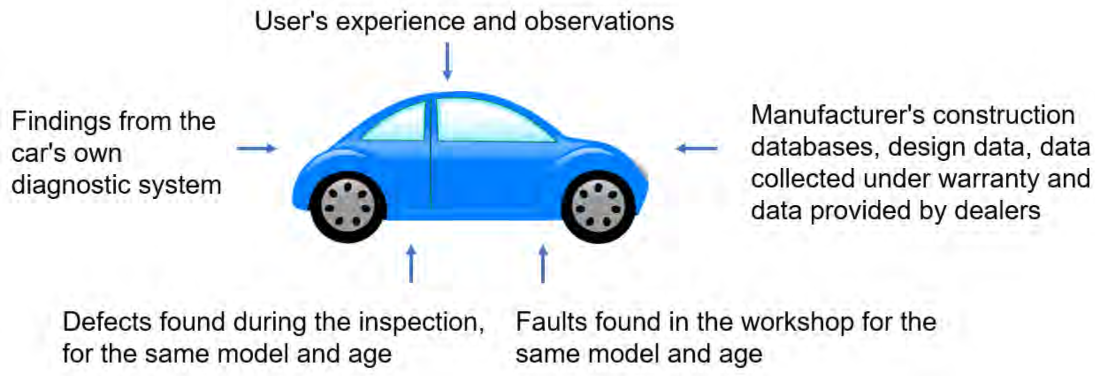


Figure 3.3. Lifecycle management information is accumulated in numerous databases and systems.

A lot of data is collected, but from a lifecycle management perspective, the data is accumulating in too many information systems, it is often incomplete and of poor quality. For example, the engineering unit often data from the field experience (from previous generations of products), reliability and maintenance analysis and simulations at their disposal. However, post-warranty performance measurement data and other pieces of information are often stored in databases for customer feedback, together with complaints, spare parts, non-conformance reporting, monitoring, and service. A key question is how this information is compiled for use in engineering department and to an individual design engineer? In terms of dependability, the integration of multiple data sources is not regarded as an information systems issue, but rather a matter of collaboration and lack of tradition to retrieve data for common basis of decision-making (Ahonen et al., 2012).

Data related to dependability is stored at different stages of the product life cycle by multiple actors in many information systems, such as:

- Supplier's Product Data Management (PDM) or Product Lifecycle Management (PLM) contain data related to product design, manufacturing, sourcing, and customer deliveries.
- Design systems and software that contain documents generated during product design, such as structural drawings, diagrams, documents, and specifications.
- Enterprise Resource Management (ERP) contain e.g., cost information. ERP systems can also contain a maintenance management module.
- Enterprise Asset Management (EAM) that covers the tasks of maintaining physical assets and the event history throughout the life cycle of each asset.
- Computerised Maintenance Management System (CMMS) that collect the maintenance organisation's work orders, material and resource tracking and procurement.
- Automation and process control systems
- Manufacturing execution system (MES), operational data (e.g., control room logbooks and diaries in electronic format).
- Condition monitoring
- Databases or other repositories of documents in which inspection reports and the like are stored.

Asset information systems (CMMS, ERP, EAM) are increasingly linked to production control and automation systems and data can be retrieved from these systems. Further steps towards better communication include applications that allow a fault or incident report handled by the maintenance information system can be made, for example, via the operating organisation's logbook or the production management system.

In the concept and development stage, literature and databases also provide some initial information. Table 3.1 provides a summary of the databases that offer dependability and reliability data from different sectors. More comprehensive list of sources for reliability data is published by Norwegian center for reliability and safety studies (ROSS)[1].

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[1] More information on ROSS and the reliability databases, see https://www.ntnu.edu/ross/info/data.

Table 3.1. Dependability data in databases

DATABASE	DESCRIPTION
OREDA - Offshore and Onshore Reliability Data	Components and equipment for the oil and gas industry
T-Book	Reliability data of components in Nordic nuclear power plants
EiReDA - European Industry Reliability Data	Reliability data bank providing reference data to safety studies for power plants and other industrial installations
MIL-HDBK-217F	Reliability of military electronic equipment and systems
Handbook of Reliability Prediction Procedures for Mechanical Equipment	Reliability data for mechanical equipment (defence applications)
Reliability Data for Control and Safety Systems - PDS Data Handbook	Sensors, detectors, valves, and control logic
Exida- Safety Equipment Reliability Handbook	Safety management (sensors, logic units, actuators)
CCPS Guidelines for Process Equipment Reliability Data and PERD - Process Equipment Reliability Data	Process equipment reliability Information (AiChE)

Product data

Product data refers broadly to all data and information related to a product. Product data can be roughly divided into three categories: product specification, life cycle data and metadata (Saaksvuori & Immonen, 2004).

- Product specification
  - the physical, functional, and technical characteristics of the product and its structure, and
  - specification data include product drawings, pictures, and descriptions.
- Product life cycle data
  - information related to the product life cycle stage and the order-to-delivery process, and
  - covers the entire life cycle of a product, from technology research to product development, manufacturing, support, and end-of-life.
- Metadata is information about data
  - metadata describes the product data: what the data is, where it is located, who stored it and how it can be accessed, and
  - metadata is also needed to retrieve information from databases.

Product data can be static or dynamic (Främling & Rabe 2006). Static information is mainly data collected during the design phase about a particular product type. Dynamic data, on the other hand, includes data accumulated throughout the life cycle of the product, especially during the use phase and thus it includes user experiences. Examples of static information are data related to the materials, components, manufacturers, configuration, and the initial maintenance programme of the delivered product. Long-lived and slowly changing data is also often referred to as master data. Typical master data include product data, organizational data, information on resources (employees) and various code systems.

Dynamic product data includes real-time information, the key feature of which is that it is constantly changing, and the volume is increasing. Examples of dynamic product data include recorded data entries on maintenance events, and the changes in conditions, loads or use profile. The distinction between the static and dynamic data is blurred since the data classified as static may in certain cases be variable. In product development and asset enhancement stages, changes are made to products, which in turn lead to extensive changes in the product design documentation. Data collected during the product's use stage can be used as feedback in product development, whereby the collection of dynamic data influences the content of static data.

Product data management during the life cycle

The supplier's product information management system collects, stores, and retrieves information related to product design, manufacturing, and customer deliveries. *Product Data Management (PDM)* has the focus in an item that has a life cycle both in technical and commercial sense. Life cycle may refer to a product population (e.g., certain type or product generation), but it refers also to a specific product entity. Product life cycle management of an individual item or a item population covers the stages from product development to disposal or to the end of commercial life. Product data is increasingly accumulating in situations where a company's product portfolio is growing and, at the same time, the (commercial) product life cycles are shortening. The customisation of products and the resulting product variations increase the challenge of data management.

From the manufacturer's perspective, product life cycle is a sequence of decision-making points, from defining the product requirements to closing the production and replacing the product with a novel one on the market. *Product lifecycle management (PLM)* refers to a company's concept for managing the product lifecycle and the necessary decentralisation and management of lifecycle data, but nowadays PLM also refers to an information system that aims to cover the entire product life. Although PLM systems are intended to be used at all stages of the product life cycle, their use is often focused on and limited to product design (see Part 1, Figure 1.2). The need for product data management in the utilisation, enhancement and disposal stages is increasing along with life cycle service business.

The product structure forms the core of a PDM/PLM system (Saaksvuori & Immonen, 2004) and the key concepts of product data management are, in addition to the product model (or product structure), the product data model and the *Bill Of Materials (BOM)*. A BOM is, as its name suggests, a list of parts and components of a product. The product structure is a hierarchical description of the product structure and the systems, subsystems and their parts and components that are used to build it. At the conceptual level, the product structure of the physical world corresponds to the product data model in the digital space.

PLM applications are used to manage product data throughout the product life so that all the necessary up-to-date documents and information are easily available for different purposes. This enables the retrieval, discovery, processing, distribution, and reuse of information. In other words, PLM systems enable the collection and sharing of information from different systems and stakeholders. PLM extends the vision of PDM. In practice, the distinction between the concepts of PLM and PDM is blurred.

Despite of the extensive information systems the designers and engineers often difficult to find data on dependability and related issues and to use this data when developing of new equipment. Measurement data and other information related to reliability after the warranty period is often scattered in various databases of customer feedback, complaints, spare parts, incident reports, and service. The development of these information systems has not considered the dependability tasks that take place during the concept and development stages. Identification of the real users of the data and their needs, and systematic planning of data collection will ensure that the data contained in the information systems meets the demand. Systematic data collection planning and implementation eliminates duplicated work in data collection and collected data the needs of different user groups. If data management system is based on real data use cases, data effectively supports the decision-making and data is more likely retrieved (Ahonen et al. 2012).

Product data exchange between different stakeholders

PDM/PLM systems are designed to gather essential information throughout the product lifecycle for all stakeholders who need it. Exchanging large data sets requires the development and standardisation of data models and the development of integration architectures. Cooperation between stakeholders is supported by the *STEP (Standard for the Exchange of Product Model Data)* family of standards. The STEP standard is used for the integration of computer-aided design (CAD) and manufacturing (CAM). The structure of the STEP standard is described in ISO 10303-1 (1994). The STEP standard also provides a uniform way to construct and describe data models and thus improves the data interoperability and applicability (e.g., ISO 10303-11, 2004 and ISO 10303.28, 2007).

In an investment project or procurement, the end user receives not only the physical product but also a huge amount of product-related information. If the format for the delivery of the master data is not specifically agreed, the data may be delivered in hardcopy, electronically in PDF format, on a CD or on a memory stick, from where it is manually entered to the customer's ERP/CMMS or EAM system. Spreadsheet software (MSExcel, etc.) is also used as a data exchange tool. Information that is essential to maintenance planning, such as a maintenance manual, can be a word document with the preventive maintenance interval mentioned in the text. When information cannot be exchanged automatically, the customer must manually input every data item into his own EAM or CMMS system. Another problem, especially in a greenfield investment project, may be that the plant hierarchy has not been created and the positioning of equipment (e.g., Figure 3.4) lack, so that equipment cannot be linked to any structure. There will be many changes, and each change will have knock-on effects. In delivery projects, data is still exchanged by e-mail and there is no agreement on a common data structure. The development leads towards "intelligent data exchange" between information systems i.e., via an *Application Programming Interface (API).*

Collecting data in the deployment phase

The data collected during the utilisation and enhancement stage is needed both by the asset users and the original equipment manufacturer. The manufacturer´s product development benefits from the fault, malfunction, and repair time data from the field and from the important feedback. According to EN 60300-3-2 (2005), dependability information during the operational phase should be collected systematically and it plays an important role in dependability issues, such as:

- maintenance planning,
- justification of modifications,
- calculation of future resource and spares requirements,
- confirmation of contractual satisfaction,
- assessment of the likelihood of achieving a successful mission,
- feedback to design and manufacturing,
- estimation of cost of warranty period,
- improve dependability requirements,
- collection of basic data for possible liability cases, and
- collection of usage data to determine field customer requirements which provide the basis for supplier dependability test specifications and demonstration programs.

As the list above shows, there are many ways in which a manufacturer or supplier can use the information generated during the life cycle of a product or system supplied. Decisions may relate to the design of the product, the selection of system components, the development of maintenance services, i.e., the definition of an optimal maintenance strategy or preventive maintenance intervals, the allocation of the investment budget, the assessment of warranty periods or spare parts needs, the management of spare parts, etc. Lifecycle service providers can collect data to support service development and evaluation, and to assess performance. The data collected and analysed by the service provider can also support their customers' decisions.

The standard ISO 55002 (2014) for physical asset management states that every organisation must implement the necessary information management processes and document the information it needs. Asset management requires reliable, comprehensive, and well-documented data on the machinery and equipment and on their operation and maintenance throughout the life cycle of the assets. For the asset management, the most important information systems are therefore ERP and asset management information systems (e.g., CMMS).

Asset information systems

The asset management can be supported by a variety of information systems. Instead of a separate CMMS system, maintenance management tasks can be managed through the maintenance modules of an *Enterprise Resource Planning system (ERP).* Recent development of

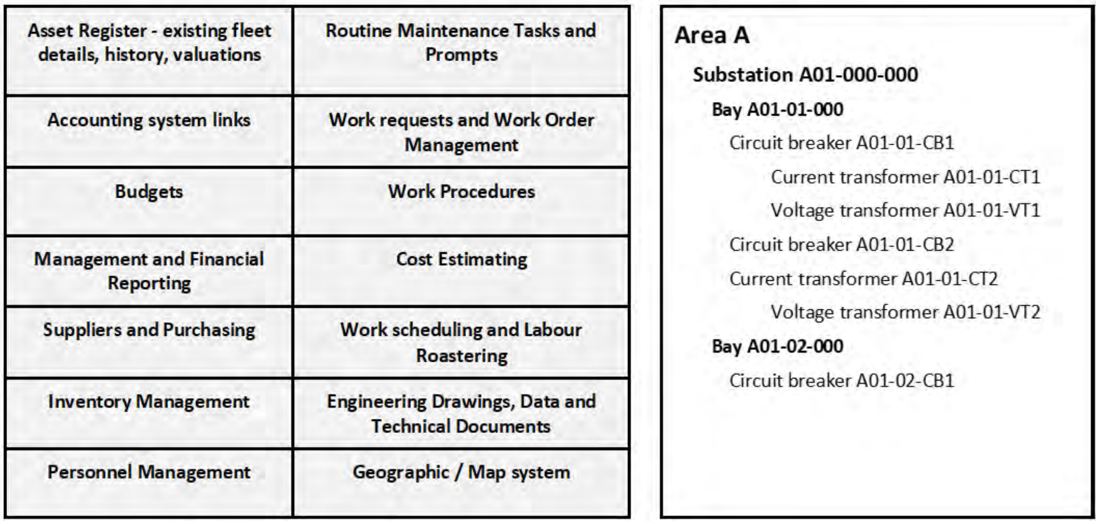
CMMS systems extends the functionalities of the system towards a comprehensive support of the entire asset life. Such systems are often referred to as *Enterprise Asset Management Systems (EAM)*. Hereafter, the “EAM system” will refer to any asset information system, as the functions that the system serves are very similar, regardless of the company or system. An EAM system typically includes several components, such as equipment data, a logbook application, maintenance control, material control, cost accounting and reporting. The EAM system is used to plan, optimise, execute, and monitor maintenance tasks and their performance, as well as the priorities, capabilities, materials, tools, and information associated with these tasks. The EAM system covers all phases of the asset life cycle. Thus, it enables the management of work orders, material and resource tracking, procurement, and the collection and reporting of event history and cost data.

The key data for the asset management are:

- What machinery, equipment, and asset system we have?
- Where are these assets located?
- What is the condition of our assets?
- What are the most critical assets in terms of business?
- What is the remaining life of each asset?
- What are the biggest risks?

The EAM system should also include visual material such as maps, satellite images, photographs, and images from surveillance cameras that determine the location of items and illustrates operating and environmental conditions.

The event history relevant to maintenance management, investment planning and the development of dependability is generated by the entries of maintenance personnel in information systems. The content of these records is determined by the data model contained in the system. An example of an EAM system is shown in the following Figure 3.4.



Asset Register - existing fleet details, history, valuations	Routine Maintenance Tasks and Prompts
Accounting system links	Work requests and Work Order Management
Budgets	Work Procedures
Management and Financial Reporting	Cost Estimating
Suppliers and Purchasing	Work scheduling and Labour Roastering
Inventory Management	Engineering Drawings, Data and Technical Documents
Personnel Management	Geographic / Map system

Area A
- **Substation A01-000-000**
  - **Bay A01-01-000**
    - Circuit breaker A01-01-CB1
      - Current transformer A01-01-CT1
      - Voltage transformer A01-01-VT1
    - Circuit breaker A01-01-CB2
    - Current transformer A01-01-CT2
      - Voltage transformer A01-01-VT2
  - **Bay A01-02-000**
    - Circuit breaker A01-02-CB1

Figure 3.4. An example of the EAM system data content and functional location coding (Hastings, 2015)

Asset register including listing of maintainable assets with full range of configuration management parameters, cost and depreciation information, valuation, and condition information is the core of any asset information system. EAM requires the introduction and implementation of a systematic classification and coding system. Systematic numbering of machinery, equipment and systems by equipment location or position code is important to ensure that a failure, work order or maintenance task, spare parts used and working time can be assigned to the right item. The coding also assures that items can be located and identified in a large plant. An example of activity-based numbering is shown in the Figure 3.4. It should be noted that the location code often remains the same even if the machine or piece of equipment is replaced by a new one.

Different industries have their own established practices for establishing the coding framework. A general model is provided by EN 17485 (2021), which defines plant hierarchies in four different categories. These groups are location hierarchy, process hierarchy, equipment hierarchy and other hierarchies. The category 'Other hierarchies' includes e.g. cost centre hierarchy and document hierarchy. In a location hierarchy, the structure is formed according to the physical location of the equipment. The levels of the location hierarchy are continent, country, locality, site, plant, facility, region, and location. In a process hierarchy, the hierarchy of a plant is constructed by considering the interdependencies between the plant's functions, with the following levels:

- a complex of several plants/factories
- plant/factory,
- production unit,
- production line,
- process,
- sub-process,
- function, and
- sub-function.

In the equipment hierarchy, equipment is further divided into components and further into parts. The equipment hierarchy allows failure events and work orders to be allocated even to individual parts of the equipment. A single device can be associated with more than one hierarchy and the user himself chooses which hierarchy he wants to use. Thus, for example, electricians can view work orders in the electrical hierarchy and mechanical installers in the mechanical hierarchy. A position number can also be assigned to a device in the equipment hierarchy in the automation system.

From a lifecycle management perspective, the usability of the data stored in EAM systems is often hampered by the fact that the data is stored at too general a level (no item-specific data, no plant/equipment hierarchy established) and that repair times and the consequences or causes of failures are not recorded. Event descriptions at free format are often vague and brief (see for example (Figure 3.5). In addition, some repair or inspection activities may not be recorded at all. The further exploitation would be easier if at least following issues of a repair activity would be recorded (Kortelainen et al., 2003):

- Description of findings - what did you find?
- Description of the work done - how did you solve the problem?
- Description of the challenges encountered in the work - what problems or delays were did you have?
- What were the reasons for any delays?
- Is the work done or do you or someone else have to continue the work in one way or another?

- Is a follow-up of the case needed?
- What can or should be done to prevent a recurrence?

Classification of the data collected in the field

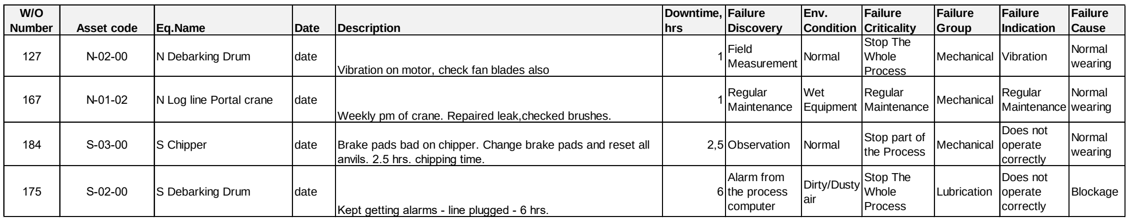
IEC 60300-3-2 (2004) provides guidelines for the collection of data relating to reliability, maintainability, availability, and maintenance support performance of items operating in the field. The collected data should consider inventory, usage, environment, and events:

- *Inventory* – information proving that a particular item exists in the field, how that item is configured, and what other items that item contains.
- *Usage* – information about when an item was placed into the field, how that item is operated in the field, and when that item was removed from the field.
- *Environment* – information about the operating conditions of the item, often in terms of factors that are considered important to the dependability of the item.
- *Events* – information about anything that has happened to the item during its life, these will include failures, repairs, upgrades, etc.

The more detailed the data, the better it can be used both for maintenance development and for the equipment manufacturer's product development. Among others, Kortelainen et al. (2003) have developed a classification method to describe failure and malfunction events and their consequences. A well-executed classification of failure data can enhance and facilitate the analysis of a large data set. Classification fields, lists of options and ready-made drop-down menus speed up data entry and reduce errors, thus improving the quality of the data collected. This classification model (see Figure 3.5), the failure-related data is supplemented with the following pull-down menus:

- Device name and tag number.
- Failure discovery: condition monitoring, field measurement, automation system alarm, quality control, scheduled maintenance (the term used at the plant is regular maintenance), observation.
- Environmental conditions at the time of detection of the fault: normal, dirty/dusty air, high temperature, dirty equipment, wet equipment.
- Effect to the production: stops entire production line/sub-process, stop equipment, reduces production speed, quality degradation, no effect, scheduled maintenance.
- Failure group: mechanical, electrical, instrumentation, lubrication, hydraulic, computers, automation.
- Failure indication: leakage, vibration, noise, overheating, etc.
- Failure cause: corrosion, blockage, normal wear, installation error, lack of preventive maintenance, user error, etc.

As an example of the classification model described above, the maintenance data collected from two wood processing lines are shown in Figure 3.5. The maintenance and failure data were collected using a separate data collection application connected to the mill's EAM system. The data entries build up a failure report. Data entry is simplified by pull-down menus. As the data is entered to the system manually, must the work be as quick and easy as possible. For this reason, the data collection process and procedures of the facility need to be developed in cooperation with all stakeholders, so that the procedures and the information system can be mutually supportive.



W/O Number	Asset code	Eq.Name	Date	Description	Downtime, hrs	Failure Discovery	Env. Condition	Failure Criticality	Failure Group	Failure Indication	Failure Cause
127	N-02-00	N Debarking Drum	date	Vibration on motor, check fan blades also	1	Field Measurement	Normal	Stop The Whole Process	Mechanical	Vibration	Normal wearing
167	N-01-02	N Log line Portal crane	date	Weekly pm of crane. Repaired leak,checked brushes.	1	Regular Maintenance	Wet Equipment	Regular Maintenance	Mechanical	Regular Maintenance	Normal wearing
184	S-03-00	S Chipper	date	Brake pads bad on chipper. Change brake pads and reset all anvils. 2.5 hrs. chipping time.	2,5	Observation	Normal	Stop part of the Process	Mechanical	Does not operate correctly	Normal wearing
175	S-02-00	S Debarking Drum	date	Kept getting alarms - line plugged - 6 hrs.	6	Alarm from the process computer	Dirty/Dusty air	Stop The Whole Process	Lubrication	Does not operate correctly	Blockage

Figure 3.5. Maintenance and failure data collected using the classification model (Kortelainen et al., 2003)

The Finnish standard PSK 9101 (2018) provides a set of minimum data items required for meaningful analysis of event history. The data allows to calculate, for example, different metrics of availability performance, mean time to failure (MTTF) and mean time to restoration (MTTR). The initial data are divided into two categories: data items containing timestamps and items containing pre-determined values (Table 3.2).

Table 3.2. Minimum required data items concerning event history (PSK 9101, 2018)

DATA ITEMS INCLUDING TIME STAMPS	DATA ITEMS CONTAINING PRE-DETERMINED VALUES
• Time of deviation observation • Start time of deviation consequence • Start time of action consequence • End time of action consequence • Time of recovery to production	• Object of deviation observation • Type of deviation • Consequence of the deviation to production before action • Timing of action • Consequence of the action to production • Consequence of the deviation to production after action

Consequence of the deviation to production before action describes the immediate effect on production of the detected disturbance before operation or maintenance has started to take action to correct the problem. For example, a deviation may decrease performance or quality performance before system is stopped to perform the action, but the action required to correct the problem requires the site to be shut down for the action (action consequence). The duration of the pre-action consequence is attempted to be obtained as the difference between the start time of the action consequence and the start time of the deviation consequence.

Examples of pre-determined values that relate to the consequences of a deviation or action include:

- no effect,
- no separate effect,
- stops the production,
- decreases production by 50%,
- decreases quality performance by 10%, and
- other indirect cost effects.

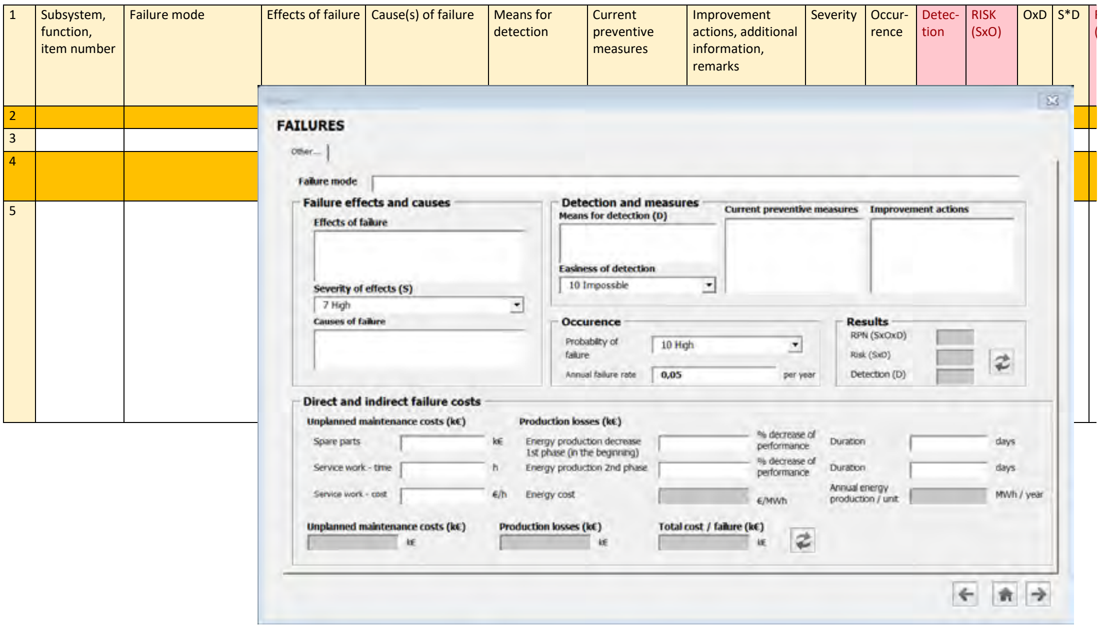
Leveraging the knowledge of experts

In addition to information systems, users are often a useful source of data, and the information collected among the users and experts is often the quickest way to get an overview of the system's dependability and development needs. Experts may even be the only source of information if the studied event is very rare, if there are only few observations, if a new technology is considered for which no field data is available, or if future developments are assessed.

Expert judgements are prone to errors because people tend to perceive and weight their perceptions, interpretations, and information in certain ways (Baybutt, 2018). For this reason, particular attention must be paid to the expertise and commitment of experts, and to the comprehensiveness of the expert group. Attention must be paid to teamwork and mutual trust. A common goal makes it easier to get to work and helps even strangers to work effectively together.

A guided expert process such as a workshop makes explicit, visible knowledge, as well as tacit knowledge, available to the expert group. In a workshop, the team produces more knowledge than the members could individually produce. In this way, knowledge is accumulated, and new perspectives are brought to the surface. The visual worksheets used in workshops can also be seen to have a place in bringing out tacit knowledge, and keywords that guide group work help to focus quickly on the task at hand (Molarius, 2015).

If no comprehensive failure statistics is available for the subject under consideration quantitative methods offer a way to proceed in assessing dependability or risk. Qualitative methods are based on experts´ knowledge of the of the object and its characteristics, use and maintenance. In most cases, the analyses also assess and quantify the criticality of the identified failure modes. Typical qualitative methods include *potential problems analysis (POA), fault trees (FTA), reliability block diagrams (RBD), failure and effects analysis (FMECA), hazard analysis (e.g., EN 1050 Check list)* and *maintenance analysis (e.g., RCM).*



1	Subsystem, function, item number	Failure mode	Effects of failure	Cause(s) of failure	Means for detection	Current preventive measures	Improvement actions, additional information, remarks	Severity	Occur-rence	Detec-tion	RISK (SxO)	OxD	S*D
2													
3													
4													
5													

FAILURES

Severity of effects (S): 7 High

Easiness of detection: 10 Impossible

Probability of failure: 10 High

Annual failure rate: 0,05 per year

Figure 3.6. FMECA worksheet and MS Excel application to support FMECA teamwork, data recording and reporting (Tiusanen et al., 2020).

Figure 3.6. shows an example of FMECA worksheet and the MS Excel application developed to support the analysis. In this case, the FMECA analysis was carried out to support the development of a completely new product. As there is no user experience or field data available, predefined ratings help to assess the factors. FMECA analysis is complemented by an assessment of the economic consequences of failure and malfunction events.

Key lessons

- Life cycle data and information is diverse, including not only numerical data but also pictures, diagrams, written text, human and expert knowledge, and tacit knowledge.
- Data is a raw material and rarely useful or valuable as such. The value of data is created when it is processed into a usable and easily understandable form (information, knowledge, wisdom).
- Life cycle data is often scattered, as data accumulate in several information systems and across several stakeholders. This fragmentation often makes it difficult to make use of the information.
- In terms of life cycle management, the key information systems are the product data management (PDM, PLM) of the equipment manufacturer or supplier and the asset information systems (CMMS, ERP, EAM) of the asset user and maintenance organisations.

3.2. CONDITION MONITORING

Jouko Laitinen

Introduction

As physical assets and equipment become more complex, the failure behaviour becomes more difficult to predict. In addition, most of the equipment with random failures are not possible to maintain effectively only according to the specific usage like running hours or a fixed time interval. Condition monitoring has proven to be the best and most feasible way to manage this situation, with maintenance based on the condition of the equipment. The advantage of this method is that there is no need to predict or guess anything, but the assessment of the maintenance need is based on the operating condition of the equipment and on the information it provides. The challenge has been to choose the appropriate method of condition monitoring. Extensive condition monitoring involving multiple sensing devices or systems also requires advanced analytics to enable automated condition monitoring.

Choice of condition monitoring method

The choice of the appropriate condition monitoring method also depends on the object to be monitored. For example, visual inspection is the most suitable method for structural condition monitoring, while vibration analysis is the most suitable method for bearing condition monitoring. The choice of inspection method is also influenced by the early warning of an impending failure. If the equipment is not critical, it may even be decided to allow the equipment to fail before repairing it. For critical equipment, on the other hand, the aim is to anticipate failure as early as possible to decide on the appropriate time for maintenance or repair action (Fig. 3.7).

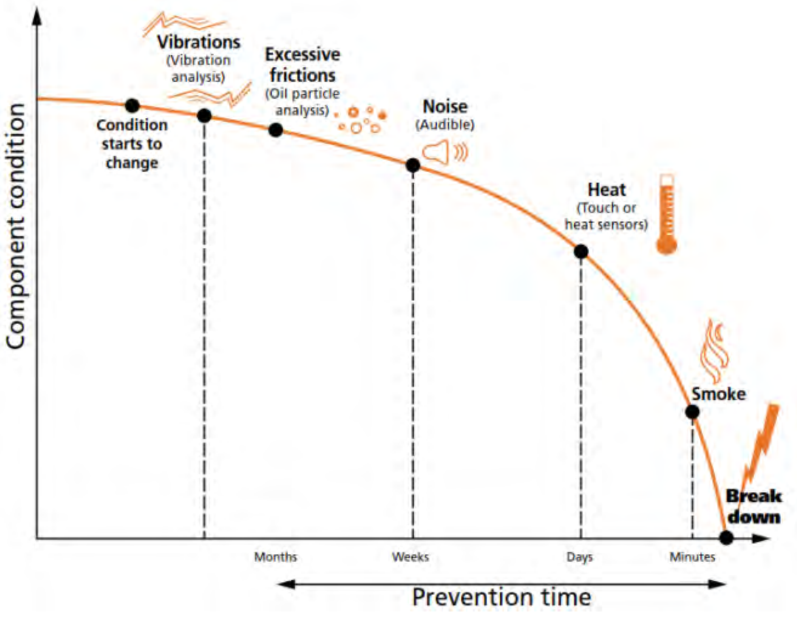


Figure 3.7. Examples of predictive failure data from different condition monitoring methods.

Different methods of condition monitoring:

- Vibration analysis
  - is probably the best-known and best-researched method, especially for rotating machinery.
- Visual inspection and non-destructive testing (NDT)
  - is most provided as an external service. NDT is a specialised area of expertise that requires training and certification of experts.
- Performance monitoring and analysis
  - not a particularly well-known method, although equipment failure usually results in a significant increase in energy consumption.
- Particle analysis (oil analysis)
  - provides information about an impending fault earlier than most other methods.
- Thermal camera
  - Can be used to inspect large areas quickly and is suitable for both mechanical and electrical equipment.

The sensor and measuring equipment prices have fallen rapidly, making condition monitoring increasingly affordable. However, the challenge is to automate the processing of the data. As systems can be extensively sensed, the amount of data that can be analysed increases. Analysing large amounts of data requires automated processes and advanced analytics, including.

- methods for estimating remaining life expectancy,
- models for automated diagnostics,
- advanced signal processing and analysis
- standardised solutions for monitoring different failure modes in different applications.

Condition monitoring uses not only sensor data but also process data from the system or equipment, especially if it is not possible to retrofit the equipment to be monitored with actual condition monitoring sensors.

Key lessons

- Condition monitoring allows maintenance of the equipment to be based on the condition of the site.
- The prices of sensors and measuring equipment have fallen rapidly, making condition monitoring increasingly affordable.
- Extensive monitoring also means a large amount of data to analyse. Analysing large amounts of data requires automated processes and advanced analytics.

3.3. PROCESSING AND REFINING DATA

Helena Kortelainen and Toni Ahonen

Introduction

Data collection is naturally the starting point for the processing of data into forms that support decision making in everyday life. The widespread perception seems to be that a large amount of data as such is sufficient to support both product development and the provision of data-intensive services. However, this is not the case and the well-known saying "Garbage in, garbage out" holds true. The quality, completeness and reliability of the data are absolute prerequisites for reliable conclusions. Data analysis requires both analytical skills and an in-depth understanding of the application and context. This chapter presents data processing towards knowledge at a general level.

Refining data

The *DIKW (Data - Information - Knowledge - Wisdom)* model does not take a position on the process or the tools for processing information. Applicable data analysis methods depend both on the purpose and needs of the analysis, and on the data available. The data determines whether qualitative methods, i.e., those that analyse textual data, or quantitative methods, i.e., those that analyse numerical data, are used. However, in general terms, the process of transforming data into information and knowledge can be illustrated by the following six steps (cf. Figure 3.8):

- data collection,
- data pre-treatment,
- descriptive data analysis,
- data modelling,
- refining the data with data from other sources (e.g., by tacit or expert knowledge), and
- decision options,

Processing of data to information is generally a technical issue that can be automated once the appropriate data collection methods have been selected and in place, and the reporting models defined. The higher levels of the hierarchy, knowledge, and wisdom, require a broader understanding of the subject and the mere collection and processing of data is no longer sufficient. In addition to the analysis of numeric data, information on the business environment, tacit knowledge of experts, etc. must be used to establish insights of the possible alternative solutions, and of their advantages and disadvantages.

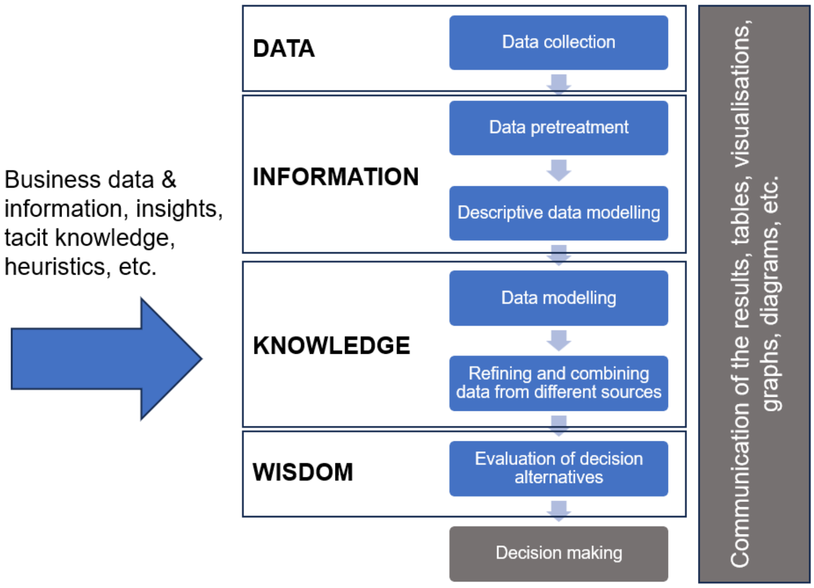


Figure 3.8. Data processing and DIKW hierarchy (Kunttu et al., 2017).

Data collection

Data collection is naturally the starting point for the processing of data towards information or knowledge. Data collection should be designed with a view to making use of the information, for instance, by developing use cases or scenarios. It is typical that some data collection is designed and carried out for a specific purpose and analysis method in mind, and some data is stored in databases mainly because of existing routines and reporting practices. The CMMS/EAM system is often used only for the management and reporting of work orders and material flows, but there is no planned use of the transactional data that accumulates there. In contrast, *condition monitoring (CM)* data collection is often carefully designed for maintenance activities.

Asset life cycle and lifecycle management data is stored in many different IT systems, which have been extensively discussed in Part 3. Instead of the quantity of data, the challenge is mostly the quality and completeness of the data. Some important pieces of data (e.g., repair times, consequences of failure) are only seldom recorded. Important information may also be in a format that is difficult to use like written text or images. The transactional event data stored in information systems often needs to be complemented by expert judgements, also because the decisions at hand often require insight into the future development of physical phenomena (say, corrosion or wearing), business or market (Kortelainen et al. 2014).

Data pre-pretreatment

Collected raw data is rarely useful as such and may require a lot of work before intended data analysis can be conducted. Data quality is crucial to the success of the data analysis. Thus, the data set must be critically assessed. Factors that degrade the data quality can be random or systematic. Random errors, if the number of them is reasonable, are not typically crucial for data analysis because they do not cause bias to result. Random errors can be traced, for example by visualisation or cross tabulation.

Systematic errors can skew the results. The main cause of systematic errors can be traced back to the data collection, either to inadequate instructions or recording practices. To identify systematic errors, the person analysing the data needs an in-depth understanding of how the data were collected, what information the variables contain, how and when the data were recorded and what practices were followed. Practical data collection or recording may differ from the guidelines. Formal instructions or recording practices tend to change over time if the data collection period is long. If data is collected by several stakeholders, there are probably also several ways to collect and record data. (Kortelainen et al., 2019)

Descriptive data analysis and data modelling

Statistical data analysis methods can be used to compare groups, find correlations or other relationships between variables, define clusters, find normal values and anomalies, detect trends or other patterns and so on. Descriptive data analysis provides summaries of the collected data. Summaries can be basic measures (e.g., mean, median, variance), or tables (e.g., frequencies, cross tabulations) and figures (e.g., bar charts, boxplots, spider/radar charts) presenting relevant features of the data. Descriptive data analysis creates understanding of the data content and delivers first impressions of interesting relationships between variables. An example of descriptive data analysis (Figure 3.6) provides a quick illustration of issues such as gaps in data collection and anomalies in the time series.

Data modelling requires the ability and skills to choose the right models, methods, algorithms, and tools depending on the scope and objectives of the analysis. Understanding the behaviour of the system under study is a key element of modelling, and data analysis can be supported by qualitative analysis. There is a body of literature presenting methods for modelling different types of data (see e.g., Hoyland & Rausand, 2009), so individual methods will not be discussed here. The real added value of data analysis comes when the data can be used to predict the future behaviour and performance of an object, estimate the remaining useful life, identify system weaknesses, and support planning and decision making. Figure 3.12 illustrates the use of data in two scenarios. In one scenario no action is taken, and the failure rate continues to increase, in the other scenario the obsolete system is replaced by a new system. The modelling can be used to calculate the monetary benefit of replacement and to estimate the profitability of replacement.

Failure and restoration times, described by statistical distributions, are also important models in life cycle reliability and availability performance studies. Often the failure rate is assumed constant when modelling the time between failures and an exponential distribution applied. For repair or restoration times, a normal distribution is usually used. Statistical distributions are discussed in Chapter 3.5. The distributions of failure and restoration times can be used to simulate the evolution of system availability. However, building a simulation model requires the integration of complex data, modelling of the technical system and modelling of the couplings between functions. Individual simulation runs produce failure combinations that could occur in real life. Simulation can also be used to examine individual life cycle phases, such as the burn-in period and ageing behaviour, if the necessary data are available.

Combining quantitative and qualitative data

Estimating statistical distributions and the parameters of distributions requires a lot of information. If there is too little event (failure, repair) data, the estimated distribution may be wrong or the distribution may not be estimated at all. Insufficient or missing data can be supplemented by expert judgement. *Expert elicitation* often aims to specify not only the mean or expected value of a given parameter or variable, but also the parameters of the distribution. Since estimating the parameters of a distribution is very difficult, even for experienced experts, experts may be asked to estimate the mean and the upper and lower quartiles of variable X, either as numbers or by means of a histogram (Morris et al., 2014). A visual method that allows the expert to construct the probability distribution of choice by moving the sliding bars is presented in Chapters 4.8 and 4.10.

Traditional physical models for predicting e.g., corrosion or wear are either very complex and resource-intensive, or they are highly simplified and therefore unable to describe the behaviour of an object with sufficient accuracy. Data-driven and predictive methods *(Prognostics and Health Management, PHM)* use pattern recognition and machine learning to detect changes in system state. Qualitative methods such as risk and reliability analyses, e.g., Hazard and Operability study (HAZOP) and Failure Mode Effect and Criticality Analysis (FMECA), provide qualitative information related to the object. Qualitative analyses help to understand the causal chains of a system, linking a failure indication or anomaly to a chain of events and possible consequences. This allows the user to make predictions about the progression of the phenomenon and take proactive actions in a timely manner. (Valkokari et al. 2004: Kortelainen et al., 2019)

Semi-quantitative methods can also be used in life cycle management applications. Semi-quantitative methods differ from qualitative methods in that they use numerical scales to assess consequences and probabilities. Semi-quantitative methods are an intermediate form of qualitative and quantitative assessment methods, using both approaches (EN 31010, 2019).

Data-driven models and PHM algorithms use pattern recognition and machine learning techniques to detect changes in system states. Qualitative information like risk and reliability analyses, e.g., HAZOP and FMECA, support the analysis phase providing essential information about the target application. These analyses could provide cause-consequence chains that connect failure indications or initiation patterns or a deviation with a certain chain of events and link the emerging event with expected consequences (Valkokari et al. 2006). This allows the user to make predictions and to take proactive actions in time.

Key lessons

- It is not the quantity of data that matters, but the quality - "*garbage in, garbage out*".
- Plan your data collection with a view to data exploitation.
- Careful pre-treatment of data is often time-consuming, but an inevitable and crucial part of the process.
- The real added value of data analysis comes when the data can be used to predict future behaviour and performance, estimate remaining lifetime, identify system weaknesses, and support planning and decision-making.
- Numerical data often needs to be supplemented by expert judgement.
- Data-driven predictive methods are under intense development.

3.4. EXPLOITING THE DATA IN INFORMATION SYSTEMS

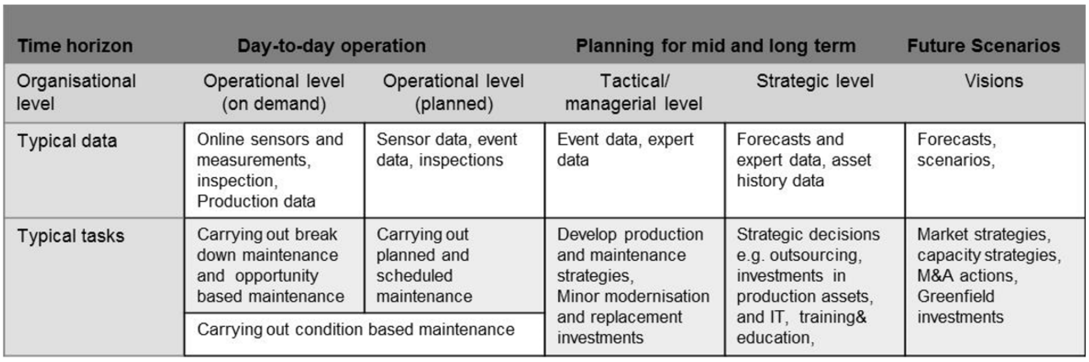
Helena Kortelainen and Toni Ahonen

Introduction

Companies have a plenitude of data stored in their information systems, and this data could allow data-base or knowledge-based decision making. Concrete decision situations are very diverse and situation dependent. Decision situations related to production equipment can be divided into three main types (Kunttu et al., 2017):

- operational decisions in the everyday maintenance and operation,
- tactical decisions to upgrade existing equipment and functions, and
- strategic business decisions.

The decision situations can be characterised by the time frame, the frequency of the decision, the importance of the decision and the activities or tasks involved in the decision case. At the operational level, the aim is to achieve the objectives set for the equipment or asset system, while at the tactical level, the aim is to modify and develop the functions and assets and raise the target levels of efficiency and profitability. Strategic decisions aim at the overall development of the company and strengthening its position on the market, for example through increased capacity or launching new products. Decision-making situations also require different types of information as illustrated in Figure 3.9.



Time horizon	**Day-to-day operation**		**Planning for mid and long term**		**Future Scenarios**
Organisational level	Operational level (on demand)	Operational level (planned)	Tactical/ managerial level	Strategic level	Visions
Typical data	Online sensors and measurements, inspection, Production data	Sensor data, event data, inspections	Event data, expert data	Forecasts and expert data, asset history data	Forecasts, scenarios,
Typical tasks	Carrying out break down maintenance and opportunity based maintenance	Carrying out planned and scheduled maintenance	Develop production and maintenance strategies, Minor modernisation and replacement investments	Strategic decisions e.g. outsourcing, investments in production assets, and IT, training& education,	Market strategies, capacity strategies, M&A actions, Greenfield investments
	Carrying out condition based maintenance				

Figure 3.9. Using information at different levels of decision-making (Kortelainen et al., 2014).

Event history and other information stored in asset information systems (ERP, CMMS, EAM etc.) is particularly useful for operational and tactical decision-making. Decision situations at the operational level are related to the execution of daily maintenance tasks and the operation of equipment. Decisions are often taken on demand, for example as a failure or incident happens. Decision making is characterised by the need to react quickly, and the necessary information must be readily available. Although the business impact of a single decision is rarely significant, it should be noted that a recurrence of similar events changes the decision situation. Recurring events may require a more tactical approach and correctness of the decisions becomes business relevant. Decisions at the tactical level relate to the development of existing assets or operations, such as the development of a maintenance programme and the planning of replacement investments and modernisations.

Manufacturer´s or supplier's data (PDM, PLM etc.) on the *fleet* of equipment distributed to international markets enables the development of data-intensive services to support the operation and maintenance of the fleet. However, in addition to data, models, methodologies, and skills are required to analyse the data and to exploit the resulting knowledge to support a wide range of end-user/customer decision situations. The Industrial Internet and cloud computing will make sensor, equipment, and process data available in digital form and enable the further fleet service development.

Stakeholders and knowledge-based activities

Technical and economic data on an individual product, information on a project delivery of tailored equipment or the documentation on a whole asset system is vast, multifaceted, and usually fragmented entity among the company information systems. Knowledge is also accumulated in the form of tacit knowledge and expertise to all stakeholders. The effort to manage data is meaningful only if there are prospects for the exploitation of the gathered data. Some examples of how maintenance-related data and knowledge can be exploited are summarised in Table 3.3. The user may be a maintenance service provider, an in-house maintenance organisation or the operator responsible for the maintenance of an individual piece of equipment.

Table 3.3. Examples of opportunities for exploiting maintenance-related information (Ahonen & Reunanen, 2009)

DATA TYPE	**DATA EXPLOITATION PATHWAY**
Process and environmental data: temperature, humidity, air pressure, EMI, EMC, vibration data etc.	Equipment or system failure behaviour modelling enables the predictive actions and maintenance program adjusted to the prevailing process and environmental conditions.
Information on the load and use mode: continuous, intermittent, standby/redundancy, manual/automatic control,	Accurate and up-to-date information on the equipment use mode and its role in the asset system provides information for maintenance planning and for allocation of upgrade and improvement investments, for example.
Failure event data: mean failure rate, MTTF/ MOTBF/MTBF, annual number of failures, fault detection and diagnosis time, downtime, MTTR, active maintenance time, etc.	The information can be used for example in domains including defining preventive maintenance scheme or investments in maintenance personnel or infrastructure, development of maintenance work processes, and identification of competence needs and in developing cooperation between stakeholders on reporting practices and information exchange.

Lack of spare parts, lack of human resources, lack of test equipment.	Shortages refer to shortcomings in supply chain or spare parts inventory management. Items with complex technology often require specific resources and working and testing equipment.
Item level data including maintenance history and activities carried out on the item, criticality classification.	Item specific maintenance history enables forecasting of the spare's consumption (management of spare parts inventory), human resource management and incurring of costs. The stated equipment criticality influences the maintenance strategy, allocation of maintenance effort and investment decisions.
Maintenance strategy (e.g., scheduled/unscheduled, preventive/corrective/condition based). Effectiveness of preventive maintenance activities	The effectiveness of preventive maintenance can be estimated in advance by evaluating the total cost of available maintenance strategies. The evaluation includes the costs of unavailability caused by the maintenance activities and by production interruptions. The information helps to improve the equipment or asset system maintenance strategy and to allocate the preventive maintenance activities in a cost-efficient way.

Stakeholders have different needs in terms of life-cycle data. For example, an equipment supplier may plan to extend the after sales business by service solutions based on the life cycle data. Even if the asset system has a lifetime of decades, it contains subsystems, parts, and components with a much shorter life expectancy. Delivery of spare parts offers a continuous cash flow, and this flow could be increased by solutions for renewal, upgrades and modernisation as technology evolves and by other operator support services of even by remote operation and control. The customer feedback and the data accumulating from the supplied fleet helps to develop and optimise spare parts services and the quality and features of the supplied products. Digital solutions can be used to monitor the fleet and measure the performance, and usage of individual equipment, regardless of geographic location. With digitalisation (e.g., Industrial Internet; Internet of Things, IoT; Industry 4.0; Cyber-Physical-Systems, CPS), sensor, equipment and process data can be made available to all stakeholders in a comprehensive way (e.g., Lee et al., 2015).

Lifecycle service provider uses life cycle data to develop and implement the service products themselves, such as the efficiency of maintenance activities and spare parts inventories. Lifecycle information can also be the core content of knowledge-based services. The focus is shifting away from minimising failures and their impacts towards a broader performance optimisation that considers the criticality of the equipment in the customer's operations (Kortelainen et al. 2017). Service providers need to cover aspects such as end-product quality and raw material efficiency, system performance, energy costs, environmental emissions management, efficiency, and human safety (Valkokari et al., 2016). This also requires an understanding of the factors affecting the customer's business, such as the impact of changing market demand or legislation. In addition, the service provider needs to understand factors related to the customer's production environment, such as operating conditions (process abrasiveness, dust, temperature, humidity, load), equipment criticality and maintainability.

Reporting

The interest of users and owners of physical assets is typically focused on the development tasks of their own production process or on the decision-making and implementation issues of day-to-day operational activities. Life cycle data for individual assets and the entire system relate to identifying problem areas, improving production processes through replacement and modernisation investments, and predicting failures and other disturbances. The following are examples of the reports which are generated from the EAM system, and some of possible utilisation pathways of the data (Hastings, 2015):

Table 3.4. Examples of EAM system reports (Hastings, 2015)

DATA TYPE	DATA EXPLOITATION PATHWAY
Asset identification, location, and valuation	
Budget expenditure year to date by account code, by equipment type, by location.	This report helps with current budgetary management, and with the assessment of future resources.
Operational loss reports.	Check causes and follow up to improve performance and reliability.
Unscheduled work orders	Check causes and follow up to improve performance and reliability. Check history to see if job is recurring, if so investigate, improve—Pareto analysis. Review downtime and seek reductions using rotating devices, repair kits, better diagnostics, training, spares, and support equipment availability. Update job procedures and job requirements. Review inspection and replacement intervals.
Manpower utilization by trade; by equipment type; by location.	This report helps with the allocation of staff by location, and with determining staff requirements.
Maintenance cost by item type by year of life.	This report provides a basis for replacement planning.
Spares utilization by part number.	This report provides the basic input into stock control parameter setting and reorder decisions. Use forecasting and reorder analysis to review spare parts holdings.
Failure frequency by failure mode and year of life.	This report provides a basis for determining optimal component replacement and inspection policies.

Performance measurement and indicators

Performance measurement is based on reliable, accurate, timely and comprehensive data on which to base the calculation of metrics. EAM systems play a key role here. *Key performance indicators (KPIs)* are measurable quantities which are intended to show the extent of which, a system is meeting the expectations, which are placed on it. KPIs for maintenance performance and efficiency are described in standards such as EN 15341 (2019). The EN standard also provides a very practical way of calculating the various KPIs using data from information systems. Practical examples of the KPI calculations are presented in Table 3.5.

Table 3.5. Examples of performance indicators for the two production lines (see Figure 3.5 for details).

PERFORMANCE INDICATOR (KPI)	**EN 15341 CODE**	**NORTH LINE**	**SOUTH LINE**
Operational availability due maintenance, %	PHA8	95,7	97,2
Availability based on operating time, %	M11	97,3	97,9
Mean time between failures (MTBF), hours	M5	256	309
Mean time to recovery (MTTR), hours	O&S16	7,2	6,7
Downtime due to corrective maintenance, %	E9	58,9	56,7
Downtime due to predetermined maintenance, %	E11	41,1	43,3

The KPIs in Table 3.5 are described in more detail in Part 5. Our case allows a comparison between the two lines. The South line seems to have a higher reliability: the MTBF is longer, and the percentage of downtime due corrective maintenance is lower than on the other line, hence the operational availability is higher. The production lines, which are identical to each other, process different raw materials and the North line is subject to more severe stress. This higher stress is recognised in the maintenance planning and the North line is subject to more predetermined i.e., planned maintenance. As the required operating time of the North line is shorter than that of the South line, there is little difference in availability based on operating time. The actual availability due maintenance considers both corrective and scheduled maintenance, so the difference in performance between the two lines is obvious in this availability indicator.

Performance measurement and metrics present their own challenges. In our example, scheduled maintenance, time- and condition-based maintenance, and corrective maintenance tasks were carried out during regular maintenance periods, and it is not possible to distinguish between the maintenance types as such information is not recorded in the system. The time spent on individual maintenance tasks is neither recorded, so only downtimes can be considered. The downtime may then consist of one or more tasks carried out one-by-one or parallel. Further challenges in calculating the metrics include that a root cause may cause several repair works, and that rework due to (not recorded) errors during the maintenance activities.

Pareto analysis

According to the well-known Pareto principle, 20% of the issues cause 80% of the consequences and for this reason it is often referred to as the 20:80 rule. When applied to maintenance, this rule means that a few pieces of equipment or failure modes cause a large proportion of the observed failures. Since Pareto analysis requires event data, it is best suited to assessing a system at the utilisation and enhancement stage.

Pareto analysis is easy to perform and produces a clear and easy-to-read graph. The chart ranks the items (e.g., failure modes or equipment) in order of magnitude according to a selected criterion (e.g., cost, failure rate). The Pareto principle (20/80) applies only seldom as such in maintenance data. However, bar charts plotted against different variables are useful in terms of visualisation and can help to identify areas that need special focus.

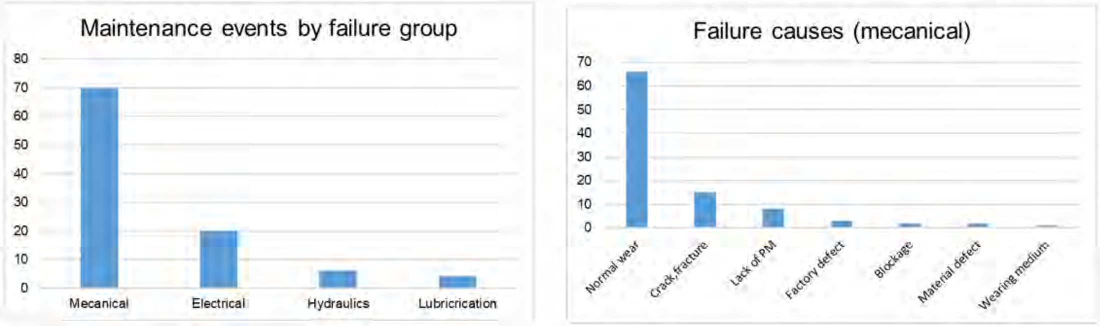


Figure 3.10. Pareto graphs of the example data (see Figure 3.5 for details).

Bar charts in Figure 3.10 illustrate well the significant factors. The sample data contains four broad failure groups (mechanical, electricity, hydraulics, and lubrication) and the majority (about 70%) of maintenance tasks are caused by events that are classified as mechanical. A closer look at this group reveals that the majority (around 65%) of activities are due to normal wear.

Exploitation of the data in the field

In addition to maintenance planning and performance measurement, the data recorded in the maintenance history is also needed for the investigation of failure events, root cause analysis (RCA) and the detection of recurring failures. High-quality event data can also be used to transfer tacit knowledge across the maintenance organisation and stakeholders.

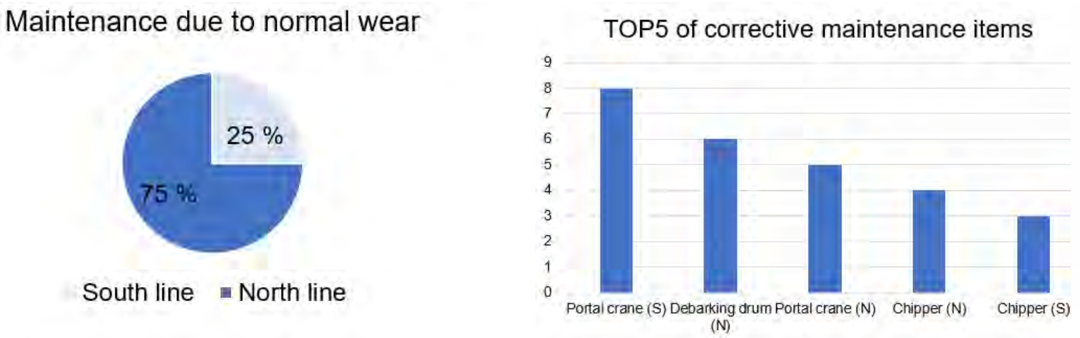


Figure 3.11. Maintenance due to normal wear on two parallel production lines (left). Top5 of items requiring corrective maintenance (right) (see Figure 3.5 for details).

Figure 3.11 clearly shows the difference in the abrasiveness between the two production lines: 75% of all repair actions classified as normal wear are carried out on the northern line.

A more detailed analysis of the data will help to focus the analysis on the equipment on this line, so that the incident data can be used to consider requirements for construction materials, for example for spare parts purchases or redesign.

The Top5 graph of our case example shows that most of the corrective maintenance work has been done on cranes, especially the crane on the southern line has experienced several failures. This crane has failed 8 times in this data collection period. Most of the failures have caused a loss of production by stopping the whole line. The failure causes vary but the detailed failure reports show that the events concentrate on specific parts. Failure reports allow a better understanding of the failure mechanisms and cause and effect relationships. It is also easy for the user to follow the distribution of, for example, typical fault groups from the reports and compare, for example, equipment operating in different environments or containing components delivered by different vendor. With more data available, typical failure causes and particularly frequent failure patterns will be identified, allowing for a well-founded update of the maintenance programme or redesign of components.

Figure 3.12. Combining data to support maintenance tasks.

Event history complies one, but an important group of information that supports directly field activities. In practical work environment, the data must be easily accessible, the data must be comprehensive and, because there is a lot of data, it must be possible to retrieve it using various search functions.

Failure arrival plots

A useful tool for analysing data collected over a long period of time is the failure arrival plot. For the graph, data points are arranged in order of event time and pairs of points are plotted on a coordinate grid, where the horizontal axis represents time, and the vertical axis represents the number of accumulated failures (Figure 3.13). The graph can be used to determine whether the failure rate of the studied system is increasing, constant or decreasing.

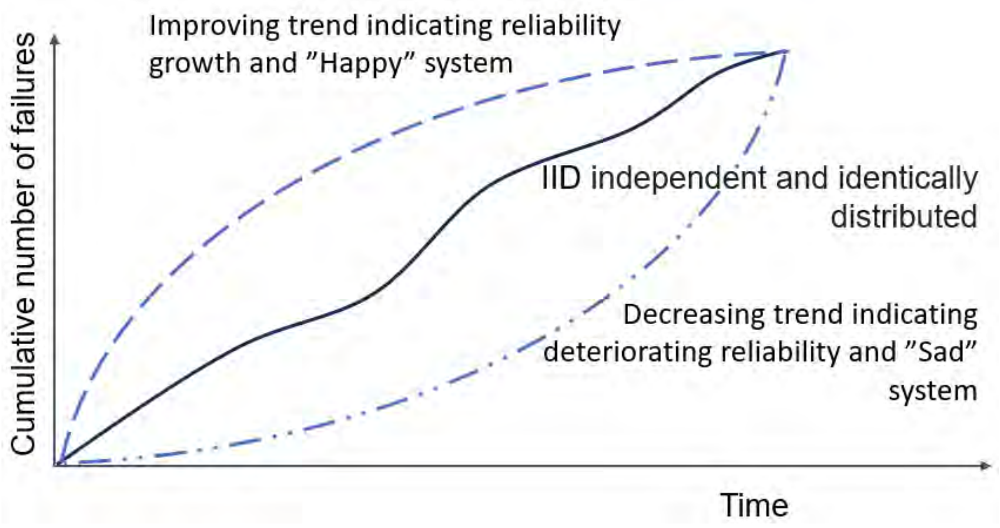


Figure 3.13. Testing the trend. An improving trend occurs if the fault frequency of the target decreases as a function of time. A deteriorating trend is typical of an ageing system where the failure frequency increases.

A trend - a systematic change - can be observed in the failure rate graph, indicating that the system is systematically improving (failure rate decreases) or deteriorating (failure rate increases as a function of time). A system that indicates reliability growth is also called 'happy system' in contrary to 'sad system' that is characterised by reliability deterioration. If no trend is observed, the failure rate of the system remains statistically constant. *IID (Independent and Identically Distributed)* describes a system whose failure observations follow the same statistical distribution and are independent of each other (Bohoris, 1996). A statistically constant failure rate means that the frequency does not systematically increase or decrease but varies according to a given statistical distribution.

Often, the failure arrival graph alone reveals an existing trend or lack of trend. If no trend is observed, a failure rate function can be estimated from the observed data using known statistical models and distributions. If the graphical analysis does not allow sufficient confidence in the existence of a trend, statistical tests can be used to facilitate the assessment (trend/no trend). There are several tests and, depending on the specific characteristics of the data, some tests work better than others. One trend test suitable for identifying a monotonic trend is Laplace's test, where the test coefficients can be used to test the basic hypothesis of "no trend" (Bergman 1998).

The data stored in the EAM system does not always allow to determine whether a maintenance event is due to a failure and whether the failure has been really repaired. Predictive maintenance may also require shutting down the operation, so production time is lost due to both unplanned and planned activities. For this reason, instead of looking at failure arrival curves, it may be useful to look at accumulation of maintenance events, such as Figure 3.14.

The data collected at industrial sites often contain clusters of events as in the example shown in Figure 3.14. Reasons for such accumulations include:

- The corrective action is focused on the consequences of the failure and not to the root cause. Thus, the failure repeats. The problem will only go away when the root cause is removed.
- A temporary solution or "fix" is provided to get the machine up and running as quickly as possible. The actual corrective action is deferred.
- A human error, maintenance work is incorrect or incomplete.
- A follow-up period that includes a more intensive than normal monitoring or maintenance of the system
- The burn-in period after the commissioning of a new item. A similar increase in failure rate is also often observed after a major outage or modification.

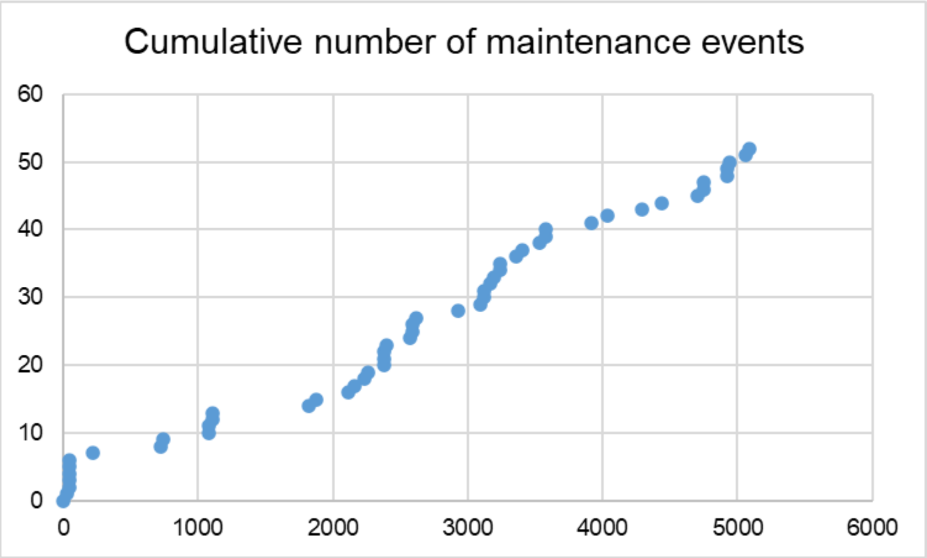


Figure 3.14. Examination of the example data using the accumulation graph. The events observed are both failures and scheduled maintenance activities.

If the records were sufficiently detailed and the arrival plots were systematically used, the graph would quickly reveal "too frequent" faults and other events (e.g., maintenance). This would allow corrective action to be directed more quickly to rectify the actual failure cause or problem or to improve the quality of maintenance. Systematic event description and recording will only become embedded in the work process over time, and it requires continuous managerial efforts.

Prediction and modelling

The event data contained in a EAM system is also valuable when assessing investment needs and other improvement measures. In the case of upgrading a system that has been in operation for a long time, the event data can be used in the feasibility assessment. Figure

3.15 illustrates the use of the data in two scenarios. The example shows a clear upward trend in the failure rate of the system and the system is in the end-of-life phase. In one scenario no action is taken, and the failure rate continues to increase. In the other scenario the obsolete system is replaced by a new one. In this case, the failure rate of the new system is assumed to settle at the same constant rate as the existing system. If the maintenance costs of the existing system and the value of the lost production due to failures are known, the costs of the alternative scenarios can be calculated. The payback period of the investment will then be affected by the reduction in maintenance costs and the increase in production time due to the reduction in downtime caused by failures.

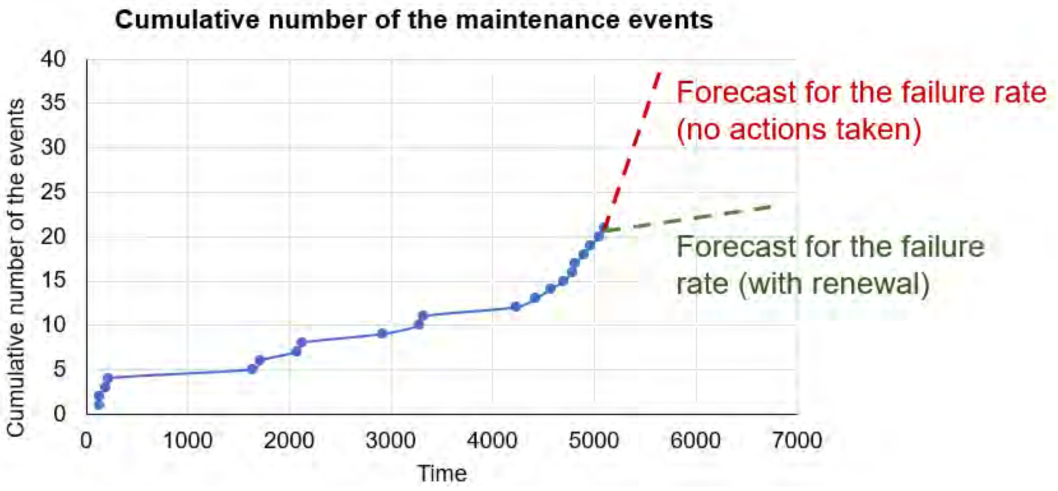


Figure 3.15. Using event data from a maintenance information system to assess the profitability of system renewal (Kortelainen et al., 2019).

For investments, the focus is on the future and the assessment of the return on investment combines data from the EAM system with information from other sources. Investment decisions are often much more complex than the straightforward replacement presented in Figure 3.15. In industrial companies and infrastructure systems must set priorities and study alternative objects. Good quality information on the condition of the machinery and equipment in the system and reliable estimates of their remaining life help in this task. Investment proposals need to be considered from multiple perspectives, using risk identification methods and strategic analysis methods in addition to technical analyses. The methods applied are often semi-quantitative in nature (Räikkönen et al., 2020a). Methods for assessing investments are described in more detail in Section 2 and examples are given in Section 4.

Developing a maintenance programme by combining and enriching data

By analysing the fault statistics in EAM system, the occurrence of certain types of faults can be demonstrated. However, the available event data, rarely covers all failure modes, or there are few events. Expert judgement is therefore often needed to supplement the recorded failure data. Methods for criticality assessment are described in Chapter 2.5.

Previous experience with same of similar systems can serve as a good starting point for defining a maintenance programme. The actual and accumulating experience should be used to update this initial knowledge. Advanced Maintenance Planning Methodology (Figure 3.16) incorporated the idea using different data sources in the continuous development of the maintenance programme.

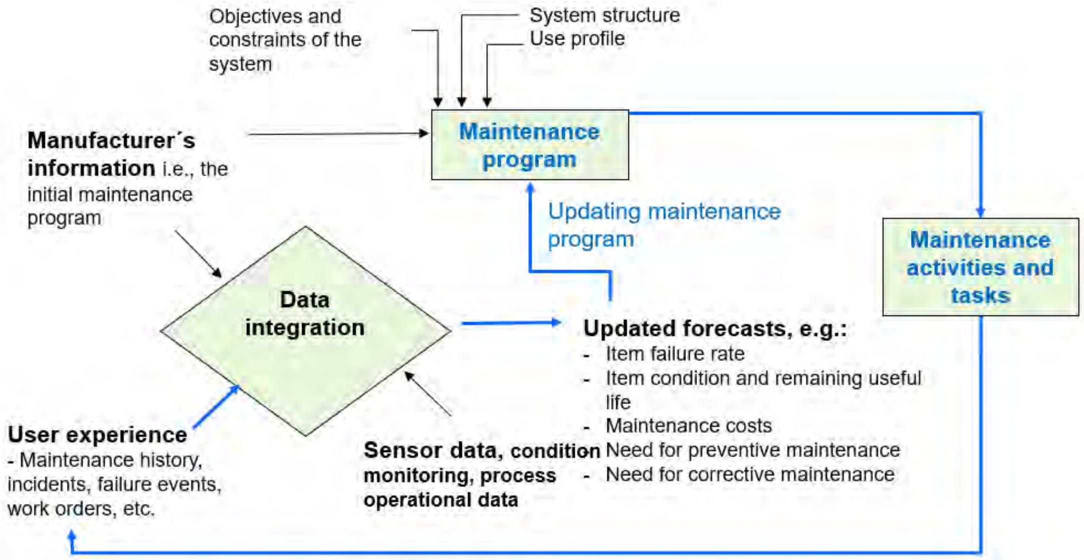


Figure 3.16. Maintenance planning combining information from different sources.

Failure records often contain text in free format, and the classification by failure type, position or equipment hierarchy is not done, or it is incomplete. High quality records facilitate data analysis and guarantee reliable results. An advanced maintenance planning methodology explicitly requires the application of appropriate experience and data.

Fitting all available information into a mathematical algorithm is difficult, and often not practical. The decision model should always be application specific. Planning based on maintenance history, measurement data, system usage and user expertise (see Figure 3.16) can be achieved in a very practical way and through collaboration between experts. It is often worthwhile to make better use of 'tacit data' and to integrate it, for example, with the processing of recorded data. This will go a long way towards the idea of continuous improvement of the maintenance performance.

Role of the failure data in product development

The product manufacturer has incentives to collect failure data from the installed base in the field and use this information in the product concept and development stages. Collecting data from an *installed base (fleet)* quickly increases the flow of data compared to the limited number of data bits produced by a single installation. Thus, the manufacturer is in the position to draw more reliable conclusions for developing the maintenance program or allocating condition monitoring etc. However, system configurations and maintenance procedures and objectives and data collection processes vary from one plant to another. In general, it is expected that not all failure events will be recorded in the first place, but it is likely that significant failures are in the records. The product manufacturer can limit the analysis to significant failures and items, but smaller recurring events and minor incidents can be significant if they are large in number.

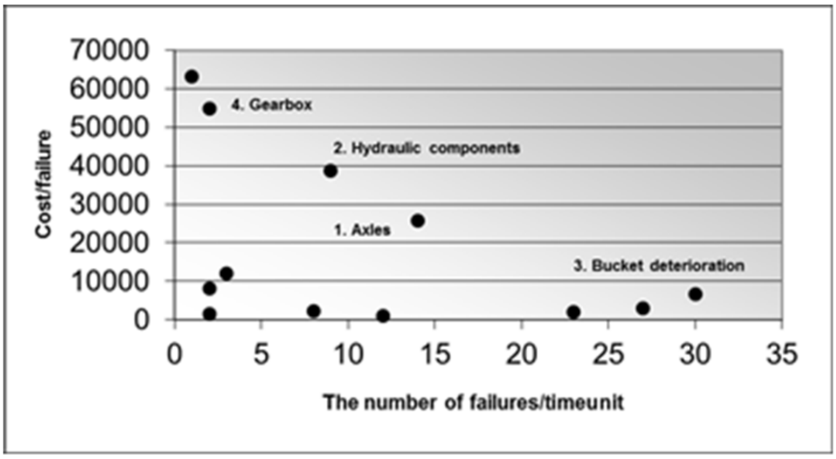


Figure 3.17. Example of a manufacturer's failure data analysis (Ahonen, 2005).

Figure 3.17 illustrates a criticality assessment that shows the cost of failure of different parts of the system as a function of failure frequency. The failure frequency is based on the recorded events occurring at customer sites. The consequential costs are not recorded, and they had to be estimated in an expert session. The criticality of an item can be due to the high cost of a single failure event (e.g., gearbox) but also to a high failure frequency (e.g., bucket deterioration). In the latter case, the problem can be brought under control, for example by improving the maintenance programme or by redesigning a frequently failing item. In the case of scarce historical data, and especially in the case of seldom failure modes, the inclusion of FMECA analysis is suggested to complete criticality analysis.

The concept of *FRACAS (Failure Reporting, Analysis and Corrective Action System)* is closely related to dependability management FRACAS is a process that aims to make the feedback data collected from the field available to the product development and engineering organisations during the use phase of the equipment. First described in the US Army Manual (MIL-HDBK-2155, 1995), the FRACAS process establishes a closed loop in which both equipment and software failures are reported according to a set of rules, the failures and errors are analysed, and corrective actions are planned.

Data-driven lifecycle management services

The collection of data on the fleet that is distributed to global markets enables the development of data-intensive services that support the operation and maintenance of the fleet items. Mere data collection is not enough but a variety of models, methodologies, and especially human resources and skills are required to process the data before the results deliver value to the customer´s decision-making process. As the condition monitoring example in Figure 3.1 illustrated the raw data collected in databases is not yet very useful as such, but by refining and enriching the data increases its value to the end user. DIKW model (Section 3.1) also helps to classify data-driven service proposition from the customer value point of view (Table 3.6).

Table 3.6. Developing knowledge-intensive services (Kunttu et al., 2017)

DATA INTENSITY OF THE SERVICE	**DESCRIPTION**
Data as a service	Data collection and storage is a basic service that provides the tools to collect, exchange and store relevant measurement data. In new devices, the data collection capabilities are already there, and it is not necessarily even thought of as a service.
Information as a service	Information is created by producing various visualisations and calculated indicators from the raw data collected. The service can be provided either by offering the customer easy-to-use analysis tools to produce the reports they need, or by the service provider delivering ready-to-use reports to the customer. To produce ready-made reports, the service provider must have access to the data collected from the customer.
Knowledge as a service	Knowledge as a service requires a broader understanding of the client's needs and a better ability to refine and analyse data and interpret results from the client's perspective and identify needs for change and opportunities for improvement.
Wisdom as a service	Major decision situations often involve alternatives and options, advantages, and disadvantages of which are weighed up by the service provider. A thorough experience and deep understanding of the customer's business and needs is a prerequisite for the service provider to be able to produce information that is sufficiently sophisticated without major additional work from the customer. Such information can only be produced if there is a very close cooperation with the client and the service provider has wide access to the customer’s information and business data bases.

Data as a service is largely feasible with appropriate technical solutions, if there is an understanding of what kind of data is worth collecting and what kind of information is useful to the customer (Valkokari et al. 2011). This service levels do not necessarily require the service provider to have analytical skills or knowledge of the customer's asset system or business. Instead, the provision of more sophisticated services, such as determining optimal alarm limits or comparing alternative approaches, requires the ability to refine the information collected and combine the knowledge generated by data analytics with the customer's business needs. Adding value to data by increasing the level of service from information provider to knowledge provider is clearly the biggest step up the DIKW hierarchy.

The information generated by the fleet can be very diverse, from online data from sensors to EAM or PLM system records. The analysis of the continuous data stream collected from sensors consists of verification, transformation, and modelling. The aim is to obtain useful information, suggest conclusions and support decision making. The analysis of the data collected from the instrumentation emphasises the collaboration between experts required for modelling and algorithm development (Backman et al., 2016).

It is neither practical nor cost-effective to monitor every component with sensors. One way to gather focussed information and thus increase the equipment manufacturer's understanding of their customers' asset systems and business is through criticality analyses. Guidance for criticality analysis is given many textbooks and standards for example, in PSK 6800 (2008). It is useful to carry out the analysis in cooperation with the customer to ensure transparency of the analysis results. In this way, the customer is also involved in identifying the viability of the service solution. At the same time, it is possible to better define a customer-specific set of service solutions to meet the customer's need to optimise production processes (Valkokari et al., 2016).

Key lessons

- The decision situations can be characterised by the time frame, the frequency of the decision, the importance of the decision and the activities or tasks involved in the decision case. Operation level decisions focus may be in day-to-day operations, tactical decisions to short and medium-term planning and strategic decisions to long-term objectives of the organisation.
- Data is generated and needed by a wide range of stakeholders, both in product development (equipment manufacturers), design (equipment manufacturers, system suppliers, engineering companies, end-users) and deployment (end-users, service providers and other stakeholders). Open collaboration benefits all parties.
- The data can be used to monitor performance trends, calculate key performance indicators, support maintenance staff in the field, and support maintenance planning.
- Prediction and modelling, even with very simple tools such as fault accumulation descriptors, helps in planning future developments.
- For the product manufacturer or supplier, user experience data is important feedback for product development and design, but also for the development of lifecycle services.

3.5. STOCHASTIC AND SIMULATION MODELS FOR RELIABILITY INFORMATION MANAGEMENT

Jouko Laitinen

Introduction

Systems and devices accumulate a lot of information related to device failure if, in connection with the dismantling and maintenance of each device, the device information and the actions taken on it are recorded in the data collection system, which can be searched using programs designed for this purpose. Without accumulated failure data i.e., failure history, it is difficult to make predictions about the reliability of equipment and systems over their life cycle. Asset owners often looks for means to reduce preventive maintenance or to improve the availability performance of a device. These efforts require an in-depth analysis of the failure history that helps to determine the best maintenance intervals in regards of the availability performance. For example, answering questions about the impact of extending/reducing the maintenance interval on the failure probability, on the number of expected failures in a certain time period, or on the adequacy of spare parts requires a thoughtful analysis of failure history. This section presents practical methods to predict reliability from the failure history.

Two types of data

Two types of data are available from the systems: process data and statistical data. Process data is real-time data exchanged between the control system and remote devices, for example via a communication network. Process data can be studied using neural network applications such as *Machine Learning (ML), Artifical Intelligence (AI)*, and multivariate methods. It is important to note that process data can only provide information about the operation of the system from which it originates.

Statistical data is obtained from the maintenance-, failure- and repair history of the system or equipment. Statistical data is collected from any group of equipment and is usually representative of the entire fleet under consideration. The data are typically analysed using statistical mathematical methods. Statistical data can be used to make predictions about, for example, the maintenance and repair needs of a fleet, the resources needed for this and, for example, warranty costs. Statistical data cannot be used to predict how an individual piece of equipment will exactly behave in the future, but rather how equipment in the same population will behave on average.

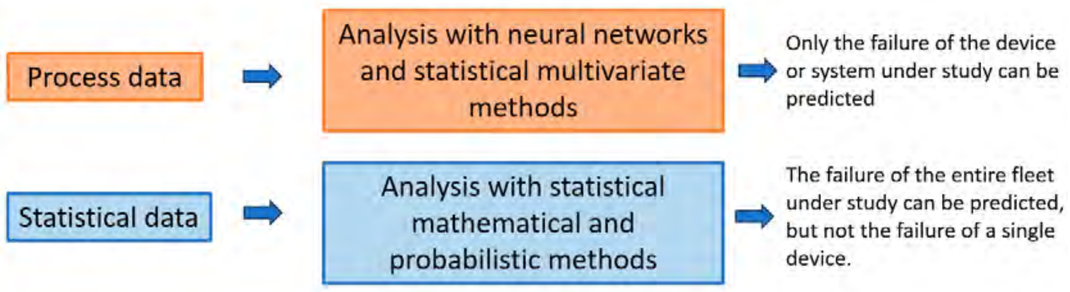


Figure 3.18. Process data vs. statistical data.

Recording of failure data

Traditionally, maintenance and failure history has been recorded manually by using spreadsheet software such as Excel. However, for a smooth and whenever possibly automated analysis of the data, the data must be stored in a database. Application of a structured database forces the data to be recorded systematically and minimises the likelihood of duplication and other difficulties when analysing the data. Databases vary in structure and principles, but the key principles for analysing data are the same.

Databases

A database is used when there is a need to store large amounts of information in a secure, consistent, and unambiguous way, and to assure that the gathered data can be further processed, retrieved, and shared flexibly and simultaneously also in the future. Another fundamental principle of a database is the separation of the data itself from its processing. The needs for retrieval and processing of data and the data being processed change at a different pace, and especially the structure of the data change remain relatively constant. A database is a collection of interrelated data. Data refers to facts that are recorded and can be accessed. For example, a telephone directory is a database.

The requirements for the database are: (Lahtonen 2002)

- each piece of information is stored in the database in only one place,
- information can be retrieved on different search criteria, including those that could not have been foreseen when the database was designed,
- flexibility to change the structure of the database, and
- database access and application programs are independent of the physical storage structure of the data.

The advantages of using a database include the control of data duplication, data consistency and the fact that by combining data, more information can be obtained from the same source data. It is also essential that the database can be used to share information and manage its accuracy. At the same time, data can be protected and secured (Conolly et al. 2005).

Database structures

Hierarchical databases

The first databases in the 1960s were hierarchical databases. As their name suggests, the information was organised in a hierarchical format (Figure 3.19). A Hierarchical database refers to a tree-like structure with the root at the top. The model is very rigid and cannot represent all data structures. Hierarchical databases cannot avoid unnecessary repetition of data, which makes it difficult to update the data (Lahtonen, 2002; Conolly et al., 2005).

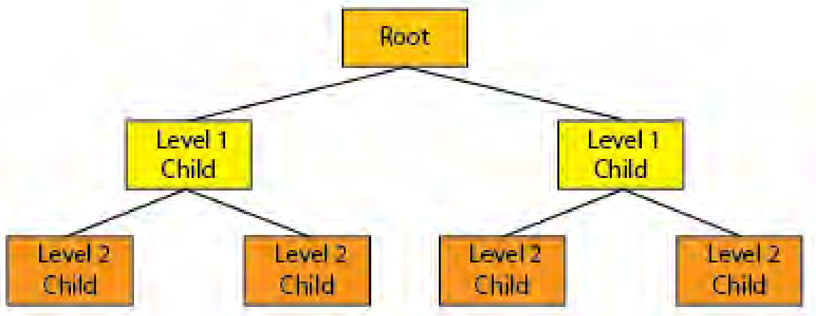


Figure 3.19. Hierarchical database.

Network databases

Network databases were designed to address the shortcomings of hierarchical databases. The relationships between data were described as sets rather than hierarchies. In practice, the difference between network databases and hierarchical databases is the possibility in network databases to assign more than one mother table to child tables (Figure 3.19).

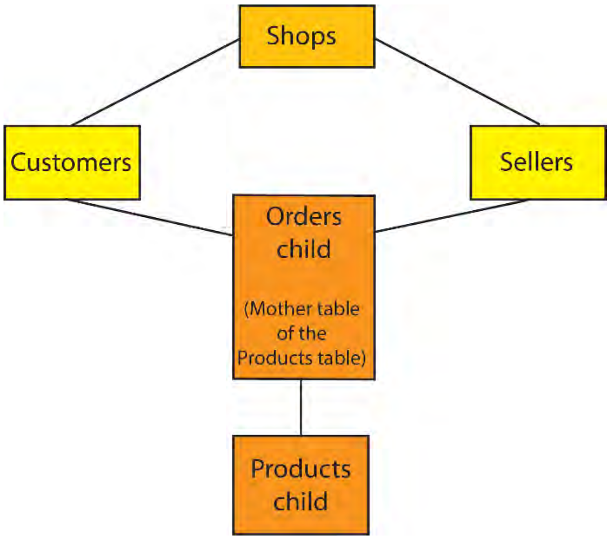
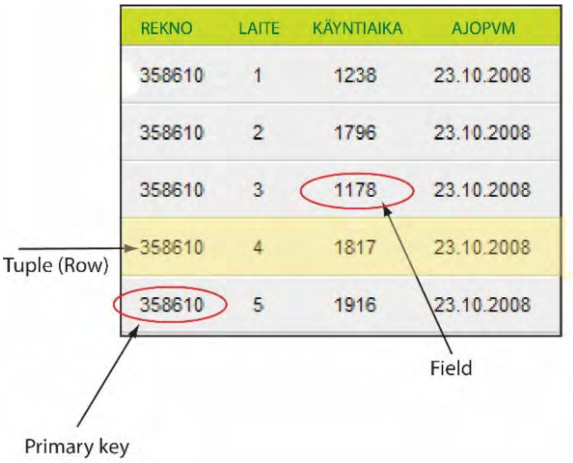


Figure 3.20. Network database.

The implementation and maintenance of network databases has proved difficult. They have been used mostly by programmers rather than by ordinary users (Lahtonen, 2002; Conolly et al., 2002).

Relational database

The relational database (RDB) is currently the most used database. It was introduced by E.F. Codd in 1970. The relational database is the simplest and most flexible of the database models, and the one that best meets the database requirements. Object-oriented databases (OOD) have emerged to meet the need of coupling object-oriented programming languages (OOP) with a database. Regardless of these developments relational databases have hold their leading position.



REKNO	LAITE	KÄYNTIAIKA	AJOPVM
358610	1	1238	23.10.2008
358610	2	1796	23.10.2008
358610	3	1178	23.10.2008
358610	4	1817	23.10.2008
358610	5	1916	23.10.2008

Figure 3.21. Relational database.

In a relational database, data is presented as *tables*, also called relations (Figure 3.21). The data in the table is retrieved using a unique key. The primary key is a field that contains data corresponding to a specified real-world object. As an example, the social security number is a primary key.

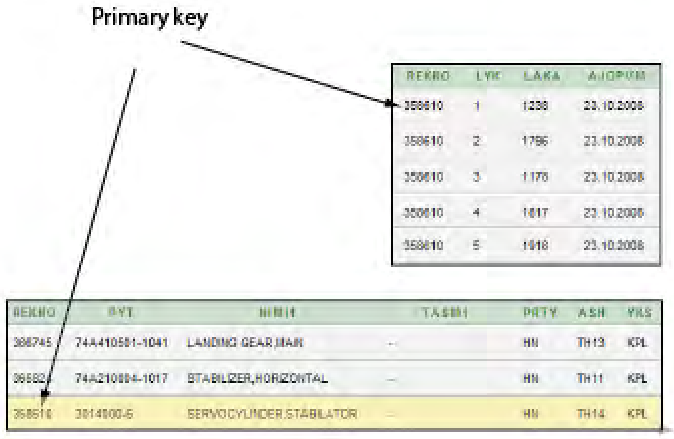


Figure 3.22. Searching for information using key fields.

SQL language

Information is retrieved from a database using a query language specifically designed for relational databases. *SQL (Structured Query Language)* is the most common query and processing language for relational databases. The mathematical foundation of SQL is based upon Relational Algebra and Relational Calculus, but it is much more flexible and expressive. With SQL, queries can be directed to multiple relations (tables) using their key fields. As a result, in a relational database, a single piece of data only needs to appear once, making it easier to update and maintain, compared to a situation where the same piece of data appears in several places (Figure 3.22).

Database management system

A database management system (DBMS) is a computer program that provides users an interface (application) to manipulate a database, i.e., it connects the user's software application to the database. It is usually the only permitted way to manipulate a database. A DBMS allows the creation of a database, its tables, and the relationships between the tables, usually using the SQL language. It allows an efficient way to process and retrieve data. It also allows the database to be maintained by adding, modifying, and deleting data, and retrieving data from the database. It can also be used to enable the controlled and secure simultaneous processing of data by multiple users (Figure 3.23).

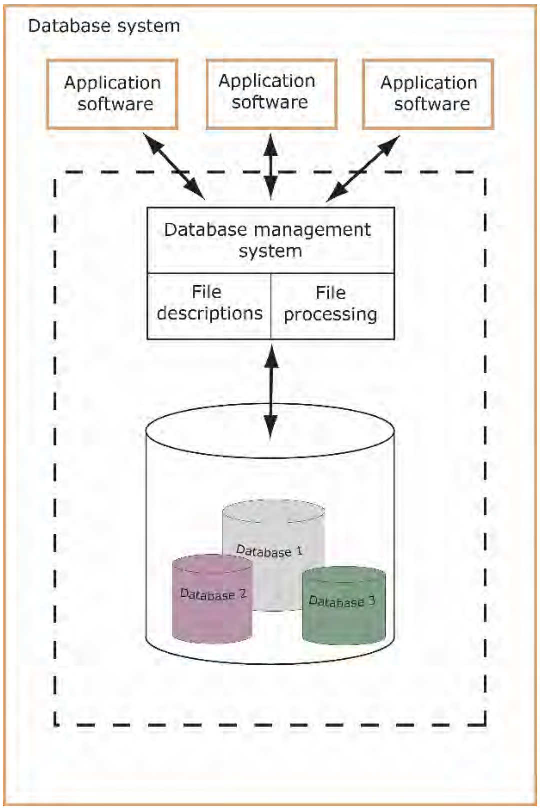


Figure 3.23. Database management system.

Database architecture

At its simplest, a database is a computer with a database program on its hard disk. Large databases are usually distributed, and a database consists of several computers connected to each other (Figure 3.24) Often the network is the internet, so that the server machine containing a database can be accessed from almost anywhere. The network can also be a secure network available only to a limited number of users, such as an internal corporate *Local Area Network (LAN)*.

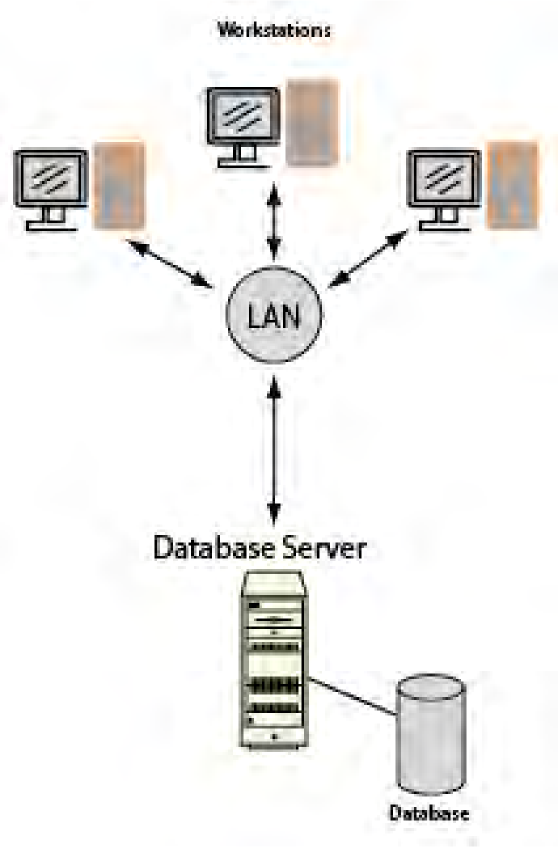


Figure 3.24. An example of a database architecture.

Basics of statistical mathematics

Event

Real-world phenomena involving random events are called random experiments in the probability theory. In probability theory, event is a set of outcomes of an experiment. Statistical experiments produce samples that are used to draw conclusions about the phenomenon under study. The samples are used to model the phenomenon under investigation.

The central concept is the random experiment. A random experiment is a process with the following characteristics:

- The experiment has several possible different outcomes.
- The result of each test performance is determined by the same mechanism, but it is random and therefore cannot be accurately predicted in advance.

The result produced of a single experiment (*trial*) is an observation (*realisation, outcome*). The set of all possible observations is called the sample space of the experiment, or population. In a statistical experiment, it is not so much the individual observations that are of interest, but whether they belong to a specific set of observations. This specific set of observations (outcomes) is called an *event*.

An event is therefore a predefined set of observations against which individual observations are compared and examined to see whether the event has been realised. (In statistics, the concept of event differs from that in everyday language. In everyday language, an event is something unpredictable (undefined) and is perhaps closer to a random experiment.).

A random variable (*stochastic variable*) X is a numerical quantity whose value depends on chance (for example, the time it takes for a bearing to fail). As stated above, a single experiment results in a single observation X_i for the random variable X. A single observation Xi always belongs to the population. The values X_i (i = 1,2,...,n) of the samples collected from the random variable are called the sample.

Probability

Experience shows that in most experiments indicate statistical regularity, i.e., the relative proportion of realised events, the frequency, seems to stabilise towards a constant value. If an experiment is run a very large number of times (N runs of N_E times in which event E is realised), the frequency of realisation of event E $f_E = N_E / N$ approaches a constant value $P(E)$ (as N becomes large). $P(E)$ is the probability of an event E.

Distribution functions of random variables

Since failures occur randomly and failure times are random quantities, the most natural way to model failure data is to use probability distributions.

To characterise a random quantity, it is not enough to define its possible values, but also to determine what is probable. If a random variable can have only a finite number of values, then characterizing that random variable is straightforward. You only need to list its possible values and associate with these values the probabilities that the random variable assigns to them. In the case of a computationally infinite case, an expression is defined which gives these probabilities. Two functions are used to perform these tasks: a probability density function and a cumulative distribution function. The former is denoted by $f(x)$ and the latter by $F(x)$.

Random variables usually fall into two categories, either *discrete* or *continuous*. Both discrete and continuous random variables can be modelled with parametric or non-parametric distributions, as appropriate.

Parametric distributions (such as Exponent, Normal or Poisson) can be defined precisely with a small number of parameters, such as mean and variance.

The parameters of non-parametric (empirical) distributions are observations from a random experiment. A non-parametric distribution can be used when it is not possible or necessary to attach a random variable to a specific parametric distribution. One advantage of a non-parametric distribution is that the model does not make any assumptions outside of the observations generated by the random experiment. This can also be a disadvantage because the observations generated by the experiments may not cover all possible values.

The nature of a random number is most completely described by its density or cumulative function, which tells us what values the random number can take and with what probability. In probability theory and its applications, including reliability theory, an important role is played by certain measures obtained from distribution functions by means of prescribed rules. These statistical measures, which are particularly important for the general quantitative estimation of random variables, are the *mean, variance, median* and *moments of different orders*.

If the researcher has only a finite number of trials or observations, the calculated values of the mean, variance, and median will be based on a sample of data rather than the entire population. Consequently, the calculated values are estimates and not true values that could be obtained if the data from the entire population would be available. Statistical methods are applied to calculate approximate values of the measures.

Continuous distribution

Continuous random variables are a concept in probability and statistics used to describe random phenomena where the possible outcomes are not restricted to specific individual values, but the random variable X can take any value within a certain range. The time between failures of a device or the time taken to repair a device are examples of random variables. Examples of continuous distributions are Gamma, Exponent, Normal, Weibull and Log-normal distributions.

Density function

Let X be a continuous random variable. A function f is called the probability density function of X if it holds:

$$f(x) \geq 0$$

$$\int_{-\infty}^{+\infty} f(x)dx = 1$$

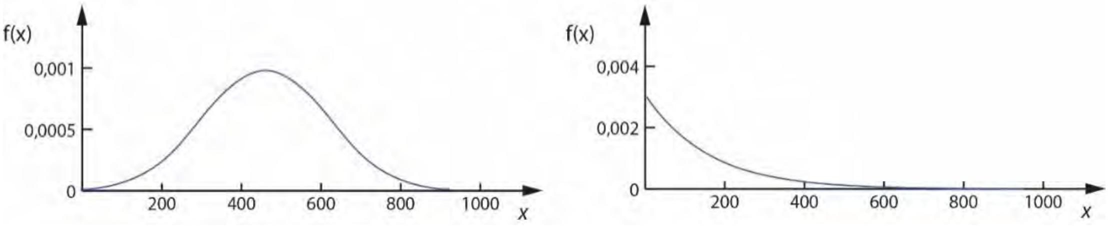


Figure 3.25. Density function. On the left the density function of the normal distribution, on the right the density function of the exponential distribution.

In Figure 3.25, the area between the blue line and the x-axis is 1.

Cumulative distribution function

Let X be a continuous random variable with density function f. The cumulative function F of X is defined:

$$F(x) = P[X \leq x]$$

$$P[X \leq x] = F(x) = \int_{-\infty}^{x} f(t)dt$$

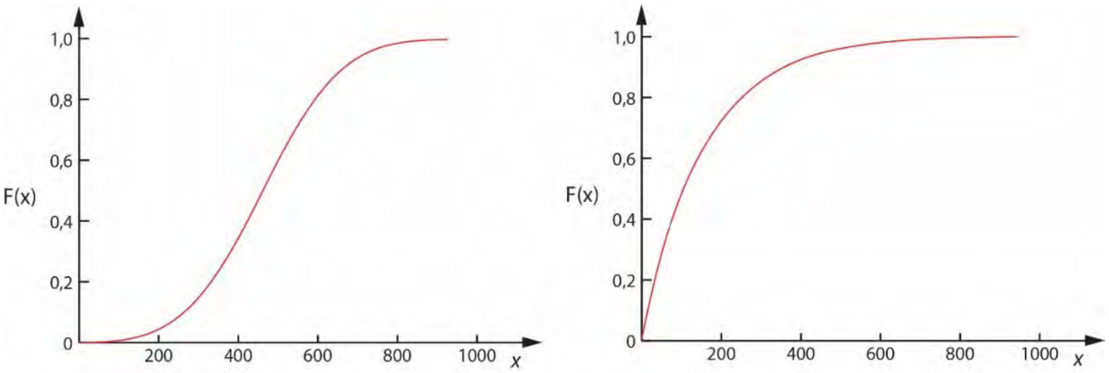


Figure 3.26. The accumulation functions. On the left, the multiplication function of a normal distribution, on the right, the multiplication function of an exponential distribution.

The cumulative function therefore gives the probability that the random variable X is less than or equal to an arbitrary fixed value *x*.

Discrete distribution

Discrete random variables are used to describe random phenomena where the random variable *X* can only have integer values. Number of failures of a device in a unit of time is an example of a discrete random variable. Examples of discrete distributions are the binomial distribution and the Poisson distribution.

Density function

Let *X* be a discrete random variable. A function *f* is called the density function of *X* with real values of *x* if it holds:

$$f(x) \geq 0$$

$$\sum_{x} f(x) = 1$$

$$f(x) = P[X = x]$$

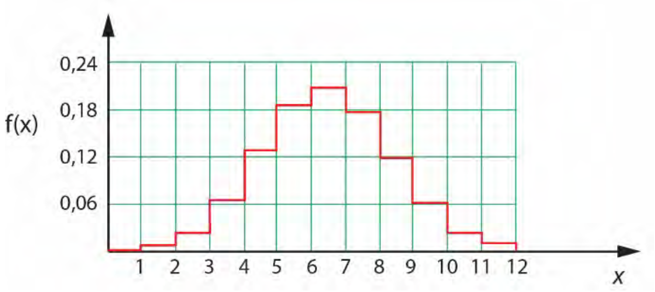


Figure 3.27. Density function of a discrete distribution.

In Figure 3.27, the area between the stepwise red line and the x-axis is 1.

f is defined for all real numbers. For any real number *x, f(x)* is the probability that a discrete random variable *X* takes the value *x*.

Cumulative function

Let *X* be a discrete random variable with density function *f*. The cumulative function *F* of *X* is defined as

$$F(x) = P[X \leq x]$$

Let's look at a specific real number. To determine the probability, we add up the values of *f(x)* for all possible values of *X*, i.e.

$$F(x_0) = \sum_{(x \leq x_0)} f(x)$$

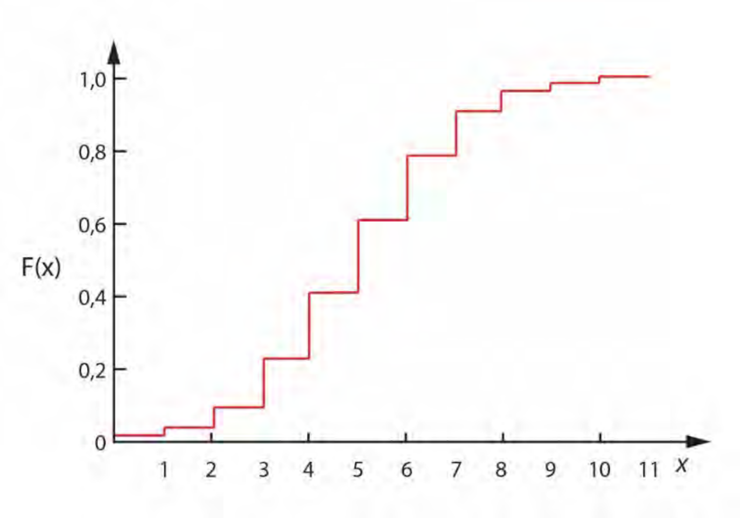


Figure 3.28. The cumulative function of a discrete distribution.

A cumulative function is a step function where steps occur at possible values of *X*: $x_0, x_1, x_2, ...$

From data to distribution

As described in paragraphs above, both discrete and continuous random variables can be modelled with either parametric or non-parametric distributions as appropriate. Parametric distributions (such as Exponential, Normal or Poisson) can be specified precisely by a small number of parameters, such as mean and variance. The parameters of the non-parametric (empirical) distributions are the observations of a random experiment.

When using data that consists of observed failure times (no censoring) the distribution can be presented as an empirical cumulative distribution function *Fn (x)*, which is a stepwise approximation of the actual cumulative distribution function *F(x)*.

$$F(x) = \frac{1}{n}\sum_{i=0}^{n-1}(X_i \le x)$$

In practice, the distribution is constructed graphically by dividing the vertical axis of the graph into as many parts as the sample size (Figure 3.29). The sample points are then placed in order of magnitude on the graph, starting with the smallest, which is placed at point 1.

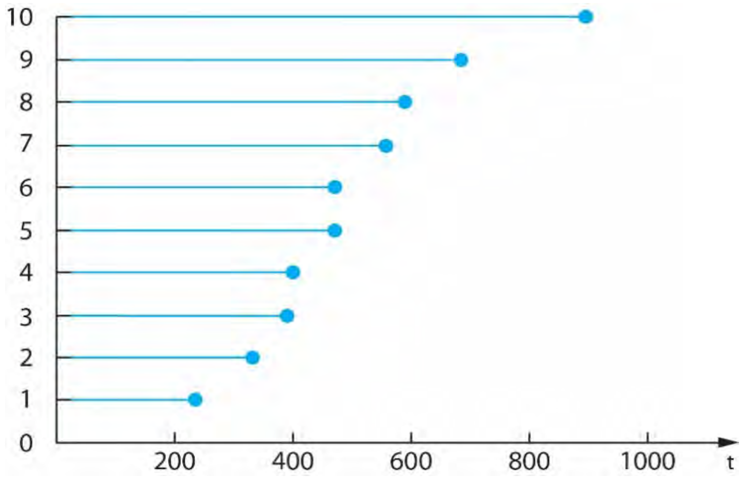


Figure 3.29. Graph of the empirical sample cumulative function, which is a stepwise approximation of the cumulative function.

The non-parametric distribution is not useful in failure analysis and simulation that require a parametric distribution. The parametric distribution is constructed by selecting the most appropriate distribution (distribution family) for the case in question as a starting point. The specific distribution of the chosen family is found by specifying the values of the parameters of the distribution so that the distribution fits the data under investigation as well as possible according to some criterion. The usual fitting method is the least squares method. The *Least-Squares Method (LSM)* is a widely used technique in statistics and mathematics for finding the best-fitting line or curve through a set of data points. It seeks values for the parameters of the distribution such that the sum of squares of the differences between the data values (failure times) and the corresponding values calculated from the distribution is the minimum (Figure 3.30).

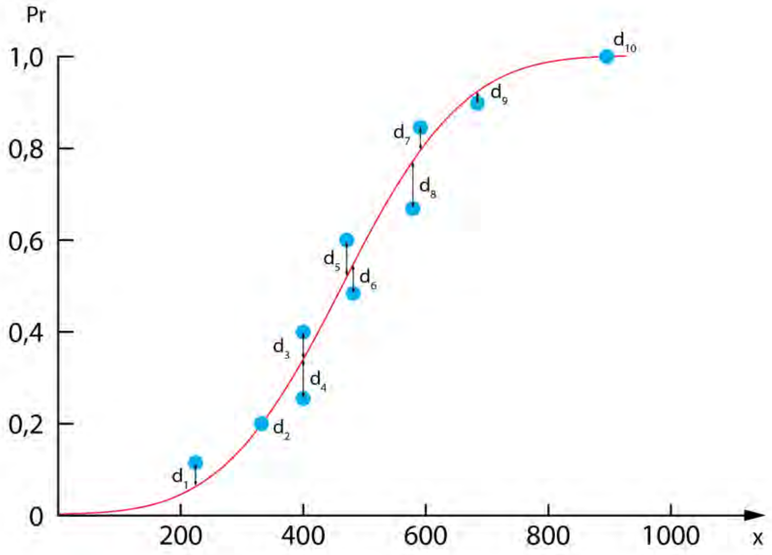


Figure 3.30. Fitting a parametric continuous distribution to a cumulative function of a discrete distribution.

Simulation models

In reliability and availability performance planning, a mathematical or logical model of the system under study that can be used to describe, explain, and predict the behaviour of the system, and to design experiments that verify these system characteristics. The experiments can be carried out in the form of computer simulations. The purpose of simulation is to predict the behaviour of the system under study, to understand its behaviour or to evaluate the effects of different strategies. Once a simulation model has been validated, it can be used to find answers to various "what if" questions about the subject. The system under study may be an existing device or system or one that is still in a design phase.

Simulation models can be classified as follows:

1. Discrete and continuous models. They are distinguished by the way they describe phenomena. A discrete model is based on single, separable events that change the state of the model. Continuous models are used to describe processes that are constantly changing.
2. Static and dynamic models. In a static model, the states of the system do not change as a function of time, while in a dynamic model they do.
3. Deterministic and stochastic models. If a simulation model does not include random factors, it is called deterministic. In a deterministic model, events and their outcomes can be determined with certainty from initial values.

However, random factors play a crucial role in many technical systems. When these random factors are considered in simulation, we talk about stochastic models and stochastic simulation. Stochastic models and *stochastic simulations* using them are the main methods used in the context of life cycle management.

The principle of stochastic simulation

Computer-aided stochastic simulation is based on a computer random number generator that uses algorithms to produce sequences of numbers that appear to be random. A random seed is the starting point for generating a sequence for random numbers. A random seed here denoted U is a random number between 0 - 1. For example:

$$U = rnd(1) = 0{,}23044029087$$

Each decimal place in a random seed can have any value, regardless of the previous decimal places. Let's say that U is uniformly distributed between [0,1].

Once a continuous distribution has been modelled from the failure data, the distribution can be used for simulation. In simulation, failure times are "produced" from the modelled distribution. The simulation is performed using the quantile function (inverse cumulative distribution function) as follows:

The original cumulative function (here the Weibull distribution):

$$F(x) = 1 - e^{-\alpha \cdot x^{\beta}}$$

The inverse of the cumulative function, the quantile function (the cumulative function is solved with respect to *x*:

$$X(U) = \left(-\frac{\ln(1-U)}{\alpha}\right)^{\frac{1}{\beta}}$$

Now to simulate, first define the size of the sample to be simulated, e.g.:

$$n = 1000$$

and an index:

$$i = 0 \ldots n-1$$

the variable *U* is a random number *rnd(1)*:

$$x_i = \left(-\frac{\ln(1-rnd(1))}{\alpha}\right)^{\frac{1}{\beta}}$$

where the parameters α and β are the parameters of the modelled distribution.

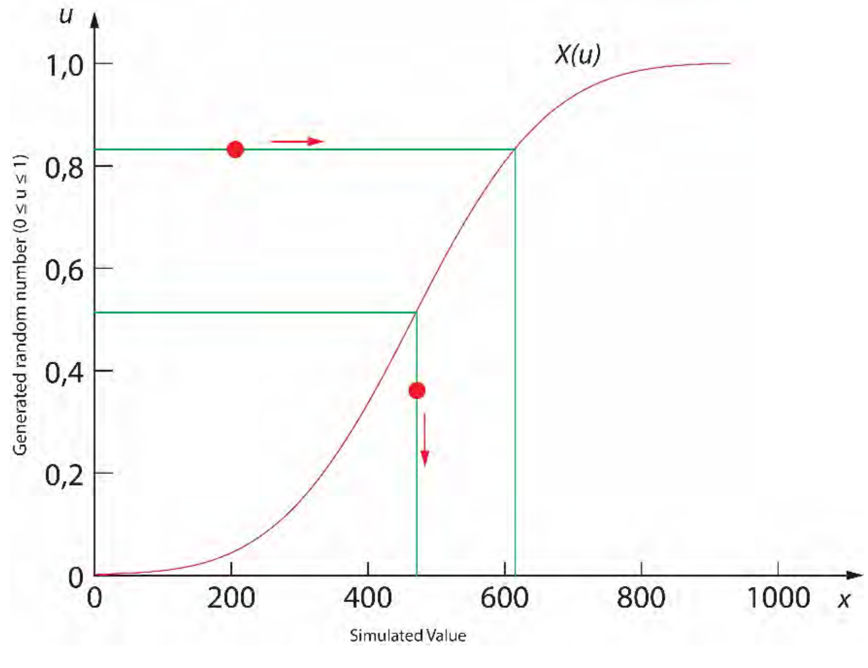


Figure 3.31. Principle of simulation.

Simulation example: using simulation to determine the maintenance period

Stochastic simulation can be used, for instance, to model the effect of the length of the maintenance period on failure frequency. The simulation is performed as follows: first set the desired maintenance period M-M. Then generate a failure time X from the quantile function, which is compared to the maintenance period. Figures 3.32 and 3.33 present two cases in which the failure time is greater, and shorter than the maintenance period. If the failure time is greater than the service period, this means that the device was maintained before it failed If the failure time is shorter than the maintenance period, it means that the equipment failed before it could be maintained.

The simulation is repeated until there is no longer any significant variation in the result. The simulation results can be used to calculate the probability of equipment failure for a given maintenance period. If the probability of failure is too high, the service interval is shortened, and the simulation is repeated. If the probability of failure is too low, the maintenance period is extended. Too few failures can occur if the maintenance period is suspected to be too short, i.e., the unnecessary maintenance and servicing carried out. Simulations can be used to experimentally find the appropriate length of the maintenance period, so that no unnecessary maintenance is performed, and at the same time, the number of failures is tolerable.

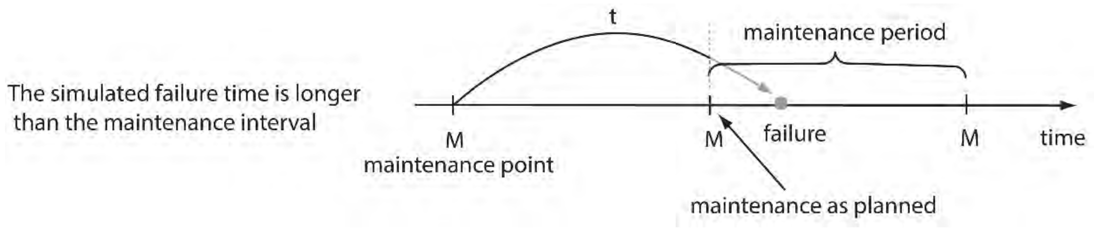


Figure 3.32. The simulated failure time is longer than the service interval, allowing the equipment to be serviced before it fails.

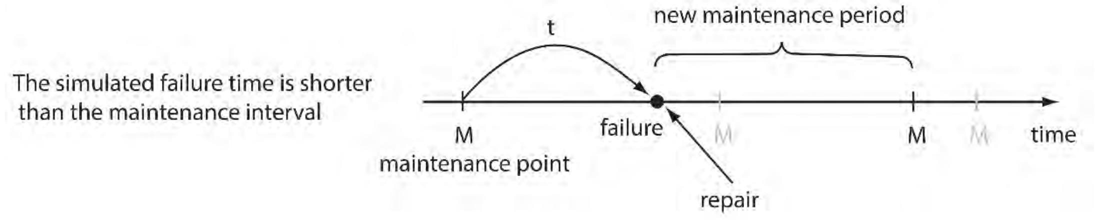


Figure 3.32. The simulated failure time is shorter than the maintenance interval, so the device will fail before it can be maintained.

Combined repair-fault and fault-repair process

The models discussed above can be combined into a repair-failure-repair process, using failure and repair history as input data (Figure 3.34). The left side of the figure illustrates the failure modelling. The starting point is the data on the failure times of the studied item, both at the site in question and across the fleet. The failure data are used to determine the cumulative function *F(t)* and further the reliability function *R(t)* of the failure distribution as well as the failure frequency *f(t)* and the (instantaneous) failure frequency *h(t)* *(hazard function)*. The right side of the figure shows the repair of the item. The starting point is the data on the repair times of the studied item, both at the operation site and at similar locations. The repair data are used to determine the cumulative function *G(t)* of the repair distribution, the repair density *g(t)* and the repair frequency *m(t)*.

The bottom part of the picture shows the combined repair-failure-repair process. Starting from the failure frequency and repair frequency functions *f(t)* and *g(t)* defined above, the results include the average number of failures and repairs $\Lambda(0, t)$ and *V(0, t)* of the part, the unavailability *Q(t)* and the availability *A(t)*.

In the following picture (Figure 3.34), a further example result is shown simulating the number of failures and repairs during the warranty period.

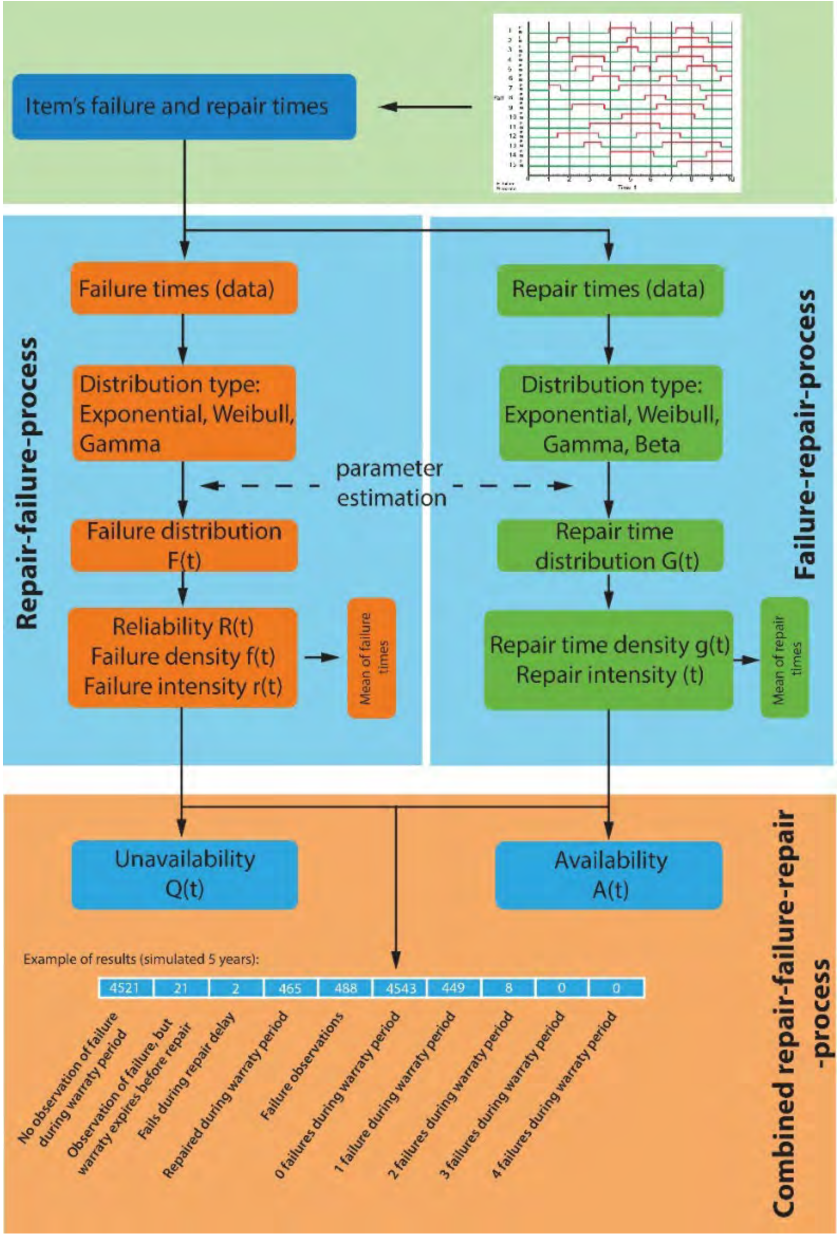


Figure 3.34. Block diagram illustrating the analysis of the repair-fault-repair process.

Key lessons

- Process data can only predict the behaviour and possible failure of a single piece of equipment or system.
- Statistical data can predict the behaviour of the population (fleet) from which it is collected, but not the failure of a single piece of equipment.

3.6. FUTURE PROSPECTS

Helena Kortelainen and Toni Ahonen

Introduction

Digitalisation, Industrial Internet (IoT, Industy 4.0), development of the cloud computing, and ever-increasing machine-to-machine communication and networking are generating huge amount of data, and this trend is expected to be further boosted by the proliferation of 5G networks. In industry, data is already being collected in large quantities and stored in information systems - where, unfortunately, it is often forgotten. Even more data will flow along the level of automation, as automated or fully autonomous operations require considerable sensoring and communication. The development of data-driven solutions has continued to focus on point solutions, and the development of factory and system-level solutions have proven to be a challenge. In terms of data analysis, much hope is placed on *Machine Learning (ML)* and *Artificial Intelligence (AI)* applications. At the same time, there is an identified need to develop competences for system-level modelling, combining data expertise with phenomenological expertise at different hierarchical levels of systems and beyond individual technical systems. In the following sections, these developments are considered from three perspectives: machine learning, the digital twin and cloud computing.

Artificial Intelligence (AI) and Machine learning (ML)

AI-based solutions can be used for maintenance in a variety of sectors, from real estate maintenance to industrial systems and mobile machinery. Maintenance is therefore seen as one of the most important areas for the use of AI in industry. In an extensive review of the use of AI solutions in industry (Bertolini et al. 2021), maintenance is the third most common area of application after quality control and production control. The use of AI can be divided into failure mechanism analysis, condition monitoring and minimisation of production downtime. AI, in particular machine learning, is seen as essential for modern production, with the concepts of sustainable production and Industry 4.0. The massive amount of data available will enable predictive maintenance, supported by automated failure and fault detection and diagnostics, with the aim of minimising production downtime and increasing utilisation and remaining service life (Çınar et al. 2020).

Big data methods, such as machine learning and especially neural networks, are mainstream AI. As their name implies, they require a lot of reliable and structured data, and their use requires a sufficient level of digitalisation in the organisation. Over the last decade, this has happened due to the development of IoT, cyber networks, employees' personal digital devices and, above all, organisations' data strategies. Machine learning is often divided into guided and unsupervised learning. In the former, the data must be *labeled*, i.e., a meaning must be attached to the data, such as "defective"/"intact". In unsupervised learning, the system tries to classify the data samples itself (clustering). Guided learning is more popular than unsupervised learning. The most used supervised learning methods are neural networks, support vector machines and decision trees. (Kortelainen et al., 2022)

Machine learning

Machine learning is a way of teaching a computer to recognise, classify and predict real-world phenomena and patterns (Bishop 2006). In ML, a machine or program learns from data by teaching without having to write programming for every possible situation. ML is a branch of artificial intelligence that aims to make software perform better based on the underlying data and the actions of potential users. In machine learning, a machine learns from repeated events without being explicitly taught by a human. Machine learning aims to automate the interpretation of data and extend the machine's perception through complex algorithms instead of a traditional model based on boundary values.

ML- algorithms are classified based on the instructional data they are given and are (Jordan & Mitchell, 2015):

- Unsupervised learning (no prior knowledge of teaching data). This method is particularly useful in applications that seek to identify clusters, clusters of data, categorise data or identify outliers (Lee et al., 2018).
- Guided learning (the desired output is known from the teaching data). Typical applications of supervised learning include various classifications and regression problems. Guided learning uses neural networks that mimic the human brain to some extent. Applications of supervised learning include quality control, predictive maintenance, and process optimisation (Wuest, 2016)
- Reinforcement learning (learning occurs because of continuous interaction between the model and the environment). Reinforcement learning is of particular interest for future autonomous technologies (Antonoglou et al., 2015)

In supervised learning, the machine is taught with classified data and the goal is that the machine can perform the desired classification on similar data. Unsupervised learning mimics human learning. It uses raw data to teach and tries to find similarities and relationships between different inputs, with similarities seeking proximity to each other. Reinforcement learning is a situation where a machine learns based on feedback from the environment.

Machine learning involves the following five steps:

- Collecting data: data can be raw data from Excel, Access or it can be data generated from text files. The data collection phase forms the basis for future learning. The quantity, quality and relevance of the data are important.
- Data preparation: the success of analytical processes depends on the quality of the data used. Time can be spent determining the quality of the data and taking corrective action, such as fixing missing data or anomalies in the data. Exploratory analysis is one method for examining the nuances and details of the data.
- Teaching the model: this step involves choosing an appropriate method and a format for representing the data in the form of a model. The processed data is divided into two parts: teaching and testing. The first part is used to develop the model and the second part is used as a reference.
- Model evaluation: testing accuracy. The second part of the data, the test part, is used to evaluate the model. This step determines the accuracy of the method selection based on the output.

- Improving efficiency: this step may involve choosing a different model or adding variables to improve efficiency. This will require significant time to collect and prepare data.

Figure 3.35 illustrates the principles of creating and maintaining a service based on machine learning. Machine learning solutions can support lifecycle decision making in many ways. Machine learning solutions enable the detection of interlinkages and cause-effect relationships that would not be discovered by other methods. Through supervised learning, neural networks find connections between multiple parallel time series, such as measurement data from sensors, weather data, failure records and process data. The Industrial Internet plays a key role in the efficient collection of training data. In some applications, machine learning can also automate decision making.

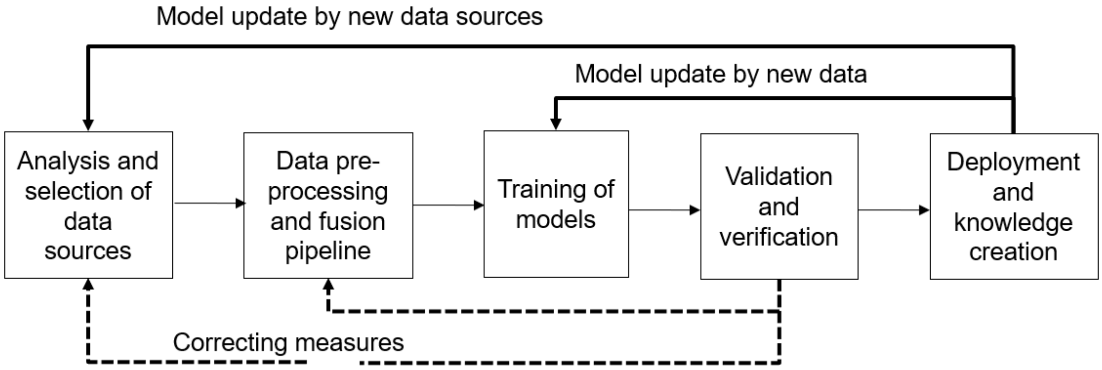


Figure 3.35. Creating and maintaining a machine learning-based service (Hanski et al., 2019).

Concrete applications for machine learning include the development of knowledge-based services for optimizing energy consumption and predictive maintenance of refrigeration equipment (Hanski et al., 2018). The energy consumption optimisation solution exploited the information contained in the cooling system. The parameters that best describe the causes of energy consumption were identified in the system through a collaboration between unsupervised learning models and system experts. Then, using supervised learning, new models were trained to simulate the behaviour of the system. The models created allowed us to examine the impact of the equipment settings on energy consumption under the predicted environmental conditions. The optimisation of the energy consumption of the cooling system was therefore based on the control of several parameters, including external factors. This approach could also be extended to predictive maintenance. From the condition monitoring, process and maintenance data, the most predictive variables are identified, and their behaviour is modelled with neural networks. This provides insight into the operating conditions under which the equipment drifted into critical areas and how to avoid critical states.

Digital twin

Digital twin is a concept that links a physical item and its associated information. According to Lee (Lee et al., 2013), a digital twin is like an image or counterpart of a physical object in the digital world. The idea of a digital twin stems from the NASA definition (Shafto et al., 2010):

"Digital twin (DT) is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin."

A digital twin can be established at the design stage of a product or system, allowing the simulation models created at the design stage to be used to support operation and maintenance throughout the life cycle. The digital twin can be used to test and predict the impact of, for example, different usage patterns, process parameters or other factors on the operation of the process in real time, using measurement data. If wear, corrosion, and other failure phenomena can be modelled, the digital twin can also be part of predictive analytics and help in predictive maintenance (Figure 3.36).

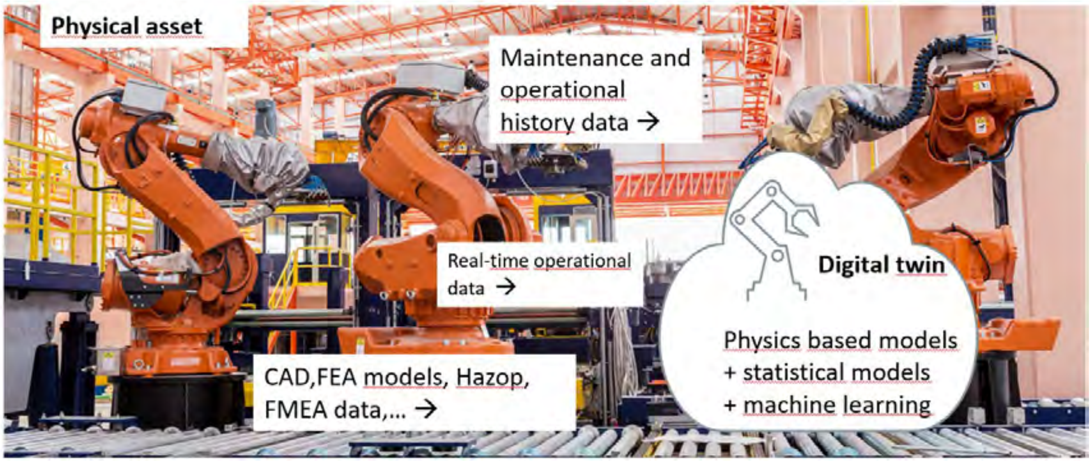


Figure 3.36. A physical device and its digital twin (Kortelainen et al., 2019).

The use of digital twins - either static or dynamic - in product design is growing rapidly. Applications are also being actively developed, for example to support more efficient production processes. In support of maintenance and asset management, DT would offer significant advantages by bringing together life cycle information that is currently fragmented. However, there are many challenges, including the need to continuously update the digital content of the information as the physical system changes. For asset systems already in operation, the source data is often not in a machine-readable format, the data is incomplete, making it costly and cumbersome to produce a digital twin. However, applications already exist, such as the DT propeller system for ships, which uses virtual sensors, or physical models, and virtual components, or design models, to predict the expected lifetime of an object (Räikkönen et al., 2020b)

Sharing information between actors in the network

Cloud computing provides a single means of exchange data between businesses. Cloud service providers represent a third party that has no direct interest in the actual content of the data but has a strong interest in ensuring the confidentiality of the data for the continuity of its own business. The cloud service provider is responsible for sharing the data so that each party can only see the content that is specified for them. For example, the equipment manufacturer is only entitled to the data related to their equipment and the end user only to the data related to their equipment. The information that manufacturer or supplier receive from the operational phase focuses on failure events and consequences at the equipment level. Centralised data collection provides the equipment supplier with a better understanding of the relevance of their equipment to the customer's overall production system. For example, by linking failure data of individual devices to the operation of the production process, the equipment supplier gains insight into how the failure of the equipment they supply directly affects the efficiency and output of the production process (Kunttu et al., 2016; Kortelainen et al., 2017).

The networked environment brings its own additional challenge to the information available to equipment manufacturers. Equipment manufacturers' clients are typically system suppliers, whose customers are the end-users. In the absence of a direct business link or contract between equipment manufacturers and end-users, it is difficult to obtain information on the time of use of the equipment. Cloud computing allows equipment suppliers to have better access to in-use information, even in the absence of a direct relationship with the end user.

In addition to easier information exchange, data collected in one place can be used, for example, to assess compliance with contract terms. The values of indicators defined in contracts, such as availability or overall performance, depend on the data used and the definition of the indicator. Indicators reported from data collected in one place can contribute to reducing ambiguities when assessing compliance with contractual conditions.

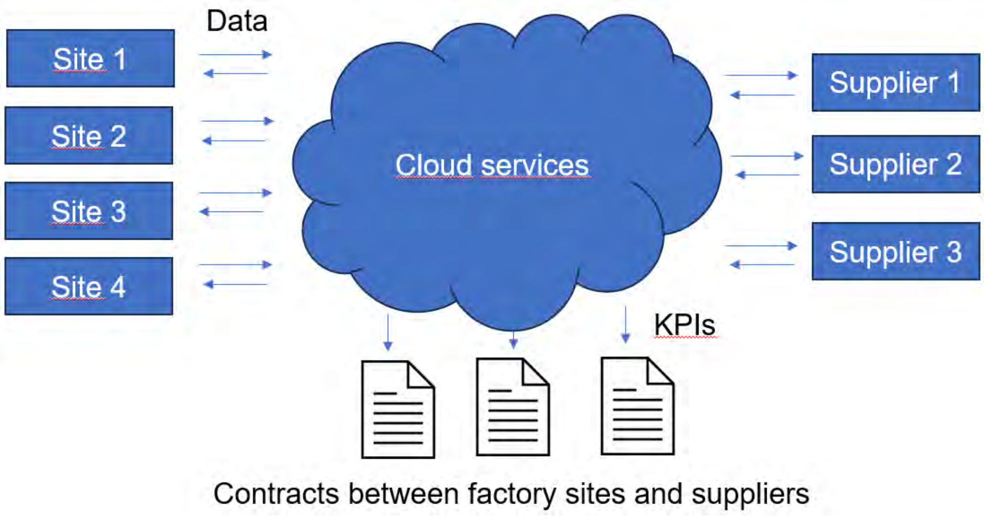


Figure 3.37. The concept of information sharing based on cloud computing (Kunttu et al., 2016, Kortelainen et al., 2017).

In Figure 3.37 the concept of centralised data collection provides a simpler means of exchanging information between different stakeholders than current practices. Centralised data collection offers many advantages, but also risks from a practical implementation point of view, of which the partners need to be aware when weighting the benefits. End-users, who are the producing the raw data, need to assess when data is critical for their business and if data accumulation can lead to a knowledge leak in a long run, even if individual data items are not critical. Similarly, system providers and equipment suppliers need to assess whether the data mass accumulating in the cloud can become critical to their business. The risks associated with data delivery should be identified and assessed but should not be exaggerated.

Key lessons

- Machine learning solutions enable the detection of interlinkages and cause-and-effect relationships that other methods would not reveal. Machine learning has many applications in areas such as system performance optimisation and condition-based and predictive maintenance.
- Digital twin connects the physical product and its associated data.
- Digital twin can be used to simulate the effect of different operating modes, process parameters or other factors on the operation of a process in real time.
- Digitalisation enables the sharing of information in collaborative networks. In addition to technology, optimisation solutions that cross system boundaries require collaboration between different stakeholders, combining technological, data and expertise on the physical phenomena at different system levels.
- Barriers to information sharing are more often related to trust between partners and conflicting business objectives than technical issues.

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PART 4
METHODS, TOOLS, AND TECHNOLOGIES WITH APPLICATIONS EXAMPLES

4.1. FORESIGHT METHODS TO SUPPORT TECHNOLOGY CHOICES

Jyri Hanski and Anu Nousiainen

Introduction

Technology investments are good examples of strategic choices made by companies. They involve a high degree of uncertainty in terms of total costs and benefits, life cycle, market changes and new technological advances. Foresight methods support companies in considering alternative futures associated with strategic choices. They allow companies to assess the need for technological investment and to make longer-term plans for the introduction of new technologies. Life-cycle management methods should consider possible changes in markets, trends, and legislation, which are also reflected in customer demand for the technology. Commonly used foresight methods include morphological analysis, roadmaps, modelling, and simulation, Delfoi, and scenario methods. These are well suited for analysing business, societal or technological developments.

In morphological analysis (Zwicky, 1967), a solution to a complex problem is sought by identifying all the possible dependencies and factors that the problem contains. Morphological analysis identifies the phenomena or factors associated with the challenging problem and what are their possible outcomes in the chosen time frame. A typical representation for morphological analysis is a table, which is used to generate alternative scenarios by combining cells in the table in different ways. Alternative scenarios include the status quo and the future to be pursued or avoided.

When analysing technological change in the longer term, it may make more sense to focus on a few key drivers. In such cases, for example, the scenario method presented by Schoemaker and Mavaddat (2000) can be applied. This method identifies a list of variables that affect the future and ranks them in a quadrilateral according to the uncertainty and impact of the variables. From these, the variables with the highest impact and uncertainty are selected for analysis. The independence of the variables from each other is then assessed and different scenario matrices are constructed using the independent variables (Figure 4.1).

Business model

Data ownership	**Incremental change**	**Radical change**
Incremental change	• Closed data • Actor's own business models • Business as usual in business model development	• Closed data • Ecosystem business models adhere to the principles of circular/platform economy • For example, ecosystems do not share information externally, but strive for the circular economy principles
Radical change	• Open data • Actor's own business models • For instance, regulation-based OREDA in Norwegian oil and gas industry	• Open data • Ecosystem business models adhere to the principles of circular/platform economy • For example, ecosystems transparently share information with external parties and operate in accordance with the circular economy principles

Figure 4.1. Scenario method example: alternative pathways for the development of smart cities.

Delfoi is a forecasting method based on multi-stage expert assessments (Rowe and Wright 1999). In this method, the same panel of experts is presented with a set of questionnaires which are refined in each round based on the experts' comments and assessments. The aim is to reach either a consensus or a broader understanding of the phenomenon under study. Delfoi is a demanding method to implement, and its success depends to a large extent on the selection and commitment of the expert panel.

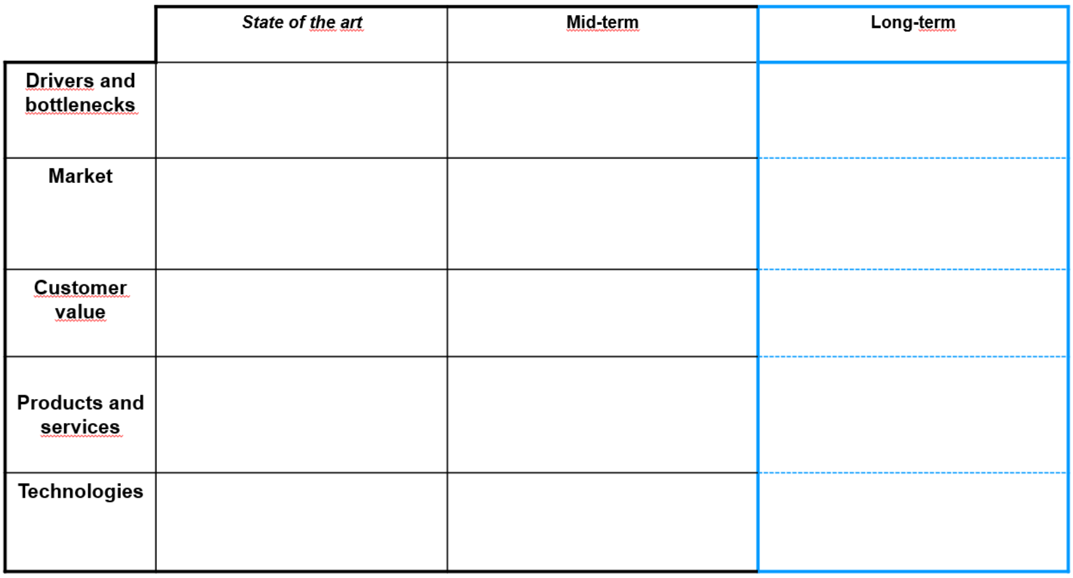
Modelling and simulation are used to represent different phenomena in mathematical form. They aim to create a meaningful and simplified representation of reality. Modelling and simulation can be used to generate information to support scenario work, to analyse the behaviour of complex systems and to test scenarios. However, the complexity and laboriousness of models limit their use in enterprises. Traditional modelling methods include system dynamics, discrete event modelling and agent-based models. Today, machine learning-based models have become more common for predicting and optimising system behaviour.

Roadmap method

A roadmap is a method to support foresight and strategic planning. A roadmap typically goes through three phases:

- choice of destination and time span,
- forming a vision, and
- producing the roadmap content.

Although roadmapping is a well-established method, there are many different applications. One example is the 'backpocket roadmap' (Ahlqvist, 2007; Paasi et al., 2008), which starts with a definition of the current situation in terms of drivers and bottlenecks, market, customer value, products and services, and technology (Figure 4.2). The next step is to define the timeframe of the roadmap and create a vision and objectives for the selected timeframe. This is followed by the creation of milestones to achieve the vision and objectives. The benefits of roadmap work are not limited to the final output, but the roadmap process itself increases the understanding of its authors on the topic at hand.



	State of the art	Mid-term	Long-term
Drivers and bottlenecks			
Market			
Customer value			
Products and services			
Technologies			

Figure 4.2. Template for roadmap work.

In roadmapping work, foresight is particularly about visioning: taking a leap into the long-term future and mapping the desired future pathway into a target state. The visioning process starts with the definition of a focal question, familiar from scenario work, which helps to describe the use case (user narrative) of future technologies at a given point in time, from the perspective of a given actor and in a relevant everyday context. The key to visioning is to identify future drivers of change and use them to imagine what might be different in different contexts of our daily lives.

Visioning requires holistic and interdisciplinary thinking and expertise, so it is always a co-creation exercise. Combining the approaches of design and foresight, or futures design

(Ojasalo et al., 2015), helps organisations to create a shared understanding of comparable alternative futures, identify their role in the related future markets and create a desired future through innovation and investment activities. An example of a futures design method that supports visioning and roadmapping is the Experience Path (Koskelo & Nousiainen, 2019) (Figure 4.3). The *Experience Path* animates and seeks to empirically model the stories of possibilities, visions, and intentions of needed change agents in a form that is understandable to all through empathy and ideation. The method combines foresight knowledge (e.g., trends, vision, scenario) with the design persona tool (Persona), the service pathway canvas (*Journey Map*) and the '*A day in the life*' exercise (Stickdorn et al., 2018).

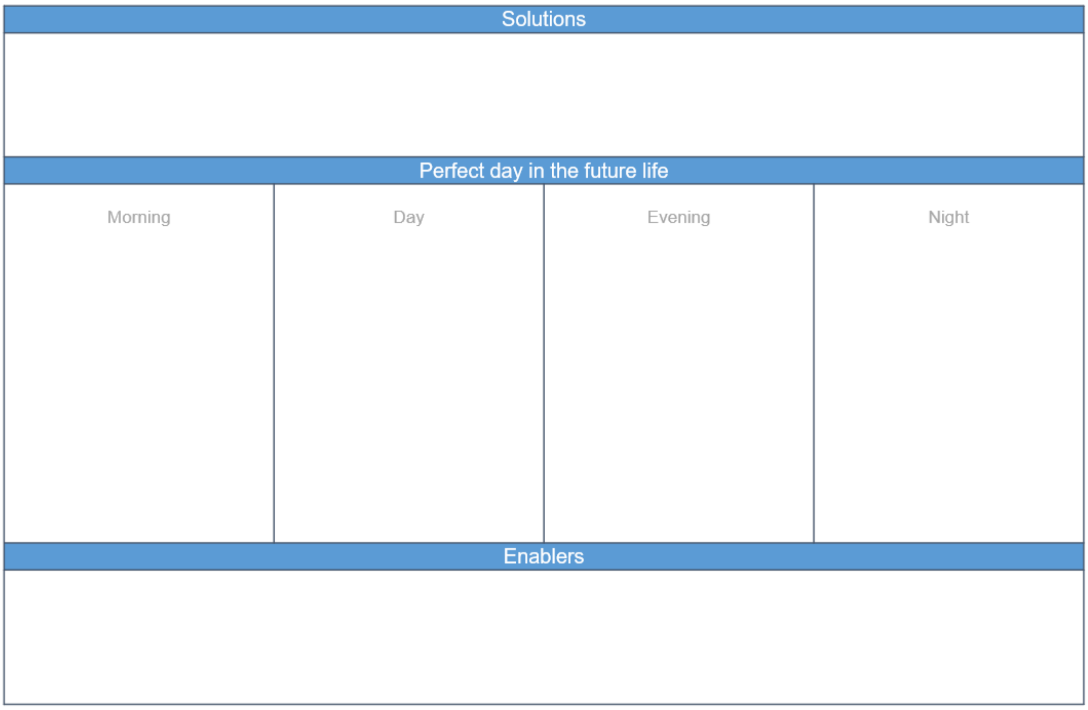


Figure 4.3. Foresight in roadmap work: the "Experience Path"

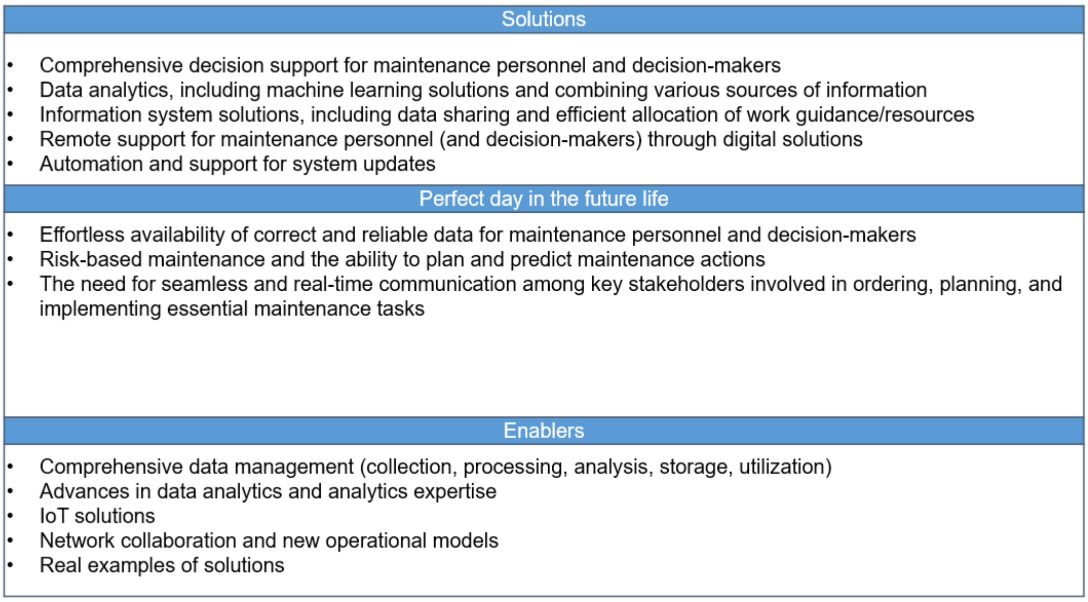
The method imagines that when we wake up tomorrow, we will already be living in a vision of the future, where the forces and phenomena of future knowledge are part of everyday life. In the "Perfect day in the future life" section, the participants live and imagine together a story about how, from the perspective of the selected person, everyday life would be most perfect "when everything is possible". This is where we look at what people aspire to and do, how they interact and with whom, what services, tools, and information they use to achieve their goals, what surprises can happen and how they cope. Visual storytelling will be used: by drawing and illustrating a story, the context of future everyday life will be shown in its diversity and participants will identify new interaction surfaces and service needs.

As the perfect day is captured, new solutions will also start to appear and will be raised to the top of the board. At this stage, participants brainstorm more solutions and consider at the bottom of the table what more is needed (enablers) to make the imagined day a reality and the solutions operational. Enablers can be related to technology, resources of actors, skills, or partners, among others. The ideas generated can also be prioritised in terms of their impact and readiness to be implemented now, to be implemented next and possibly to be implemented later (roadmap).

In addition to bringing ideas and visions to life, the Experience Path highlights the role of the user and decision-maker (change agents), and the problems and opportunities they perceive in the adoption of technologies. Key drivers of change are thus brought to the level of real problems, opportunities, and decision-making situations.

Case: Experience Path in forecasting maintenance trends

The Experience Path method was applied to predict the future of smart grid maintenance (Figure 4.4). The foresight work was part of the Smart Otaniemi[1] innovation ecosystem pilot project "Managing reliability in smart energy systems". Participants were instructed to imagine themselves at work in a future where new digital technologies are commonplace. Participants told and wrote a story about a perfect day where anything is possible. There were two perspectives to consider: the maintenance worker and the decision maker. Participants described a future working day in the field and decision-making situations. Based on this description, they assessed the issues and solutions needed to make the imagined day a reality. Finally, they considered how the solution could be implemented and what enablers would be needed.



Solutions

- Comprehensive decision support for maintenance personnel and decision-makers
- Data analytics, including machine learning solutions and combining various sources of information
- Information system solutions, including data sharing and efficient allocation of work guidance/resources
- Remote support for maintenance personnel (and decision-makers) through digital solutions
- Automation and support for system updates

Perfect day in the future life

- Effortless availability of correct and reliable data for maintenance personnel and decision-makers
- Risk-based maintenance and the ability to plan and predict maintenance actions
- The need for seamless and real-time communication among key stakeholders involved in ordering, planning, and implementing essential maintenance tasks

Enablers

- Comprehensive data management (collection, processing, analysis, storage, utilization)
- Advances in data analytics and analytics expertise
- IoT solutions
- Network collaboration and new operational models
- Real examples of solutions

Figure 4.4. Future maintenance solutions for the smart grid

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[2] Smart Otaniemi, see https://smartotaniemi.fi

The experience pathway method was used to identify key technology selection factors that can be used to target and prioritise lifecycle management solutions. It supports the allocation of limited development and investment resources, alongside other methods.

Key lessons

- Foresight methods support the development of life cycle management.
- Roadmaps can be used to plan future technology investments.
- The Experience Path method considers the role of key user profiles in designing technology choices.

4.2. ANALYSIS OF RELIABILITY DURING THE CONCEPTUAL PHASE OF THE PRODUCT DEVELOPMENT PROCESS

Tero Välisalo

Conceptual risk analysis can be carried out at different levels of detail, which influences the application of individual methods and the way the analysis is carried out, as well as the choice of risk analysis methods. A risk analysis package may also consist of the use of several complementary methods.

The selection of risk analysis method is influenced by the resources available: skills, time and other constraints, and budget. In the early stages of system development, less detailed methods can be used, in later phases the work can continue with more refined analyses as more information becomes available. Risk analysis of technical systems - and the selection of risk analysis methods - is discussed in more detail in EN IEC 31010:2019, Risk management. Risk assessment methods.

Among the risk analysis methods for technical systems, *Failure Modes and Effects Analysis (FMEA)* or *Failure Modes, Effects and Criticality Analysis (FMECA)* with its variations is a typical method used in product development. The standard IEC 60812:2018 deals with the use of failure and effects analysis method. The aim of the FMECA is to identify significant risks to reliability and safety as early as possible and to develop a preliminary set of ways to handle the identified risks. However, the actual implementation of improvement measures is a normal design exercise, the analysis only aims to identify areas for improvement.

The risk analysis can be based on the functions of the system under consideration, rather than on the technical structure and components of the system. At the conceptual design stage, there is usually not yet a very clear picture of the details of the system and the choice of components, but the functions that the system is intended to perform are already known. One of the objectives of the risk analysis at the conceptual stage is therefore to provide better information to support, for example, the choice of components or technologies. It is also essential that the analysis draws the team's attention to the most critical aspects of the planned system, which require particular attention to the more detailed design.

A conceptual risk analysis includes aspects of a functional failure and impact analysis, which pays attention to the failures and malfunctions of the equipment under consideration, the consequences of failures and malfunctions, and preventive measures and contingencies. The conceptual risk analysis considers a broad range of risks over the life cycle of the system that can be influenced by the design.

The main task of the analysis is to identify the most significant risk factors and determine measures to eliminate them or reduce their consequences. One of the key results of risk analysis is an increased understanding of the critical functions of the system, which can be planned with proportionately more effort based on the new information. The implementation of the improvement measures identified in the analysis is a standard design activity.

The risk analysis in the conceptual phase is carried out in a working group, the composition of which can be revised at each working meeting according to the part and theme of the system chosen. The key is to draw on different perspectives, expertise, and experience in the analysis. The role of the analysis leader is to ensure that the full potential of all those involved in the analysis is exploited. Attention will be paid to the following issues:

- Function: describe the function based on the functional description of the system developed in the previous step. In addition, if possible, at the design stage, specify which subsystems or components are involved in the implementation of the function under consideration.
- The functional failure/malfunction/problem and its possible root causes are identified and described.
- A description of how a failure can be detected and defines how the problem that has arisen can be eliminated, repaired, or reduced by preventive maintenance to reduce the likelihood of its occurrence.
- Evaluate the consequences at an appropriate level, e.g., impact on the performance of the production process or on operating costs.
- Identify measures to reduce the consequences or likelihood of consequences, note any ideas that arise to support the test plan and record any other comments.
- Identify the person responsible for implementing the planned measure, designing the measures, or otherwise addressing the identified problem.

Risk is typically defined as a combination of the consequences and probability of an event. Due to the high uncertainty and scarcity of information associated with the conceptual stage, a reliable probability assessment is not realistic. As a result, the risk analysis in the conceptual phase focuses only on assessing the impact of risk scenarios and the selection of key development areas and the design of measures based on this information. It is also important for risk management to plan how the effects of the measures taken will be monitored.

The documentation of the risk analysis should be prepared in such a way that, when the analysis is reviewed afterwards, anyone has the possibility to understand not only the risk scenarios identified, but also the criteria used to assess the impacts and design the measures. Consequently, attention must be paid to the quality of the documentation and to the level of detail. For example, the easiness of updating the analysis where necessary or of making effective use of the results depends on the quality of the documentation. It is useful to compile the key findings of the analysis, and in particular the measures, into a separate document so that both the planning team and the external expert can quickly gain an overall understanding of the results of the analysis.

Managing reliability in a product development project

Often in product development projects, the product being developed is based on a previous generation machine/equipment model, to which new features or other improvements are added. Even in such a project, challenges may arise that need to be identified at an early stage to avoid problems in the future. However, the most important thing in such a product development project is that the development work is carried out in a controlled way and that any investment in, for example, reliability improvements can be justified.

Functional description: SADT and IDEF

One option for a product development project's reliability management framework is a functional description. A functional description is prepared to provide the project members with a common understanding of the functions of the system under consideration. On the other hand, documented functional descriptions can be used as a basis for a subsequent functional risk analysis. Since the risk analysis in the conceptual phase is structured around an analysis of the system's functions rather than a component-based approach, the functional description forms the backbone of the analysis. Thus, the key output of the functional description for the conceptual risk analysis is a list of functions that will be performed when the target system is used.

Depending on the nature of the operation and use of the system, the relationship between the user (e.g., consumer, operator, driver) and the operation of the system should be included in the description. There are several methods for describing the functions in different situations. A method suitable for describing different systems, originally developed for software development, is *SADT*[2] *(Structured Analysis and Design Technique)* and the *IDEF0*[3] *(Integration Definition for Function Modeling)* modelling methodology based on it. The IDEF0 principles are applicable both to new systems under design, where the key issue is to define requirements for functions, and to older systems where it is desired to model and analyses the functions and dependencies between functions.

The SADT-based modelling approach gives the best results when the overall activity of the target system consists of a series of different activities as a continuous process and the interdependencies between the activities remain essentially static during the activity. By using the SADT modelling approach and principle, and by modifying the inputs and outputs of the representation, a system with a different nature and more complex interconnections of functions can be described. On the other hand, a system whose operation involves different subsystems interacting in different ways and at different times, and where the object to be modelled is, for example, an IT solution that also requires modelling of the communication signals, may require a different modelling approach depending on the objective.

The most important thing is that the description provides a clear, common picture of how the target system works that is simple enough to form the basis of the analysis. Basically, a functional description can be just a bulleted list of system functions. In some cases, this approach may provide the necessary level of detail for a risk analysis in a timely and resource-efficient manner.

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[2] https://en.wikipedia.org/wiki/Structured_analysis_and_design_technique

[3] https://en.wikipedia.org/wiki/IDEF0

Functionalities help to identify new challenges and interfaces in incremental development that may cause problems, even if the new configuration is built from components already familiar in other applications. The functional description allows the identification of uncertainties and the identification of measures to either eliminate or substantially reduce them.

The range of measures can be wide. Often, only certain risk analysis methods are regarded as tools to improve reliability, which of course they are, but many other tasks in a product development project also serve to improve the reliability of the final product. These include, for example, strength calculations, cooperation with component suppliers or the development of test programs. Most importantly, if specific activities are selected for a product development project, they must be clearly justified, and their outputs utilized during the design.

Case: Reliability management method in a product development project

In RelSteps-research project and in a case study in cooperation with Sandvik Mining and Construction, a light procedure for managing the reliability of a product development project was tested. The challenge was that the previously used reliability analysis procedures seemed too heavy for Sandvik's product development projects.

At the beginning of the case, a functional description of the Sandvik product development project item was prepared, in which the functions of the device and their sequence of operation in a normal production process were recorded. The functional description was discussed in detail with a team of experts selected by Sandvik. During the review, both completely new functions and items that were otherwise uncertain in terms of reliability were identified, together with possible solutions or further clarification. After the experts had gone through the functional description in their respective technical areas of expertise, the VTT scientists proposed further actions. The proposed follow-up actions were discussed in the project steering group and most of the findings that were taken forward for further analysis, feasible improvement measures were identified. As a follow-up, VTT carried out a failure mode analysis for a selected new component type, identifying the potential failure modes of the new component and its impact on the Sandvik application.

Based on the experience of the case study, the reliability management procedure based on the functional description worked quite well in the product development project. The description can be reused as a basis for the next product development project, i.e., the workload for establishing Reliability Management Procedures in the next project is reduced. By using the description, the site could be systematically reviewed, and more specific measures could be targeted to specific areas.

Key lessons

- In terms of reliability, a detailed analysis of solutions that have been tested in practice is not very resource-efficient, as it rarely identifies significant new failure modes.
- New products that combine new components with existing solutions or use previously used components in new ways or in new combinations. In such cases, problems may arise, especially the interfaces of new combinations or solutions.
- A functional description can be used to identify such uncertain interfaces and to target measures to ensure reliability.
- In the case study, some objects were identified to which particular attention was paid in form of further reliability analysis, resulting in a substantial reduction in the resource consumption without reducing coverage.

4.3. DESIGN FOR MAINTAINABILITY

Tero Välisalo

Introduction

Maintainability is part of the reliability characteristics of a product and is defined in IEC 60050(192) as follows:

> *"Ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance".*

Maintainability is therefore a product feature built into a product, the ability of an object to be restored to working order after maintenance work. Maintenance as a term is defined as the performance of the actions required to repair defects (corrective maintenance) and to perform preventive maintenance (predictive maintenance). The IEC 60050(192) standard states the measurement of maintainability as follows:

> *"Maintainability (M (t_1,t_2)): probability that a given maintenance action, performed under stated conditions and using specified procedures and resources, can be completed within the time interval (t_1,t_2) given that the action started at $t = 0$."*

The measurement of maintainability, as defined in the standard, therefore focuses mainly on measuring the time taken to carry out an active maintenance operation. However, there are other aspects to maintainability:

- Identifying the cause of the fault:
  - In current technical systems, failure is often detected through sensor data and remote monitoring. However, diagnostics cannot directly tell which component(s) is failing and the actual cause of the observed symptom.
  - Thus, another indicator of good maintainability is whether the system is able to identify by itself the components related to the symptom that has occurred, thus reducing the time needed for troubleshooting, i.e., making it easier to identify the failed components.
- Competence requirements for the maintenance worker:
  - If a maintenance job requires special skills or formal qualifications, the resources available to carry it out are less than in a situation where the job can be done with fewer skills.
- Safety in maintenance work:
  - The design of the system can influence how safe it is to carry out the work.
  - For example, the sharp edges of structures or machine parts, which in many cases are irrelevant to the functionality of the system, but which pose a cutting hazard to the person carrying out the maintenance work.
- Specialised resources needed:
  - If some special resources are needed to maintain the site, such as lifting equipment or special tools that are not generally available, their lack can have a significant impact on maintenance delays.

- Accessibility:
  - To access to the actual item requiring maintenance, it may be necessary to dismantle a considerable number of other subsystems.
  - In some cases, very small changes to the design can influence how well an object can be accessed for maintenance.

Improving maintainability does not necessarily reduce the number of failures, because the *Time To Failure (TTF)* does not really change with improved maintainability. However, improving maintainability will reduce the *Downtime (DT)* of an object, increase production time and thus improve the availability of the object, as maintenance work can be carried out faster. Improvements in maintainability can indirectly reduce both the number of installation errors and the number of failures in maintenance work, by reducing the number of difficult and therefore possibly missed preventive maintenance tasks.

Steps of the maintainability analysis

The maintainability analysis starts with the definition of the object. The definition of the target for a maintainability analysis can be done in many ways. The definition can be physical (e.g., a specific part of the machine) or the object can be defined, for example, by technology (e.g., hydraulics, mechanics). In the maintainability analysis, it is advisable to focus on items that are new and for which feedback from the maintenance organisation is not yet available.

The actual analysis can be done either by limiting the analysis to preventive maintenance tasks only (service) or to corrective maintenance tasks only (fault repair). The object can also be analysed from both perspectives. The preventive maintenance tasks to be considered can be listed based on the maintenance program of a previous machine model or, in the case of a completely new system, by drawing it up using, for example, the maintenance programs of component suppliers and expert assessments. The results of a failure analysis of the object are needed to determine the tasks of corrective maintenance. A failure analysis of a previous model can also be used as a basis for a maintainability analysis if the structural differences between the models are not too significant.

Once the framework for the analysis is in place, the identification of maintenance development needs is carried out in a team approach, like a risk analysis. The most frequently performed maintenance tasks are analysed first and the least frequently performed tasks last. This is to ensure that at least the most frequently performed work to be carried out in a product development project is analysed, due to possible time pressures. For corrective maintenance work, the approach is the same: first, the repair work for the failures identified in the failure analysis that are considered to occur most frequently and, finally, the failures that occur rarely. It is not necessary to assess all the failure modes considered as very rare.

The analysis team should include at least representatives from maintenance and design, and a separate chairperson/secretary who will lead the analysis and document the analysis team's records. The design representative should have a good overall view of the product to be developed, so that any change requirements can be considered at an early stage of the design. The maintenance representative should have first-hand experience of carrying out field maintenance. 3D images of the site play an essential role in the analysis, and their existence is essential for understanding the different aspects of maintainability. The documentation of purchased components must be available in the analysis to determine how to maintain new components, etc.

The analysis focuses on assessing the criticality of maintenance work from different perspectives. These perspectives for both preventive and corrective maintenance are:

- safety of the maintenance work,
- accessibility,
- the required skills, and
- the need for special tools.

Evaluation of the elements of maintenance work

The corrective maintenance analysis can also assess the fault-finding properties of the system, i.e., how unambiguously the symptoms in the operation of the machine lead to the identification and repair of the fault in question. The ergonomic aspects of the maintenance work, mainly the working position, can also be assessed, but in most cases the maintenance work is carried out so quickly or so infrequently that an awkward working position is not a major inconvenience. Any problems with the working position can be highlighted in the safety assessment. All aspects were assessed on a three-point scale. The scales used for the classification are shown in the table below (Table 4.1).

Table 4.1. Scale for assessing the different elements of maintenance work.

	IDENTIFYING THE CAUSE OF THE FAULT	**SAFETY**	**ACCESSIBILITY**	**THE REQUIRED SKILLS**	**NEED FOR SPECIAL TOOLS**
3	The cause of the fault can only be identified by trial and error, and it typically takes a long time to identify.	In practice, it is very difficult to carry out maintenance work safely, and you must take risks to do the job.	Significant dismantling required to access the object/ visibility obstructed	Carrying out maintenance work requires a high level of experience and/or specific skills	Special tools are required to carry out maintenance work and must be reserved / hired specifically for this operation.
2	The cause of the fault can only be quickly identified with special tools or by experienced staff	Special equipment/ special care is required to carry out maintenance work safely.	Conventional tools required to access the service site/limited visibility	Carrying out maintenance work requires several years of experience with similar equipment.	Special tools, which are normally available to maintenance staff, are required to carry out maintenance work.
1	The cause of the fault can be easily and quickly identified by the control system and/or human senses.	Maintenance work can be carried out safely without special equipment and with normal carefulness.	No tools etc. needed to access the service area / no problems with visibility	The maintenance work can be carried out by a service technician with the usual skills.	Maintenance work can be carried out with the tools normally used by a service technician.

In addition to the above qualitative estimates, an estimate of the duration of each maintenance task and of the man-hours required is made. For corrective maintenance tasks, this time also includes the time needed for troubleshooting if the symptom observed in the operation of the machine does not directly indicate the cause of the fault. Based on this estimate, the labour costs for the maintenance personnel, and the value of the loss of production due to unavailability can be calculated. An example of a predictive maintenance analysis form completed for a single maintenance operation is Table 4.2.

Table 4.2. Example of a predictive maintenance analysis form. Explanation of abbreviations: SAF = safety, A = accessibility, D = difficulty, ST = need for special tools and T = time.

Maintenance task	Work procedure	Criticality						Proposals for improvement with justification
		Service frequency	SAF	A	D	ST	T (min)	Further information
Checking the air pressure in the tyres of a lorry.	Measurement with a tyre pressure gauge	Weekly	1	2	1	3	15	Checking the pressure in the inner tyre of a pair of dual wheels is difficult because a normal gauge does not fit the valve properly. Get valve caps that indicate the correct level of tyre pressure by colour, so that pressures can be visually checked daily.

It is not necessary to calculate an index or similar benchmark from the estimates made. In principle, all maintenance tasks that have been assessed in the most critical category from any point of view. For example, in the analysis form above, category 3 considering the need for special tools should be further discussed and proposals for improvement should be considered.

The maintainability analysis relies as much as possible on existing documents and previously conducted analyses, reducing the need for preparation. The experience gained from testing the method shows that the assessment on a three-point scale is quick. In addition to assessing the maintainability of the structure, the analysis will also check the content of the maintenance programme in general, i.e., whether the maintenance measures mentioned in the programme are relevant to the product in question. A separate assessment of the maintenance activities is somewhat difficult, because in practice several maintenance activities are carried out at the same time, so that, for example, dismantling of structures for reasons of class accessibility does not have to be done separately for each maintenance activity. However, this problem only hampers the estimation of the time needed for the maintenance work.

Case: Maintainability planning method

In the framework of the **RelSteps - reliability management in design research project**[4], a case study was carried out in cooperation with Kalmar Ltd, where the maintainability analysis method developed at VTT was tested and further developed based on the experience gained.

The analysis considers both preventive maintenance (service) and corrective maintenance (fault repair) aspects. For the analysis of predictive maintenance tasks, the maintenance programme of a previous similar product was used, as the new maintenance programme was not yet available. The corrective maintenance review was based on the failure, impact, and criticality analysis of the previous generation of products, from which the most likely items were examined. Using existing documentation, the amount of work required to prepare the analysis was minimised.

Cargotec has paid attention to maintainability in the past, for example in the form of maintainability surveys. However, in this case the machine is already at least at the prototype stage, and many design solutions have been agreed that it is no longer possible to change them. The analysis was particularly useful from the point of view of the maintenance representatives, as their opinions were considered to a greater extent than usual. Moreover, many of the improvements identified were such that they could be implemented with very little investment.

Key lessons

- Maintainability is often not considered until very late in the product development process. It is understandable that a product is designed primarily for productive work, but especially for machines that have been in use for years or decades, maintainability also starts to have an impact on productivity.
- A case study with Cargotec found sites where maintainability was a challenge, but where remedial work was very cost-effective as the product was still in the design phase.
- With very small and inexpensive changes, it was possible to make a significant reduction in the downtime and resources required to service the product, which over the long term will have a significant impact on the lifecycle costs of the product.

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[4] https://en.wikipedia.org/wiki/Structured_analysis_and_design_technique

4.4. RAMS MANAGEMENT IN A DELIVERY PROJECT

Helena Kortelainen, Tero Välisalo and Toni Ahonen

Introduction

RAMS programmes for procurement and delivery projects emphasise the interaction between supplier and customer. Smooth collaboration is particularly important when the delivered product is tailored or designed entirely to meet the customer's specific needs. The RAMS programme ensures that dependability and safety requirements are fully incorporated from the very beginning of the life cycle, and that these requirements guide the design and realisation of the system at all stages of the process. When the design is based on commonly shared and understood requirements, contract partners avoid situations where safety and dependability deficiencies are identified during acceptance or commissioning inspections or after the deployment. Compliance with the requirements can be monitored over an extended time after the commissioning and it is possible that sanctions for non-compliance or shortcomings may result in sanctions for the manufacturer for years after delivery.

The RAMS process aims to ensure that the resulting system meets the customer's requirements for system reliability, availability, maintainability, and safety. In addition, the RAMS process provides the user with the input data for planning the maintenance of the system.

Setting RAMS targets

The setting of RAMS targets is a key task of the concept design phase (e.g., EN-60300-3-4). In practice, the information available at this phase often does not allow a detailed or qualitative definition of dependability requirements. Instead, it is important to provide guidelines for dependability design and to influence key parameters early enough in the design process.

Dependability requirements can be set for all aspects of dependability – reliability, maintainability, recoverability, and maintenance support - and can be qualitative or quantitative in nature. As product development and engineering progress, the objectives will be refined and further defined. The qualitative objectives will also be used to define performance targets in quantitative terms. Typical qualitative requirements include:

- A failure of a subsystem must not stop the main process.
- A single fault must not interrupt the operation of the system (single fault criterion)
- The reliability of critical parts of the process must be ensured by condition monitoring.
- It must be possible to carry out the repair by replacing the repairable parts.
- The fault, if any, must be detectable.

Typical quantitative reliability requirements include:

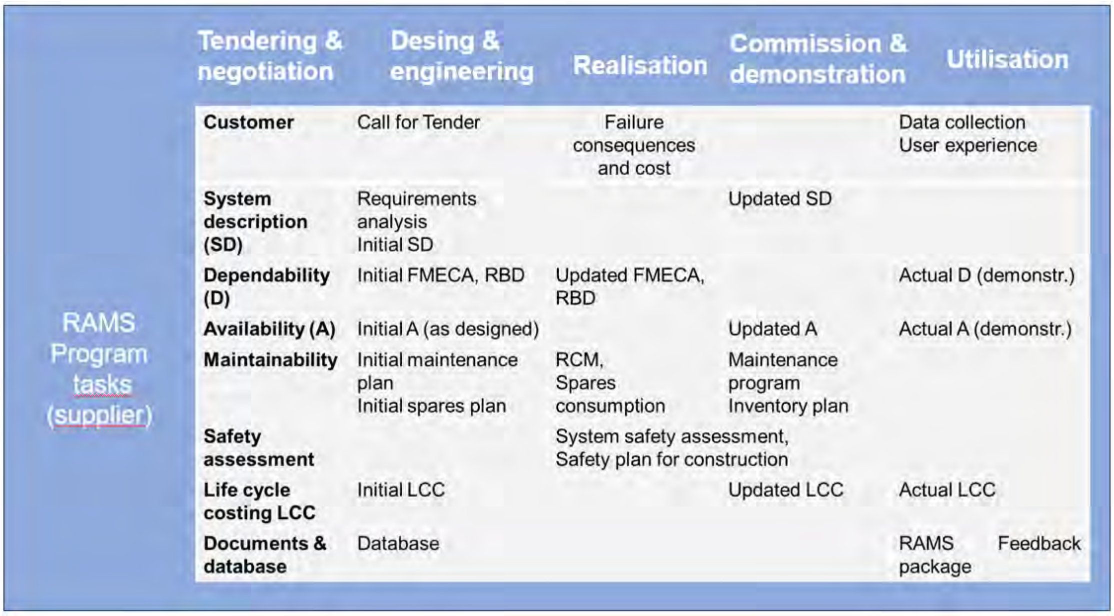
- average availability (in period X) A ≥ 0.9999,
- mean (operating) time between failures MTBF ≥ 40.000h,
- maximum active corrective maintenance time ACMT ≤ 5h, and
- mean down time MDT ≤ 7h.

Typical customer requirements relate to the implementation and performance of the tailored system, such as capacity, reliability, availability of the system and its components, and to the life cycle costs. The customer may also specify what RAMS assessments will be performed in the delivery project, how the results will be reported and what validation and verification methods will be used to demonstrate compliance.

In addition to the customer needs and requirements expressed in the call for tenders, the impact and severity of different failure types on the customer is important baseline information. The consequences can be related to the operation of the system, human safety, the environment, or the cost of repairing and mitigating the consequences of the failure. For this reason, the RAMS process is iterative and proceeds in discussion with the customer.

Case: Developing the RAMS process

The RAMS programme looks at safety and dependability issues in the context of the system life cycle. The RAMS programme typically also involves collecting feedback on the deployed system. Figure 4.5 outlines the RAMS process tasks for a delivery project.



RAMS Program tasks (supplier)		Tendering & negotiation	Desing & engineering	Realisation	Commission & demonstration	Utilisation
	Customer	Call for Tender		Failure consequences and cost		Data collection User experience
	System description (SD)	Requirements analysis Initial SD			Updated SD	
	Dependability (D)	Initial FMECA, RBD		Updated FMECA, RBD		Actual D (demonstr.)
	Availability (A)	Initial A (as designed)			Updated A	Actual A (demonstr.)
	Maintainability	Initial maintenance plan Initial spares plan		RCM, Spares consumption	Maintenance program Inventory plan	
	Safety assessment			System safety assessment, Safety plan for construction		
	Life cycle costing LCC	Initial LCC			Updated LCC	Actual LCC
	Documents & database	Database				RAMS package Feedback

Figure 4.5. RAMS process tasks for a delivery project.

The call for tender is a starting point for a requirements specification that will support the initial (preliminary) system description. The RAMS analyses are based on the system description. The main descriptions supporting the analysis are alongside the actual design documents:

- *functional description/specification (FDS), and*
- *technical description/specification.*

The functional and technical system descriptions complement each other. The functional description (e.g., SADT or IDEF0) divides the system into functional parts starting from the functions that are required from the system. The technical description, on the other hand, specifies the implementation method - the machines, equipment, components, and parts needed - to achieve this functionality.

The RAMS process for the delivery project (Figure 4.5) also summarises the main tools of the RAMS process. These methods and tools are described either in other chapters of this book or in common textbooks:

- FMECA (see Chapters 1.3 and 4.2),
- Reliability Block Diagrams (RBD, see e.g., Hoyland & Rausand, 2009),
- maintenance planning using the Reliability-Centered Maintenance (RCM, see e.g., Moubray, 2001),
- safety assessments (see Chapter 1.3); and
- Life cycle cost considerations (LCC) (see Chapter 1.5).

The results of the various RAMS analyses provide feedback on the success of the planning against the objectives set, while indicating the need for changes to the plans. The process is iterative, and the initial reviews and results will be worked out and refined in stages as the project progresses from the conceptual design during the bidding and negotiation phase through design and implementation to the system to be delivered. The role of the customer is crucial in determining the system requirements and in setting priorities by evaluating failure consequences and costs, and by contributing to the life cycle costing process.

Key lessons

- RAMS process aims to ensure that the resulting system meets the customer's requirements for system reliability, availability, maintainability, and safety.
- RAMS process requires a profound requirements definition and system description, as well as the ability to apply reliability engineering methods.
- RAMS process is iterative and proceeds in collaboration with the client.

4.5. NOVEL TECHNOLOGIES IN LIFECYCLE MANAGEMENT

Jyri Hanski, Helena Kortelainen and Tero Välisalo

Introduction

Technological solutions support lifecycle management at many stages. Examples include smart devices and sensors, tools for inspection, diagnostics, prognostics, simulation and tracking, drones, augmented and virtual/augmented reality and cloud-based tools (e.g., Holgado et al., 2016). Table 4.3 illustrates some applications of advanced technological solution in life cycle management tasks.

Table 4.3. Technological solutions for life cycle management (adapted from Holgado et al., 2016 and Rasheed et al., 2020)

TECHNOLOGY	APPLICATIONS IN LIFE CYCLE MANAGEMENT
Smart devices	Support operator in the field. Remote access to experts and to the technical item.
Smart sensors	Collect on-line data on the items and their use environment. Identify and report any malfunction of system or equipment. Remote configuration, calibration, and control of an item.
Intelligent asset information systems	Fast and flexible scheduling. Management of maintenance activities
Digital twins	Planning for reliability, maintainability, and maintenance support in the design stage. Optimising system performance. Predictive maintenance and scheduling. Real-time monitoring and control.
Inspection tools	Detect equipment or system failures. Indicate equipment or system under-performance.
Diagnosis and prognosis tools	Online fault diagnostics and root cause identification. Estimate the remaining useful time (RUL) of the system, equipment of component based on current condition and projected use. Support proactive maintenance strategies.
Cloud-based tools	On-demand network access to a shared pool of information resources
Simulation tools	Compare the effects of different maintenance policies. Compare different scenarios for equipment deterioration and failure.
Location and tracking tools	Support fieldwork with component and equipment identification. Store and link maintenance data to the right item for the traceability of past actions. Enable geo-localisation.
Augmented and virtual reality	Support man/machine or man/man exchange of information. Deliver guidance and remote advice for maintenance intervention execution

Technological solutions have been widely deployed in different industrial sectors to support lifecycle management. However, there are major challenges in deployment these technologies and determining their real benefits and costs. The implementation of technological solutions often involves many stakeholders, such as the technology developer, the service providers, and end-users. Successful deployment also requires a simultaneous update of working practices and processes (Brynjolfsson & Hitt, 2003).

Delivering guidance to the field operations

Augmented Reality (AR) and *Virtual Reality (VR)* remote support solutions are considered one of the most promising technologies to support maintenance (e.g., Palmarini et al., 2018). In AR solutions, virtual objects are added to the real world, while in VR solutions, computer-generated environments are used to simulate system interactions (Milgram & Kishino, 1994; Gavish et al., 2015). AR and VR technologies are used to train maintenance tasks, support maintenance tasks and exchange information, integrate information into the work environment, and reduce the cognitive load of workers in demanding environments. AR and VR solutions are widely used in the aerospace industry and in the lifecycle management of manufacturing plants and power grids for assembly, disassembly, repair, inspection, troubleshooting and training tasks, among others.

AR or VR solutions are not yet widely deployed. Remote support solutions are seen to have many benefits such as bringing expertise to the field and saving time spent on mobility, remote support from other maintenance workers, ensuring work safety, automating documentation, and bringing instructions into the field of vision in field conditions (Kortelainen et al., 2020).

Case: power failure troubleshooting

In this case study, a remote support solution was used to troubleshoot a power outage in a residential building. The applied solution enables voice and video, chat, image processing, data exchange, ticketing, AR, support for mobile devices and smart glasses, among other things. In the experiment, all the lights in a residential building suddenly go out for no apparent reason. The resident contacts an expert in the electricity company via a mobile app. Some electrical appliances, such as the electric heating and the streetlights on the adjacent street, still work. Therefore, the problem can be isolated to the residential building and its specific electrical circuits. The expert estimates that the problem is related to the building's residual current circuit breaker. The function of the residual current device is to protect users and equipment from electrical shock. Exposure of an electrical appliance to moisture is a typical failure mode for a circuit breaker.

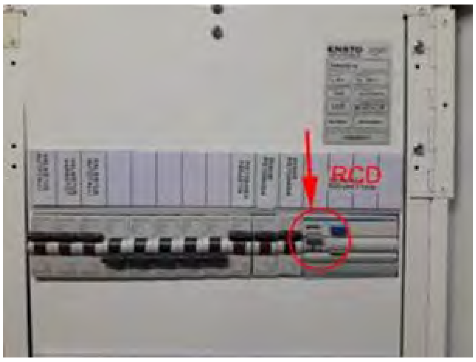


Figure 4.6. Electrical switchboard and residual current device (RCD) marking.

To solve the problem, the expert asks the resident to take a picture of the house's electrical panel and send it to him using the app. On the picture the expert marks the location of the residual current circuit breaker and instructs the resident to turn the breaker to the "on" position. When the switch is in the correct position, the lights return on for a second, after which the circuit breaker is reactivated. The root cause of the problem still exists and needs further inquiry.

The expert asks further if there are any electrical appliances that are susceptible to moisture. The resident tells that the only electrical appliance is a car engine heater, but it is not currently in use. However, the expert asks to send a picture of the heater. The heater cable has fallen into the snow and the resident notices that the timer has been activated at the same time as the power cut.

Figure 4.7. The heating cable has come loose from the connector.

The expert advises to disconnect the heater cable and then try putting the circuit breaker back in the "on" position. this time the lights stay on once lit. The expert advises to dry the heater cable properly before the next use to avoid the problem occurring again. The problem has been solved and the troubleshooting efforts are recorded in the remote support system with photos and written comments and will be available for subsequent similar service requests.

This case presented a potential remote support solution for the consumer market, where expert help is quickly made available to clients through AR and remote access. Electricity supply companies and service providers have expertise and knowledge of residential electrical solutions and an experience of potential incidents. The remote service enables the establishment of a database of incidents and their solutions, and the database is updated and expanded by every novel service request.

The need for remote support solutions is growing as smart grids and energy systems become more widespread. Smart grids have interfaces to electrical vehicles and other appliances, which may include demand response[5], renewable energy generation and other related systems. In a complex network, new failure modes appear, and maintenance personnel need new skills and sources of information. Expertise is dispersed across multiple organisations and across geographic locations. These issues are leading to an increasing need for remote support, which can be organised either from service centres or decentralised through local organisations.

Key lessons

- Key technologies to support lifecycle management include but is not restricted to smart devices and sensors, intelligent maintenance information systems, digital twins, tools for inspection, diagnosis, prognosis, simulation, locating and tracking, augmented reality (AR), virtual reality (VR) and cloud-based tools.
- The readiness to adopt technological solutions differ between industries and actors within an industry. Also, the consumer market and housing are in the middle of a change. An example of this is smart grids that require a variety of new competencies from the maintenance personnel than the traditional grid.
- Remote support solutions can deliver significant benefits in terms of lifecycle management. An example of an application is troubleshooting support.

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[5] Demand response involves shifting or shedding electricity demand to provide flexibility in wholesale and ancillary power markets, helping to balance the grid. https://www.iea.org

4.6. ASSESSING COSTS AND BENEFITS AS PART OF THE INTRODUCTION OF A NEW TECHNOLOGY

Helena Kortelainen and Antti Rantala

Introduction

Investment appraisal is supported by several rational and analytical investment, profitability and costing methods and applications that support unique and specific decision-making in both business and the public sector. For example, life cycle costing emphasises the assessment of the entire life-cycle costs of a product or service (see Chapter 1.5). Cost-benefit analysis, on the other hand, is a tool for societal decision making, which is used to determine the broad benefits of implementing a given project or a planned programme. Cost-benefit analysis thus seeks to determine whether the benefits of a planned project outweigh the costs of implementing it (Fuguitt & Wilcox, 1999; Boardman et al., 2006). Cost-benefit analysis has also been applied, for example, to the evaluation of security investments or technologies due to their societal impact (Räikkönen et al., 2013).

Cost-benefit and cost-effectiveness analyses

Cost-Benefit Assessment (CBA), as the name suggests, encompasses benefits and costs to determine the net benefit. The reference is usually the status quo. Costs and benefits may be unevenly distributed among several stakeholders, so the analysis must be carefully limited to those for whom the benefits and costs of the project are relevant (e.g., Boardman et al., 2006). The Defence Forces Project Guide (Kosola, 2012) defines the benefits as follows:

- *Benefit is the added value that a successful project brings. The benefits are often monetary or operational, but in defence projects the benefits are often difficult to measure, such as increased combat effectiveness of wartime forces or improved operational conditions. Defence credibility, public opinion and other intangibles can also be benefits that can be achieved from a project.*

Case: Examining qualitative characteristics as part of technology choices

Estimating the benefits is often very challenging. For example, when preparing a technology acquisition, the starting point for cost-benefit modelling can be a situation where the benefits of alternative solutions can be estimated to be the same or close to the same. In this case, the best option in terms of benefit-cost ratio can be selected by life-cycle costs and other qualitative factors that influence the decision. In the PVTO2017 project of the Defence Research Programme (Laarni et al., 2020), one of the objectives was to evaluate the benefits and costs of alternative sensor systems for monitoring combatant performance. For the evaluation of costs and other characteristics, the aim was to describe the solution alternatives as similar in performance as possible and thus comparable. The options to be examined are:

- Option 1: A system based on the use of a consumer product,
- Option 2: A system based on a specific product, and
- Option 3: Commercial system.

The cost comparisons were carried out with an MS Excel spreadsheet tool that was developed to calculate the life-cycle costs according to IEC 60300-3-3 of the system options. Cost data were obtained from suppliers and manufacturers' websites. In the cost analysis, a variable is the number of users, so that the calculation can be performed with the desired usage scenario. The MS Excel tool for the cost calculation is used to enter the data of the sensor solutions to be considered, and then the results can be compared with different user numbers and by several financial criteria.

In addition to life-cycle costs, the cost-benefit model allows the qualitative variables of alternative solutions to be examined and reported in a consistent and illustrative way. The analysis has included factors that are key requirements for the intended use of the measurement system under consideration. The qualitative characteristics to be assessed are:

- ease of use,
- relevance of the measured data,
- the reliability of the measurement data,
- availability of maintenance and spare parts,
- maintainability of the sensor system,
- information security of the data exchanged in the system, and
- integration with other information systems.

The qualitative characteristics of the Options 1-3 were assessed in an expert workshop. A consensus rating on a scale of 1 (very poor) to 5 (very good) was established for each assessment item. The results are shown in the spider diagram (Figure 4.8). As the project team wanted to see all influencing factors in the same graph, the "LCC benchmark" was added to the spider graph. LCC benchmark was calculated by scaling the 10-year life cycle costs of the different solutions on a scale of 1 to 5. The scaling was done in such a way that a low LCC means a high LCC and a high LCC means a low LCC.

The three options (1-3) do not have any significant differences in the comfort of use. These options differ only slightly in terms of data relevance, data reliability and maintainability. The most significant differences arise in the assessment of availability of maintenance and spare parts and integration. The consumer product-based solution (Option 1) was rated best in terms of availability of maintenance and spare parts, as its use does not require that some consumables are kept in stock and regularly distributed. The commercial system (Option 3) tested in the study was based on the use of the supplier's cloud service, which raised security concerns. The cost of a system based on a specialised product (Option 2) is higher than the other two options. This is due to both the cost of consumables and the data exchange requirements of the product.

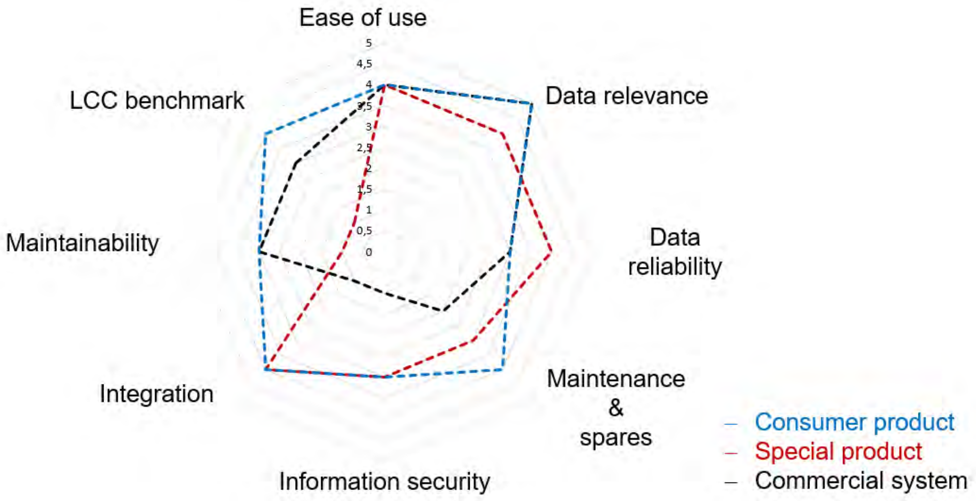

Figure 4.8. Results of the expert evaluation on the qualitative characteristics of the different solutions and the cost benchmark compiled in a MS Excel spreadsheet.

The life cycle costing is characterised with uncertainties, such as the lifetime of the electronic components. However, the resulting uncertainty is present for all options and therefore does not significantly affect their ranking. Other uncertainties included the need to use different consumables such as patch electrodes, which is highly dependent on the operating scenario. It should be noted that development is very fast, sensor prices change rapidly, and new features are constantly being added.

Key lessons

- A cost-benefit analysis aims to determine whether the benefits of a planned project exceed the costs of implementing it.
- Costs and benefits may be unevenly distributed among several stakeholders.
- Estimating the benefits is often very challenging, so the easier starting point is a situation where the performance of alternative solutions is similar.
- It is often useful to consider both economic and qualitative factors in parallel.

4.7. SELECTION OF INVESTMENT OPTIONS

Minna Räikkönen, Tero Välisalo and Helena Kortelainen

Introduction

Investment decisions always involve different perspectives, actors, and objectives, which may also conflict with each other. The total number of investment proposals from business units or business areas usually exceeds the available investment budget. Therefore, companies must prioritise their investment needs. Decision-makers also need to balance short- and long-term objectives and consider both financial and non-monetary factors and values. The methodology and related tool developed in the MittaMerkki-project[6] support decision-makers to systematically assess the impact and significance of investment options.

Case Jyväskylän Energia

The case study of the MittaMerkki project (Räikkönen et al., 2017) investigated and developed an investment comparison method for replacement investments in different infrastructure networks to support decision-making. Jyväskylän Energia manages electricity, district heating, water, sewerage, and stormwater networks in the Jyväskylä area in central Finland. A key challenge is how to decide where to invest across different networks within the limited investment budget while in tandem ensuring that the investments made maintain or improve the capability of the whole company to serve its customers as efficiently as possible. Network infrastructures usually have a very long lifetime - several decades - which means that it is not always sound to apply the payback period as a KPI when assessing the profitability of replacement investments. For this reason, a method by which the decision-makers could define an investment portfolio to reduce overall risk in the most cost-effective manner was developed.

In practice, replacement investments always aim to reduce the risk of infrastructure breakdown, system failures and disruptions and to maintain the required level of service. The risks may relate to human or environmental safety, the functionality of network assets, the security of supply for customers or, if the risks occur, they may have a direct economic impact on the company's operations and business. Reducing risks and ensuring service levels are objectives that are difficult to assess using conventional investment appraisal methods. The availability of critical infrastructure and networks that are necessary for society also has non-monetary values that need to be considered in investment decision-making.

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[6] Mittamerkki, see
https://projectsites.vtt.fi/sites/mittamerkki/www.vtt.fi/sites/mittamerkki.html

In Jyväskylän Energia, decisions related to replacement investments are made annually. All investment proposals are important, so selecting an annual investment portfolio that matches needs means that some proposed investments will be carried over to later years. In the MittaMerkki -project a methodology to compare the risk management effects of investment proposals and use the residual risk to optimise an investment portfolio that reduces risk in a cost-effective way was developed. In addition to the methodology, an MS Excel application was developed to demonstrate the methodology.

Building a risk matrix

The starting point for the risk analysis was a risk matrix, according to which risk can be defined by two variables. These variables are the probability of the occurrence and the severity of the consequences if the risk occurs (see Chapter 1.6 Risk management). The risk probability was assessed on a five-point scale. The risks identified are very diverse and it is therefore difficult to assess their consequences in a consistent way. Therefore, the risk consequences are evaluated from four different perspectives, namely:

- Consequences for human and environmental safety.
- Consequences for customers.
- Economic consequences, i.e., the cost that the company will need to pay if the risks realise.
- Asset functionality consequences, including all consequences related to a network's dependability (e.g., availability and capacity of spare parts).

A five-point scale was used for each of the four consequence categories. The economic consequences were valuated in monetary terms, while the other categories of consequences were assessed in qualitative terms. For example, the consequences for customers were assessed by determining the number of customers affected and the duration of the consequences. Based on this information, an expert judgment using a scale of 1 to 5 was made. The developed risk matrix was implemented in an MS Excel application (Figure 4.9).

Length of the investment project 1 year

Figure 4.9. Risk identification and assessment (Räikkönen et al., 2017)

Calculation of the risk index

When assessing risks, the identified risks need to be quantified. In our case study, the risk probability and consequence data collected and presented in the risk matrix were used to calculate a measure of risk magnitude, the risk index. The risk index is a numerical value that represents the criticality of the risk and can be used when prioritizing risks based on the urgency with which they need to be addressed. In general, the risk index is calculated by multiplying the values of the risk probability and consequences. Since the risk consequences are evaluated from four different perspectives, the consequence factor used in the calculation is obtained by calculating the arithmetic mean of the results of the consequence evaluations. If the consequences vary widely between categories, a weighted average can be used instead of the arithmetic average. Weighting factors are determined in our study using the *Analytical Hierarchy Process (AHP)* method developed by Saaty (1980) (see e.g., Niskanen, 1986).

Often a single investment reduces several risks. If the risks are independent, the risk index for the investment is the sum of the individual risk indexes of four categories. In practice, the risks identified are interdependent which means that the summing can cause excessively high-risk indexes for investments that affect more than one risk. In the calculation, this error is corrected by considering a percentage that reflects the interdependence of the risks.

Risk reduction and investment portfolio selection

At this step of the developed method, an estimate of the change in risk level achieved by the investment was determined. This was done for each investment selected for the assessment. The estimate was generated by comparing the risk index of the current situation with the situation after the investment has been made (Figure 4.10).

As the investment budget cannot be exceeded, the available funding must be allocated in the most efficient way. The cost-effectiveness of the investment proposal in terms of risk reduction was determined by comparing the change in the risk index with the investment cost. In this way, investments of different sizes and in different networks were made comparable. The optimization problem of a limited budget was solved by simulating the residual risk that would remain if all investments in the portfolio are selected to be made.

Total cost of investment proposals: 2 400 000 €
Investment budget: 1 000 000 €
Total cost of selected investment proposals: 955 000 €

Investment proposals

Selected invest-ments	Investment	Network	Inv. cost in the 1. year	Inv. cost in next years	Costs of aged network	Risk mitigation: Risk now	Risk after investment	Differen-ce	Rank	Cost of risk mitigation: €/point	Rank	Investment's proportion to: risk reduction	total cost	Rank	Select inv. to figures
☑	Change of medium voltage cabins	Electricity	25 000 €	€	500 €	586	5	581	4	43 €	2	8 %	1 %	3	☑
☑	Renewal of tranformer substation, Main street	Sähkö	50 000 €	€	2 000 €	586	4	582	3	86 €	3	8 %	2 %	4	☑
☑	Changing electrical enclosures	Electricity	15 000 €	€	€	580	1	579	5	26 €	1	8 %	1 %	2	☑
☑	Renewal of transformer substation, High street	Electricity	90 000 €	€	500 €	410	2	408	10	220 €	8	6 %	4 %	8	☑
☑	New pipes to area HS-40	District heat	45 000 €	€	€	257	5	252	12	179 €	5	3 %	2 %	9	☑
☑	Renovation of valves	District heat	95 000 €	€	€	433	2	432	7	220 €	8	6 %	4 %	7	☑
☑	Repair of the heat well	District heat	75 000 €	€	€	505	7	498	6	150 €	4	7 %	3 %	6	☑
☑	Renovation of pumping station	Clean water	310 000 €	€	5 000 €	1622	23	1599	1	194 €	7	22 %	13 %	1	☑
☑	Renovation of the waste water pumping station	Sewage	150 000 €	€	€	838	2	836	2	179 €	5	11 %	6 %	5	☑
☑	Renovation of clean water network in area EW-	Clean water	100 000 €	€	5 000 €	410	4	406	11	246 €	10	6 %	4 %	10	☑
☐	New medium voltage cabels	Electricity	320 000 €	€	500 €	35	4	31	15	10 418 €	16	0 %	13 %	15	☐
☐	New medium voltage cabels XX-032	Electricity	135 000 €	€	500 €	26	4	22	16	6 146 €	15	0 %	6 %	13	☐
☐	New pipes to area OT-41	District heat	60 000 €	€	€	131	5	126	13	474 €	11	2 %	2 %	11	☐
☐	Pipe renovial in city center	District heat	50 000 €	€	€									12	☐
☐	Sewage renovation in the area CC-065	Sewage	530 000 €	€	10 000 €									16	☐
☐	Renovation of clean water network in area EE-4	Clean water	175 000 €	175 000 €	15 000 €									14	☐

Figure 4.10. Interface for result table in the tool (modified from Räikkönen et al., 2017).

Key Performance Indicators (KPIs)

As shown in the result interface of the MS Excel tool above (Figure 4.10), in addition to the risk index also other KPIs (Key performance Indicators) can be calculated:

1. A risk reduction indicator that favours large investments that reduce several risks at the same time.
2. The cost per risk reduction point, which favours smaller investments.
3. Proportional cost and risk reduction – an investment can be considered cost-effective if it reduces risk more than its share of the investment budget.

The tool supports the decision maker

The objective of the KPIs and graphs was to provide information to the decision-makers about the investment options and their impacts. The KPIs (Figure 4.10) illustrate how each investment option can affect risk and which options are the most cost-effective. Although the method calculates the most cost-effective investment portfolio within the given objectives and constraints, its application requires judgement. The method only considers risk-related criteria, but of course, investment decisions can also be driven by other types of criteria, such as land use or urban planning requirements.

Key lessons

- Traditional investment appraisal is not well-suited to evaluating and assessing replacement investments that aim to reduce risk and maintain service levels. This risk may relate to human or environmental safety, the functionality of network assets, the security of supply for customers or, if realized, may have a direct economic impact on the company's operations and business.
- The developed method and related tool for assessing the importance and significance of replacement investments is based on a risk assessment before and after an investment.
- The cost-effectiveness of the investment proposal in terms of risk reduction was determined by comparing the change in the risk index with the investment cost. In this way, investments of different sizes and in different systems are comparable.

4.8. THE REPLACEMENT INVESTMENT PLANNING PROCESS

Pasi Valkokari

Introduction

The aim of this chapter is to describe an approach that can be used to plan maintenance development, especially when replacements investment options are being considered. A key part of this chapter are the criticality analysis and practical examples of how the criticality analysis has been used to achieve practical objectives.

The proposed process for planning the replacement investments is outlined in Figure 4.11.

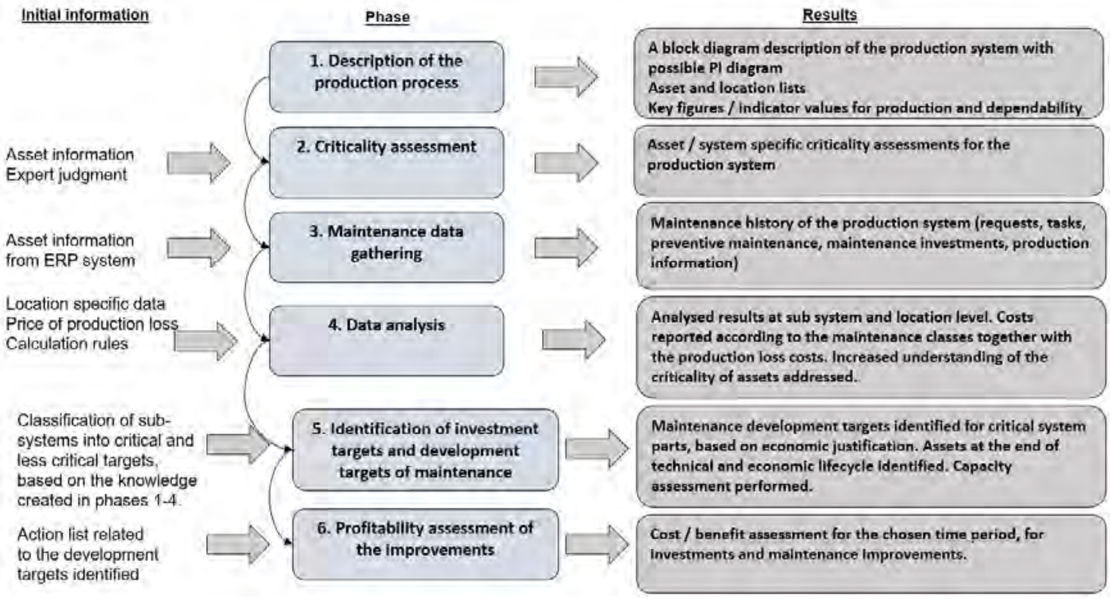


Figure 4.11. Example of the planning process for replacement investments

Practical examples

In practice, the approach described above has been applied, for instance, according to the target setting in the following case studies.

Example 1

The company has a production line, which lifetime wished to be extended for another ten years, while maintaining the current level of production efficiency. In this case, a criticality analysis of the production line was carried out with experts to identify the perceived critical points. The results of the criticality analysis were compared with the event data from the maintenance system, which showed that the results of the criticality analysis correlated closely with the actual maintenance events. This allowed to conclude that the expert assessments of the criticality of the equipment are quite reliable.

Once the criticality review was completed, the remaining life estimates of the equipment were judged with the experts. In this work, the equipment was treated according to its criticality category, moving from the most critical to the less critical equipment. This allowed to determine with sufficient accuracy the timing of the necessary replacement investments and thus to make a replacement investment plan that allowed to manage the lifetime costs of the existing production system. To compare the most relevant replacement investment proposals, life cycle cost analyses were also executed to assess the profitability of the replacement investment options.

One major result of the criticality review was the discovery of a significant production bottleneck. In this respect, it was found that if the bottleneck is removed through development investment, it is possible to achieve a significant increase in capacity for a product for which there is demand. on the markets. Different productivity scenarios were calculated resulting in development investment proposal, which led the company to positive decision concerning the proposed development investment.

Example 2

The foreign-owned factory, operating in Finland, aimed to double its production volume as new markets opened for its product. The factory therefore needed to justify to the foreign owner which parts of the production system needed to be invested in in to maintain the delivery performance when facing increase in demand and production volumes.

At this industrial site, high quality data was not available from the computerized maintenance management system, so the investment plan was based only on a criticality analysis made by experts. In the expert judgement phase of the analysis work, the impact and cost of production disturbances caused by potential failures and estimates of the remaining lifetime of the equipment, were highlighted.

These results made it possible to identify the necessary investments and to justify to the owner the expected cost implications of possible production changes if no investment was made.

Example 3

The foreign-owned process site, operating in Finland, had been in operation for 15 years. During this period, there had been no significant interruptions in production. However, the plant's equipment had begun to age as it had been running. In addition, the raw material used in the process was abrasive to the equipment, so the quality requirements for the materials used in the components of the production process were high. As a result, the delivery time for many spare parts could be up to six months.

The situation described posed a significant risk to the continuity of the process's operations. While there was demand for the product, the factory had identified a scenario where a production interruption of more than three days would cause customers to seek alternative suppliers. Consequently, demand for their product would cease and the continuity of the factory would be jeopardised.

The aim was therefore to set up a review to ensure the availability of critical spare parts. The quality of the data stored to the computerized maintenance management system was insufficient, the critical spare parts management programme was based on a criticality check carried out with the help of experts. An essential part of this was to identify not only the criticality of the components but also their delivery time. This provided the factory with valuable additional information for managing critical spare parts and thus their delivery performance.

Key lessons

- Criticality analysis can be used for several different objectives in the management of production assets.
- Currently, data from maintenance information systems is rarely available with sufficient accuracy to be used to develop asset management measures. This is not to say that the collection and use of maintenance data is not important, but that this data collection needs to be well designed to allow the data and analysis to be used without a separate criticality review.
- Experts with a good knowledge of the production system (e.g., operators, maintenance staff and supervisors) are able to assess with a high degree of confidence the critical components of the system and the consequences of their failures.

4.9. CIRCULAR ECONOMY BUSINESS MODELS

Jyri Hanski

In addition to recycling and improving resource efficiency, other forms of circular economy include the use of renewable materials, the reuse of products, increasing the productivity of assets through sharing platforms, providing products as a service, and extending product life cycles. The wide range of circular economy business models and examples are summarised in the table below.

Table 4.4. Circular economy business models (Valkokari et al., 2019)

BUSINESS MODEL	DEFINITION	EXAMPLE
Use of renewable materials	Non-renewable materials and products made from them will be replaced by equivalent renewable, recyclable, or biodegradable materials and products.	Pine oil-based diesel is made from a by-product of pulp production and replaces fossil-based diesel as a vehicle fuel.
Product reuse and resource efficiency	The aim is to find value in all material flows, including waste, used products and production side streams.	Litter and manure management services for stables. The litter needed by stables is delivered and the accumulated manure is collected for use in a local power plant.
Increasing asset productivity through sharing platforms	The sharing platform connects product owners and potential users. Sharing platforms increase the uptake of products and reduce the need to manufacture new products.	The platform solution connects production, sales, distributors, and users. Real-time sales forecasting guides production, reducing both material waste and availability problems.
Providing products as a service	The product manufacturer retains ownership of the delivered product. The manufacturer thus has an incentive to optimise the life cycle costs and use of the product.	The benefits of the energy renovation service are shared between the service provider and the customer. In addition to reduced energy costs, the customer benefits from not having to make a one-off investment.
Extending product life cycles	Extending the life of a product in its original use maximises the value of products over their lifetime.	Products or assets that become redundant are used for new investments and spare parts and sold outside the company.

It should be noted that often, putting circular economy principles into practice also requires the network to involve new actors. This is particularly important at the end of the first operational phase of equipment and systems. Change requires innovative actors, approaches, and aware users who extract the maximum economic benefit from circular economy principles.

Key lessons

- The circular economy involves a wide range of strategies to extend, narrow and close material cycles.
- Key circular economy business models include the use of renewable materials, product reuse and resource efficiency, increasing asset productivity through sharing platforms, providing products as a service, and extending product lifecycles.
- The transition to circular economy models requires innovative actors, policies, and aware users.

4.10. LIFE CYCLE COST MODELLING: THE CASE OF POWER SUPPLY

Helena Kortelainen and Minna Räikkönen

Introduction

VTT has implemented several life cycle costing and cost-benefit analysis models and demonstrated the calculation in MS-Excel environment. This chapter describes in more detail the life cycle cost model of a disturbance-free power system, and the LCC assessment has been implemented as part of the EU-funded SustainValue project (Uusitalo et al., 2015; Panerese et al., 2014). The battery back-up systems are necessary to guarantee 24/7operation of critical devices also in any failure situations of the electrical mains network. Battery back-up DC power supply system solutions are being used in many power plants and stations, substations, and other locations, including uninterrupted power supply of process automation. The use of new forms of energy generation, such as wind and solar power, also requires power continuity. The aim of the life-cycle cost modelling was to create a tool that would allow the supplier and the customer purchasing the system to have a common understanding of the costs and benefits of using the product. The case study was carried out in a series of workshops to assist the case company in understanding, developing, and applying the new value proposition and sustainable business model.

LCC model implementation

Defining the cost structure

The cost structure includes all cost factors or variables that are relevant to the cost of the system's planned lifetime. The cost structure was defined in collaboration between the company's experts and researchers. The cost structure was considered hierarchically, starting with broad categories which were refined as the work progressed. Table 4.5 gives an example of the cost categories and cost drivers identified and their associated variables. Cost drivers can be input values for the LCC calculation model as such (e.g., purchase price) or they may require detailed calculations (e.g., energy consumption or production). The third level of the cost structure represents the variables used to calculate the cost factors.

Table 4.5. Cost structure of an uninterrupted DC power solution.

COST CATEGORY	COST FACTOR	COST VARIABLE
Acquisition	Acquisition cost	
	Installation cost	
Preventive maintenance	Preventive maintenance tasks/year	
	Cost/task	Hours of work & Cost/h & Spare parts and other accessories
Corrective maintenance	Corrective maintenance tasks/year	Mean time between failures (MTBF) Batteries: temperature profile at the place of use, life expectancy, effect of temperature on lifetime.
	Cost/task	Hours of work & Cost/hour & Spare parts and other accessories
	Consequential costs/failure	Cost of unavailability/h
Energy	Electricity consumption/year	Electrical load, Efficiency & Hours of use/year & Need for air conditioning
	Electricity production (e.g., wind or fuel cells)/year	Electrical load, Efficiency & Hours of use/year & Fuel consumption/h
	Electricity transmission fee/year	
Unavailability	Unavailability time/year	
	Unavailability cost/year	
Disposal	Number of components disposed/system lifetime	
	Cost/disposal	
Basic calculation parameters	Economic parameters	Electricity price/kWh, Unavailability cost/h, Discount rate & Fuel prices
	Other parameters	Power factor (default) &need for air conditioning (default)
Description of the studied system (customisable features)	Use time	Design lifetime & Hours of use/year
	Use environment	Required electrical load, Number of outages/year, Average duration of an outage/h & Temperature profile

The next step in defining the cost structure is to define the mathematical functions for the cost variables. These functions can be very complex and require specific application expertise.

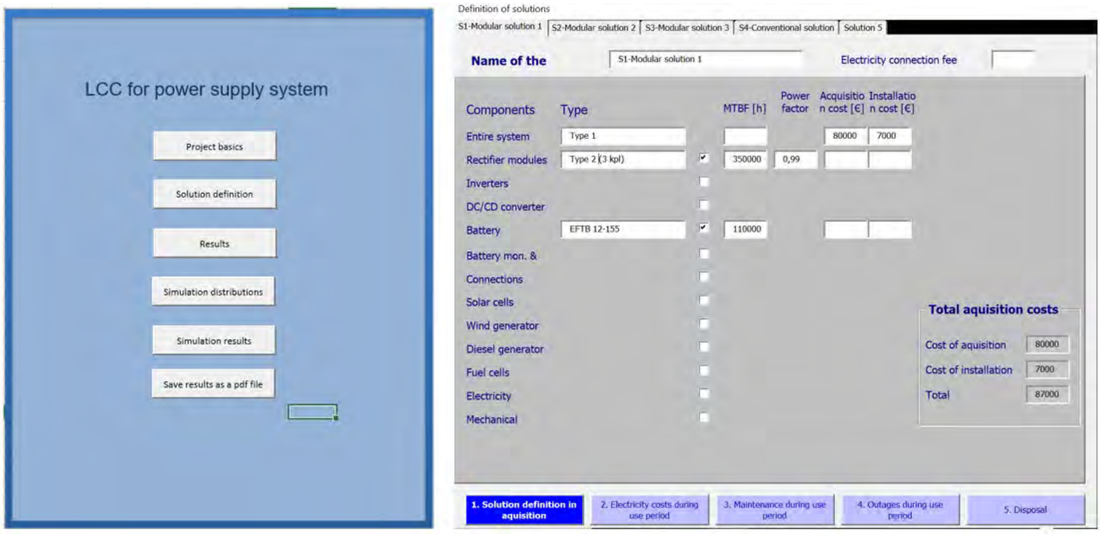
LCC model – gathering data

The cost model still requires the collection of related technical and cost data. Particular attention must be paid to the quality and reliability of the data. Some of the data required for the calculation are very easy to gather (e.g., fuel prices) and some are very specific (e.g., temperature profile of use environment). In our LCC case, the equipment manufacturer had a large amount of component-related data in its databases. Information on maintenance needs and operating environments was supplemented by expert judgements and interviews with both supplier and user representatives. Price information was obtained from public sources.

The LCC calculation is forward-looking, so there is always a high degree of uncertainty about price developments. Sensitivity analysis is used to assess the impact of data uncertainty on the results. In this case, the uncertainty is assessed by Monte Carlo simulation integrated in the LCC calculation tool.

LCC model - prototype in MS Excel environment

LCC calculation tool was implemented using MS Excel 2010. The Excel was chosen as the platform because the spreadsheet program is in common use and therefore does not require IT investment. Excel supports well the required calculations, and the application can be implemented with a reasonable amount of work and no additional training is required. The input data is provided through input pages in Excel VBA and the user interface facilitates the use of the tool in customer situations (see following figures).



Name of the S1-Modular solution 1

Electricity connection fee

Components	Type		MTBF [h]	Power factor	Acquisition cost [€]	Installation cost [€]
Entire system	Type 1				80000	7000
Rectifier modules	Type 2 (3 kpl)	☑	350000	0,99		
Inverters		☐				
DC/CD converter		☐				
Battery	EFTB 12-155	☑	110000			
Battery mon. &		☐				
Connections		☐				
Solar cells		☐				
Wind generator		☐				
Diesel generator		☐				
Fuel cells		☐				
Electricity		☐				
Mechanical		☐				

Total aquisition costs

Cost of aquisition	80000
Cost of installation	7000
Total	87000

Figure 4.12. User interface and example data entry page for the case LCC model.

The LCC model allows a comparison of five different application solutions. The data entry page shows an example of how to enter an acquisition price. At the same time, the components of the system are selected, and technical and financial information related to the selected components is entered.

LCC model - calculation results

In the case LCC model, expected annual costs, life cycle costs, discounted life cycle costs and cash flow were selected as economic indicators. The results are reported in both tabular and graphical formats, examples of which are given below.

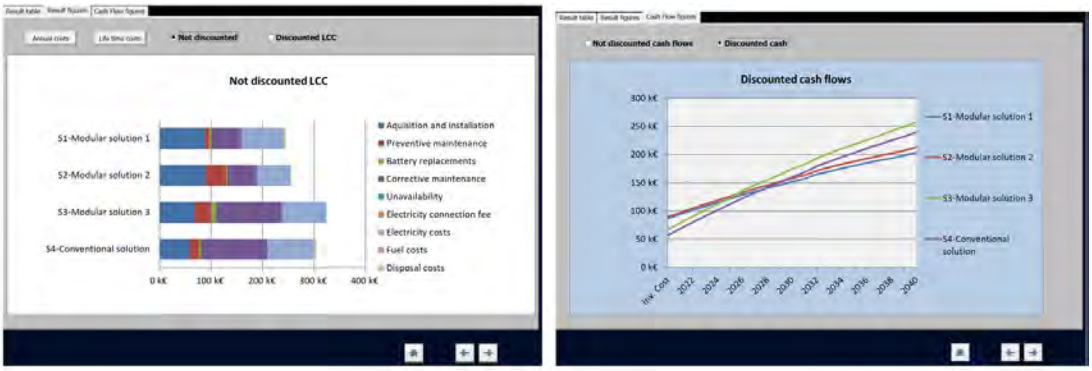


Figure 4.13. LCC model result graphs – some examples.

Uncertainty assessment using sensitivity analysis

The sensitivity analysis has been carried out using Monte Carlo simulation. The sensitivity analysis allows the decision maker to estimate, for example, how much a doubling of corrective maintenance costs would affect the profitability of the investment. For the sensitivity analysis, the user defines distribution curves for the desired parameters. A graphical tool can be used to define the distribution. A normal distribution and a Weibull distribution are available. For some numeric input parameters (e.g., number of maintenance tasks/year) only Poisson distribution is available. The input page for the sensitivity analysis parameters and an example calculation are shown in the following figure.

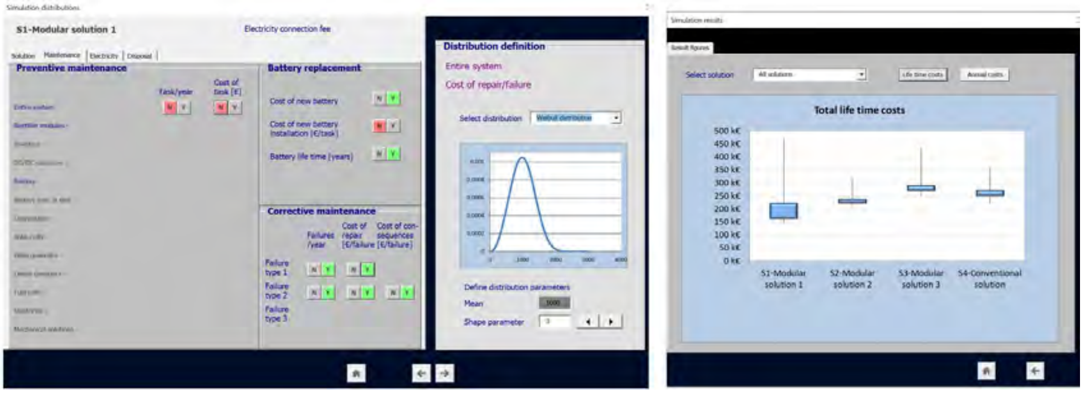


Figure 4.14. Monte Carlo simulation parameter input page and sensitivity analysis calculation example (right). The vertical line with a box (left) shows the dispersion of all simulation runs. The lower edge of the 'box' is the 25% lower quadrant, and the upper edge is the 75% upper quadrant.

In the sensitivity analysis, the impact of the need and cost of corrective maintenance on the life cycle costs of the different options was examined. After five hundred simulation runs, it can be seen how the uncertainty due to these variables affects the life cycle costs. Of the four solutions compared, (Solution 1) appears to be the most viable option, although the differences between Solution 1 and 2 are very small and the uncertainty associated with Solution 1 is significantly higher than for Solution 2. If Solution 1 is more attractive to the end-user, it would be useful to collect further data and repeat the sensitivity analysis. Solution 1 and Solution 2 would therefore appear to be very equal candidates for further consideration, and the sensitivity analysis should be continued with variations on other variables considered important.

Key lessons

- The cost structure and cost modelling must focus on cost drivers or variables that are relevant to the Life cycle cost of the planned system lifetime. This saves resources required for modelling.
- The information required for LCC assessments is available from public sources and from the databases of manufacturer companies and end-users, but usually the data needs to be supplemented by expert judgement.
- As the analyses concern future costs, the results need to be evaluated, e.g., by sensitivity analyses.

4.11. ROBUSTNESS IN STRATEGIC ASSET MANAGEMENT

Jyri Hanski

In strategic asset management, investments typically have a long-time horizon and should consider the requirements of different stakeholders, criteria that influence decision-making and possible future developments or scenarios. In addition, managing uncertainty around investments, allocating costs and benefits and quantifying decision criteria can be challenging tasks for decision makers. These factors make it difficult to assess the performance of decision options, for example through cost-benefit analyses and simulation models. For this reason, the strategies chosen should be as robust as possible, i.e., perform well enough regardless of the scenario implemented. Examples of such complex decision situations include fighter aircraft procurement and long-term investments in energy systems or production facilities.

Robust Decision-Making (RDM) is a method for managing the uncertainty associated with long-term strategic asset management. The aim of the method is to identify a set of possible future scenarios and help make decisions that are robust under as many of the identified scenarios as possible (Scrieciu et al., 2014). The *Strategy Robustness Visualization Method (SRVM)* is an application of the RDM method and can be used to assess the robustness, or conversely the vulnerability, of decision options.

The method starts by mapping the prevailing decision environment, i.e., identifying and engaging the key stakeholders that influence the decision, and selecting or creating scenarios to test the performance of the decision options. The key decision criteria are then selected in consultation with the key stakeholders, together with the scale used to score the criteria. Next, a limited number of decision options are selected or created. The performance of the decision options will be assessed separately for each decision criterion and scenario. The result is a distribution of the responses, either from the modelling or from expert judgements. To capture the robustness of the decision options, minimum and maximum pairs of results are selected to illustrate optimistic and pessimistic performance.

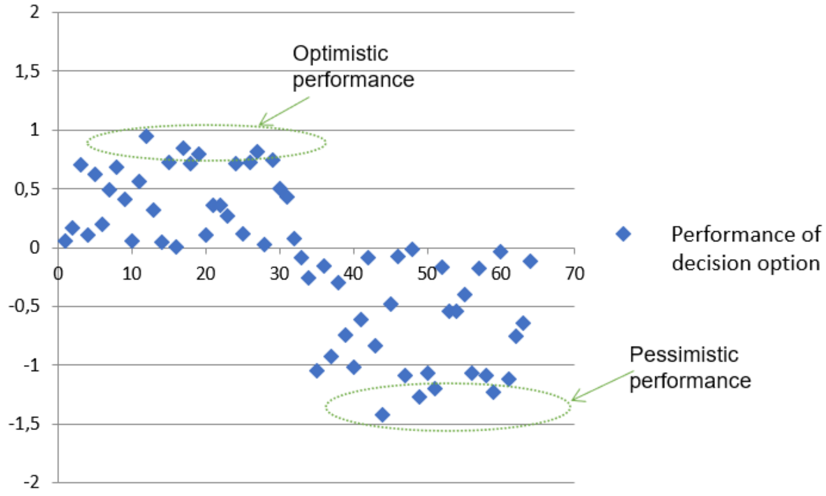


Figure 4.15. Optimistic and pessimistic performance.

The aim is to illustrate all possible scenario-performance combinations of decision options in a single picture. Uncertainty is illustrated by the distance between minimum and maximum, while robustness is illustrated by the close position of the lines relative to each other. A key contribution of the method, in addition to demonstrating robustness, is the demonstration to decision makers of the key uncertainties associated with the decision options.

Case: Climate change adaptation strategies in the energy sector

The case describes the adaptability of renewable energy production and demand to the impacts of climate change in Northern Europe in 2050. Its objective was to assess, in a multi-criteria approach, the performance of decision options related to strategic asset management. Several energy sector experts, policy makers and researchers participated in the construction and review of the case. The scenarios considered are the baseline scenario, the low climate change and sustainability scenario, and the uncontrolled climate change and inequality scenario. The baseline scenario is described as performance 0 and describes the situation at the time of analysis with respect to various criteria.

The decision options assessed include:

1. no planned adaptation to climate change,
2. the widespread use of capacity markets to increase generation capacity and demand response capacity (capacity market),
3. increasing the use of different forms of electricity storage, and
4. cross-border interconnections in the electricity market.

These decision options are assessed against the following criteria: the cost of electricity generation, the cost of extreme weather events, the security of electricity supply, the variability of electricity prices and the value to the energy industry and security of supply.

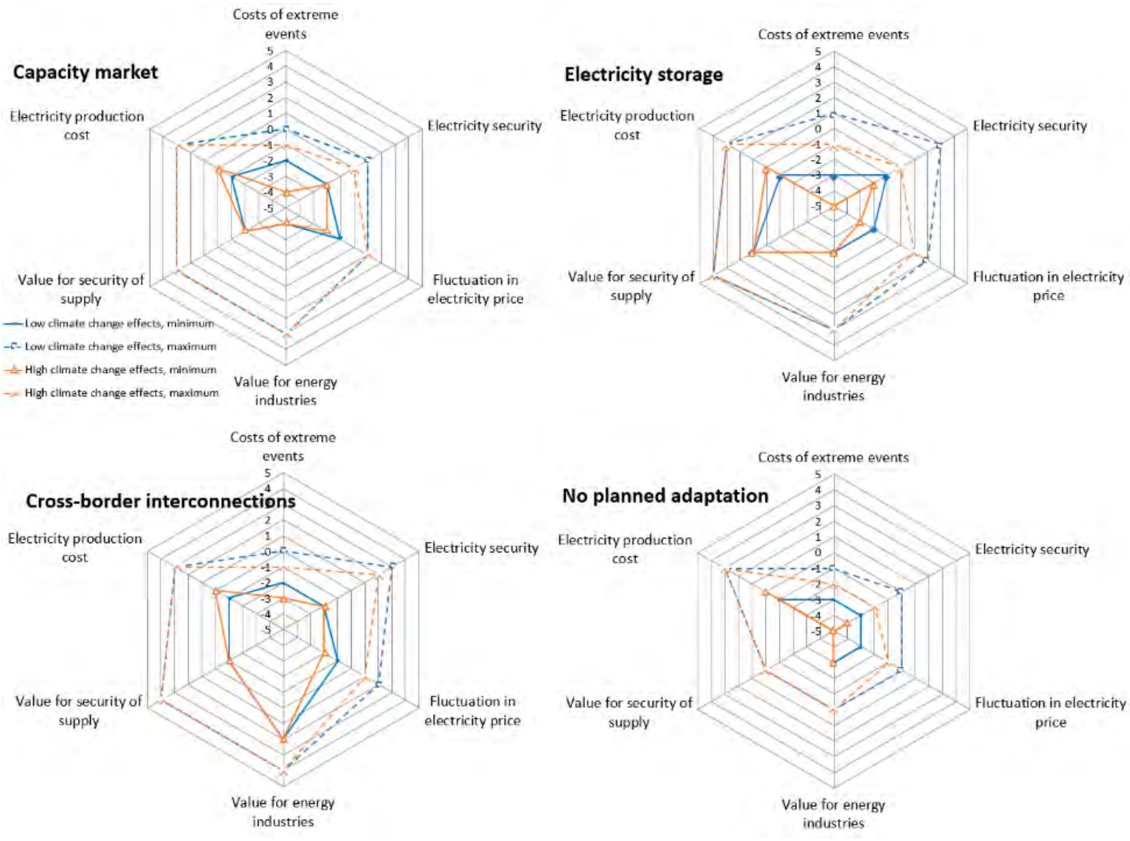


Figure 4.16. Robustness of decision options in the case "Adaptation of the energy sector to climate change in Northern Europe".

The results show that all decision options generally performed better than "no planned adaptation". The closer the lines are to the outer edge of the spider graph, the better the decision option performs on that decision criterion. Moreover, the more tightly packed the lines are, the more robust, i.e., independent of the scenario used, the decision option is. As a general observation on the results, it can be said that the different scenario combinations in this case did not show a large difference between each other, as the pairs of dotted and solid lines of different colors were generally close to each other. However, there were significant differences in the expert judgements and model outputs between the minimum and maximum. The decision maker can conclude from this that there is a reasonably high probability that the performance of the decision option and scenario falls between the dashed and solid lines.

A robust strategy should be ‘good enough’ regardless of the scenario that is implemented. The decision-maker should set a threshold value for each criterion, which could be, for example, a reference point in the present (value 0 in the spider diagram). For example, none of these decision options reaches this threshold for all criteria. A recommended solution in this case could be to find common features between the decision options and apply them. In addition, the combinability and malleability of the selected decision options should be considered in the light of new information.

Key lessons

- A robust strategy performs adequately regardless of the future scenario.
- Robustness is an important decision-making criterion in complex decision situations such as the procurement of fighter aircraft and long-term investments in energy systems or production facilities.
- The SRVM method can be used to illustrate the robustness and key vulnerabilities of decision options.

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PART 5

TERMS, CONCEPTS AND DEFINITIONS

Helena Kortelainen, Kari Komonen and Jouko Laitinen

Part 5 introduces some key terms, concepts and definitions for knowledge-based life cycle management and asset management. The terminology associated with this interdisciplinary subject is varied and application specific and the listing is not comprehensive. As this book aims to serve stakeholders in all item life cycle stages, Part 5 provides several definitions for many key terms. Whether we deal with expectations or average values depend on the perspective: we can predict future development (ex ante) or concentrate on the accumulated experience and data (ex post). In the early stages of the product life cycle, the designer deals with expectations. As the experience and data accumulates over time in the use and maintenance phase, calculation of average actual values becomes possible. Standards offer practical solutions for instance, to calculate key performance indicators from the data recorded in the asset information systems. In addition to the key terms derived from the common standards, Part 5 compiles also a set of other concepts and definitions that are important in the domain.

Asset

- item, thing, or entity that has potential or actual value to an organisation. Value can be tangible or intangible, financial, or non-financial, and includes consideration of risks and liabilities. Physical assets usually refer to equipment, inventory and properties owned by the organization. A grouping of assets referred to as an asset system could also be considered as an asset. (ISO 55000)

Asset life

- period from asset creation to asset end-of-life. (ISO 55000)

Asset management

- coordinated activity of an organisation to realise value from assets. Realisation of value will normally involve a balancing of costs, risks, opportunities, and performance benefits. The term 'activity' has a broad meaning and can include, for example, the approach, the planning, the plans, and their implementation. (ISO 55000)

Asset portfolio

- assets that are within the scope of the asset management system. A portfolio is typically established and assigned for managerial and control purposes. Portfolios for physical hardware might be defined by category (e.g., plant, equipment, tools, land). Software portfolios might be defined by software publisher, or by platform. (ISO 55000)

Asset replacement value (ARV)

- estimated amount of capital that would be required to replace the old plant or asset to the similar new asset. Replacement value is often equivalent to the fire insurance value. In the literature also plant replacement value (PRV) is widely used. (EN17485)

Asset residual value

- estimated amount that an organization would expect to obtain from disposal of an asset, after deducting the estimated costs of disposal, if the asset were already of the age and in the condition expected at the end of its useful life (ISO 55010)
- Residual value only exists where an amount received from disposal of the asset at the end of its life to a third party is greater than the estimated costs of disposal if the asset was already at the age and in the condition expected at the end of its useful life. Some residual values could need to be reviewed each year, considering associated uncertainties.
- In some cases, residual value can be a negative number because the asset requires significant disposal cost, such as demolition of a chemical plant. Again, the assessment of residual value requires advice from both financial and non-financial functional areas.

Asset specificity

- aspect or feature of an asset (such as a specialized machine) that makes it useful for one or few specific purposes, and therefore no other owner can get the same value from it. 'Asset specific' indicates high value of asset specificity (EN 17485)

Asset system

- sets of assets that interact or are interrelated (ISO 55000)

Availability

1. ability to be in a state to perform as an when required, under given conditions, assuming that the necessary external resources are provided. Availability depends upon the combined characteristics of the reliability, recoverability, and maintainability of the item, and the maintenance support performance. Required external resources, other than maintenance resources, do not affect the availability of the item although the item may be not available from the user´s viewpoint. ((EN 13306 & IEC 60050(192))
2. availability of a non-repairable item (IEC 60050(192))

$$A = \frac{MTTF}{(MTTF + MTTR)}$$

3. further availability related measures include e.g.: instantaneous/point availability A(t), inherent/intrinsic availability, average/mean availability $A(t_1,t_2)$, asymptotic availability, operational availability and steady state availability (IEC 60050(192))
4. Availability may be quantified using appropriate measures or indicators and is then referred to availability performance (EN 13306)

Business environment

- all the external factors within the market, technology and community influencing on the decision making of the organization (EN 16646)

Capital expenditure (CAPEX)

- investment used to purchase, install, and commission an asset (ISO 15663)

Consequential cost

- when an item or service becomes unavailable, a series of costs may be incurred. These costs may include warranty cost, liability cost, cost due to loss of revenue and costs for providing an alternative service. In addition, further consequential costs should be identified by applying risk analysis techniques to determine costs of adverse impacts on the company's image, reputation or prestige which may in turn result in loss of clients. (IEC 60300-3-3)

Cost element

- to estimate the life cycle cost, a division of the analysis into its constituent cost elements is necessary. This breakdown generally aligns with the level of detail at which an organization collects costs and can be distinctly defined and estimated. Cost element is the component of life cycle cost for which cost data are, or can be, collected. (IEC 60300-3-3)

Cost category

- the cost category of applicable resources such as labour, materials, fuel/energy, overheads, transportation/travel, recurring and non-recurring cost and/or fixed and variable costs (IEC 60300-3-3)

Cost Breakdown Structure (CBS)

- a cost breakdown structure is used to identify the required cost elements and involves the breakdown of the system into lower indenture levels, cost categories and life cycle stages (IEC 60300-3-3)

Critical success factor

- attribute required for an organization to ensure the success of an organization. (EN 17485)

Dependability

- ability to perform as and when required. Dependability includes availability, reliability, recoverability, maintainability, and maintenance support performance, and, in some cases, other characteristics such as durability, safety and security. IEC 60050 (192))
- ability to perform as and when required. Dependability includes availability, safety, security, durability, economics, and their influencing factors (reliability, maintainability, maintenance support performance, conditions of use and operators influence). Dependability is used as a collective term for the time-related quality characteristics of an item. (EN 13306)

Discount factor, discount rate

- factor or rate reflecting the time value of money that is used to convert cash flows occurring at different times to a base date. Discount rate/inflation – the discount rate is usually related to the cost of loans (weighted average cost of capital) and, where applicable, the returns required by shareholders. Company accountants generally compute the required rate of return for new investments, and this is the company discount rate. In this form, it usually includes an inflation component. (IEC 60300-3-3)

Engineering

- the activity of applying scientific knowledge to the design, building and control of machines, roads, bridges, electrical equipment, etc. The engineer – or more generally the designer – is concerned how things ought to be in order to attain desired goals and to functions. Examples of engineering tools are computer-aided engineering (CAE) tools, such as structural analysis and system simulation software applications. Examples of engineering and design systems are product lifecycle management (PLM) and simulation life cycle management (SLM) systems.

Failure <of an item>

- loss of ability to perform as required. A failure of an item is an event that results in a fault of that item. IEC 60050(192))
- loss of the ability of an item to perform a required function. After failure the item has a fault, which may be complete or partial. 'Failure' is an event, as distinguished from «fault», which is a state. The concept as defined does not apply to items consisting of software only. (EN 13306).

Failure rate

1. failure rate function describes the probability of failure per unit time. Failure rates are defined as the likelihood of failure in the next time interval assuming that the component has not failed up until the present time. IEC 60050(192) defines instantaneous failure rate and mean failure rate.
2. failure rate illustrates the evolution of the reliability of a component or device. The failure frequency of a system often follows a so-called bath-tub curve, where the failure rate of a system decreases during the burn-in period as a function of time to a constant value. As the system ages, the failure rate starts to increase again. At the population level, the failure frequency at a given time is the ratio of the number of failed devices to the number of devices that were in good working order at the start.
3. in the common language, the failure rate is the number of failures per unit of operation time.

Fault <of an item>

- inability to perform as required, due to an internal state. A fault of an item results from a failure, either of the item itself, of from a deficiency in an earlier stage of the life cycle, such as specification, design, manufacture, or maintenance. (IEC 60050(192))
- state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack

of external resources. A fault usually results from a failure, but in some circumstances, such as specification, design, manufacture, or maintenance, it may be a pre-existing fault. See latent fault (EN 13306).

Fleet management

- group consisting of individual machines or pieces of equipment such as trucks, aircraft, or ships.
- fleet could be related to the concept of installed base of items (equipment, machine, system) when individual items share similar characteristics, and it is useful to consider the 'fleet' as a whole. A fleet may consist of identical items, nearly similar or heterogeneous items. (Al-Dahidi ym., 2016)

Improvement

- combination of all technical, administrative, and managerial actions, intended to ameliorate the intrinsic reliability and/or maintainability and/or safety of an item, without changing the original function (EN 13306)

Item

- subject being considered. The item may be an individual part, component, device, functional unit, equipment, subsystem, or system. (IEC 60050(192)).
- part, component, device, subsystem, functional unit, equipment, or system that can be individually described and considered. A number of items e.g., population of items, or a sample, may itself be considered as an item. An item may consist of hardware, software, or both. Software consists of programs, procedures, rules, documentation, and data of the information processing system. (EN13306)

Key Performance Indicator (KPI)

- the most important performance indicators for a company and their combined result shows the performance of the whole organisation. KPIs show how the organisation is performing on its critical performance tasks. (Parmenter 2015, p.4)

Level of service

- parameters, or combination of parameters, which reflect social, political, environmental, and economic outcomes the organization delivers. The parameters can include safety, customer satisfaction, quality, quantity, capacity, reliability, responsiveness, environmental acceptability, cost, and availability. (ISO 55000)

Maintenance

- combination of all technical, administrative and management actions during the life cycle of an item intended to retain an item in, or restore to, a state in which it can perform as required. Management is assumed to include supervision activities. Technical maintenance actions include observation and analyses of the item state (e.g., inspection, monitoring, testing, diagnosis, prognosis, etc.) and active maintenance actions (e.g., repair, refurbishment). (EN 13306; IEC 60050(192))

Maintainability <of an item>

- ability to be retained or restored to a state to perform as required, under given conditions of use and maintenance. Given conditions would include aspects that affect maintainability, such as location of maintenance, accessibility, maintenance procedures and maintenance resources. (IEC 60050(192))
- ability of an item under given conditions of use, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources. Maintainability may be quantified using appropriate measures or indicators and is then referred as maintainability performance. (EN 13306)
- maintainability measures include e.g., maintenance man-hours (MMH), active maintenance time, preventive maintenance action time and active corrective maintenance time (IEC 60050(192))

Maintenance support performance, maintenance supportability

- effectiveness of an organisation in respect to maintenance support (IEC 60050(192))
- ability of a maintenance organisation to have the correct maintenance support at the necessary place to perform the required maintenance activity when required. (EN 13306)

Mean down time (MDT)

- expectation of the down time, Down state is a state of being unable to perform as required, due to internal fault, or preventive maintenance (IEC 60050(192))

Mean time between failures (MTBF)

- average of the operating times between failures. In the field of reliability, mean operating time between failures is defined as the mathematical expectation of the operating time between failures. This term is applied to repairable items. (EN 13306)

- Mean time between failures (EN 15341)

$$MTBF\ (hours) = \frac{Total\ operating\ time}{Number\ of\ failures}$$

Mean operating time between failures (MTBF, MOTBF)[1]

1. expectation of the duration of the operating time between failures. Mean operating time between failures should only be applied to repairable items. For *non-repairable items*, see mean operating time to failure. (IEC 60050(192))

Mean repair time (MRT)

1. expectation of the repair time. Repair time is the part of active corrective maintenance time taken to complete repair action (IEC 60050(192))
2. average of the repair times. In the field of reliability, mean repair time is defined as the mathematical expectation of the repair time. (EN 13306)
3. Mean repair time (EN 15341 (2019))

$$MRT(hours) = \frac{Total\ time\ to\ repair}{Number\ of\ failures}$$

Mean operating time to failure (MTTF)[2]

- expectation of the operating time to failure (non-repairable items) (IEC 60050(192))

Mean time to restoration (MTTR)[3]

1. expectation of the time to restoration. Time to restoration of an item is the time interval, from the instant of failure, until restoration. (IEC 60050(192))
2. average of the times to restoration. In the field of reliability, mean time to restoration is defined as the mathematical expectation of the time to restoration EN 13306)
3. mean time to restoration (EN 15341 (2019))

$$MTTR\ (hours)\ = \frac{Total\ time\ to\ restoration}{Number\ of\ failures}$$

Mean up time (MUT)

- expectation of the up time. Up time is the time interval for which the item is in an up state (i.e., able to perform as required). (IEC 60050(192))
- the up time is usually longer than the production period because the system may be in the up state, but the function is not needed, i.e., no production is generated.

Modernisation

- modification or improvement of the item, taking into account technological advances, to meet new or changed requirements (EN 13306)

Modification

- combination of all technical, administrative, and managerial actions intended to change one or more functions of an item. Modification is not a maintenance action but has to do with changing the required function of an item to a new required function. The changes may have an influence on the dependability characteristics. Modification may involve the maintenance organisation. The change of an item where a different version is replacing the original item without changing the function or ameliorating the dependability of an item is called replacement and it is not a modification. (EN 13306)

Liability cost

- cost associated with actual or alleged non-compliance with statutory or contractual obligations. A liability will arise where a supplier fails to comply with legal or contractual obligations. The costs for a breach of the law may need to be considered as part of the LCC. This is especially important in the case of items that have a high potential to cause human injury and/or environmental damage, or for new items where risks involved may not be fully apparent and/or well understood. Risk analyses, together with past experience, and expert judgement, may be used to provide an estimate of these costs. (IEC 60300-3-3)

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[1] Mean time between failures (MTBF) as defined in IEC 60050(191) (now withdrawn) is omitted, see Mean operating time between failures (MTBF, MOTBF) in IEC 60050(192).

[2] Mean time to failure (MTTF) as defined in IEC 60050(191) (now withdrawn) is replaced by Mean operating time to failure (MTTF) in IEC 60050(192).

[3] IEC 60050(191) (now withdrawn; replaced by IEC 60050-192:2015) defined the term ‘mean time to recovery’ as a synonym, but restoration and recovery are not synonyms.

Life cycle

1. evolution of a system, product, service, project, or other human-made entity from conception through retirement (ISO/IEC/IEEE 15288)
2. series of identifiable stages through which an item goes, from its conception to disposal (IEC 60300-1)
3. stages involved in the management of an asset (ISO 55000)
4. flow of energy and materials through manufacturing system from raw material in ground, through processing to shape, assembly of finished product and disposal following use
5. (commercial) life cycle when the product is on the market.

Life Cycle Assessment, (LCA)

- life cycle assessment includes definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. (ISO 14040 and ISO 14044) LCA is often called 'cradle-to-grave' analyses.

Life Cycle Cost (LCC)

- sum of the costs generated during the life cycle of an item. For a user or an owner of an item, the total life cycle cost may include only those costs pertaining to acquisition, operation, maintenance, and disposal. (EN 13306)

Life Cycle Costing (LCC)

- process of performing an economic analysis to assess the cost of an item over a portion, or all, of its life cycle in order to make decisions that will minimize the total cost of ownership while still meeting stakeholder requirements (IEC 60300-3-3)

Life cycle stages

1. typical system life cycle consists of concept and definition, design and development, construction, installation and commissioning, operation and maintenance, mid-life upgrading, or life extension, and decommissioning and disposal. The stages identified will vary with application. (IEC 60300-1)
2. ISO 55000 does not distinguish between the different phases with the same level of precision as e.g., IEC 60300-1, as it is not limited to physical assets alone.
3. life cycle stages are defined within various standards in slightly different ways depending on the application (e.g.: EN 16646, EN 17666, ISO/IEC DIS 25010).
4. life cycle perspective is also considered and modelled in industrial internet standards, such as the RAMI 4.0 reference architecture model for manufacturing industry

(RAMI - German Reference Architechture Model Industry 4.0) (Grangel-González et al., 2016)

Obsolescence

- inability of an item to be maintained due to the unavailability on the market of the necessary resources at acceptable technical and/or economic conditions. The necessary resources can be: one (or more) sub-items needed to restore the item, tools or monitoring or testing devices, documentary resources, skills, etc. The unavailability of the resources can be due to technological development, market situation, absence of supplier, regulations, etc. Obsolescence is not equivalent to ageing. (EN 13306)

Operating conditions

- physical loads and environmental conditions experienced by the item during a given period. Operating conditions can vary during the item's life cycle (EN 13306).

Operating constraints

- characteristics of the item, which set limits for the use of the item and may determine requirements for maintenance activities. These characteristics are the results of design and construction of the item. (EN 13306)

Operating expenditure (OPEX)

- expenses used for operation and maintenance, including associated costs such as logistics and spares (ISO 15663)

Operational mode

- configuration in which an item is operated and utilized during a given period characterized by units of use (hours, loads, number of starts/stops, number of transients, etc.). Operational mode determines the frequency, load, continuity, and performance rate of utilization. Operational mode may, or may not, comply with the inherent item specifications as defined. (EN 13306)

Operational availability due to maintenance (%)

- Operational availability due to maintenance (EN 15341)

$$Operational\ availability\ due\ to\ maintenance = \frac{Total\ operating\ time}{Total\ operating\ time + Downtime}$$

  - *Total operating time*
    Time when the physical asset is performing as required.
  - *Total operating time + Downtime*
    Time when the physical asset is performing as required plus the time lost due to failures and preventive maintenance activities.

Opportunity cost

- in order to improve an item, it is often necessary to provide additional resources early in the life cycle. Thus, to achieve improved dependability and its consequent benefits, it may be necessary to provide extra resources, such as prototypes and test facilities, in the early stages of the project life cycle. However, it is important to realize that these resources represent funds that could, at least in theory, be used for other activities of the company for example other development projects. The opportunity to earn this return is lost by the investment made to improve dependability. The lost return is known as an opportunity cost. (IEC 60300-3-3)

Ownership cost

- total cost of utilizing an item including all operating, maintenance, and unrealized risk costs until the end of its life cycle (IEC 60300-3-3)

Product data management (PDM)

- refers to centralised software concepts for the management of information related to a company's products. Typically, PDM concepts mainly contain information generated during the product design phase.

Product life cycle management (PLM)

- concept, systems, and procedures for managing the product life cycle and life cycle information. PLM is the process of managing the entire lifecycle of a product from its inception through the engineering, design, and manufacture as well as the service and disposal of manufactured products.

RAMS

- RAMS refers to the terms Reliability, Availability, Maintainability and Safety. The CENELEC - EN 50126-1 standard for railway applications defines the key processes and tasks for RAMS management throughout the life cycle of a system. The standard provides a systematic process and methods for managing conflicting requirements, and it is applicable also other industries.

Recoverability

1. ability to recover from a failure, without corrective maintenance (IEC 60050(192))
2. degree to which, in the event of an interruption or a failure, a product or system can recover the data directly affected and re-establish the desired state of the system. The length of unavailable period following a failure, that a product is not available at the same level of use as before the failure, is determined by its recoverability. However, recoverability of product depends on a recoverability of computer system on which the product operates or a subset of its functions. (ISO/IEC DIS 25010)
3. the level of recovery capability, whereby the product or system can, in the event of an interruption or failure, restore the data content and system operation that was being modified to the desired state. After a failure, a computer-based system may be unavailable for a period of time. The recovery capability determines this period.

Reliability

- ability to perform as required, without failure, for a given time interval, under given conditions. Given conditions that affect reliability, such as: mode of operation, stress levels, environmental conditions, and maintenance. (IEC 60050(192))
- ability of an item to perform a required function under given conditions for a given time interval (EN 13306)
- reliability $R(t_1,t_2)$ is the probability of performing as required for the time interval (t_1,t_2) under given conditions (IEC 60050(192))
- in addition to probability of performing as required, common measures of reliability include failure rate and frequency and number of failures over time.

Required function

- function considered necessary to fulfil the given requirements. The required function may be stated or implied (i.e., that the purchaser would be entitled to expect). The required function, by implication, also covers what the item shall not do. Essential functions of a system, which may not be visible to the user, are also required functions. (IEC 60050(192))
- function, combination of functions, or a total combination of functions of an item which are considered necessary to fulfil a given requirement. Necessary to fulfil a given requirement may also include asset value preservation (EN13306)

- for example, the required functions of a pump may include pumping liquid, mixing liquid, keeping liquid inside the pump, and keeping external media such as sealing water outside the pump.
- complex item may have numerous required functions, often only some of which are identified. Rausand & Øien (1996) have proposed a general classification of functions to facilitate the identification.

Requirement

- need or expectation that is stated, generally implied or obligatory. 'Generally implied' means that it is custom or common practice for the organization, stakeholders that the need or expectation under consideration is implied. A specified requirement is one that is stated, for example in documented information. (ISO 55000)

Risk

1. effect of uncertainty on objectives (ISO 31000)
2. effect of uncertainty on objectives. An effect is a deviation from the expected – a positive and/or negative. Objectives can relate to different disciplines (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product, or process). Risk is often characterised by reference to potential events and consequences, or a combination of these. Risk is often expressed in terms of a combination of the consequences of an event and the associated likelihood of occurrence. (ISO 55000)

Stakeholder

- person or organisation that can affect, be affected by, or perceive themselves to be accepted by a decision of activity. (ISO 55000)

Strategic asset management plan (SAMP)

- documented information that specifies how organizational objectives are to be converted into asset management objectives, the approach for developing asset management plans, and the role of the asset management system in supporting the achievement of the asset management objectives. (ISO 55000)

System

- a set of interrelated items that collectively fulfil a requirement (IEC 60050(192))

Total cost of ownership (TC0)

- Total cost of ownership is defined as a philosophy for understanding all relevant supply chain related costs of doing business with a particular supplier for a particular good/service. TCO considers total cost of acquisition, use/administration, maintenance, unrealised risks until the end of a given item/service (Ellram & Siferd, 1993)

Unavailability <of item>

- state of being unable to perform as required, due to the internal fault, or preventive maintenance. Down state relates to unavailability of the item. (IEC 60050(192))
- Instantaneous unavailability $U(t)$ is the probability that an item is not in a state to perform as required at a given instant (IEC 60050(192))
- In general, unavailability is $U=1-A$

Uncertainty

- the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood. (ISO 55000)

Usability

- Capability of a product to be used by specified users to exchange information between a user and an interactive system via the user interface to complete the intended task. Usability in product quality model and its sub-characteristics focus more on a set of interactions with users (or operators) to do the specific tasks for their intended use, while usability in quality-in-use model comprehensively focuses more on outcomes of use to determine whether user specific tasks are achieved by users with effectiveness, efficiency, satisfaction, mitigated risks and so on. (ISO/IEC DIS 25010)

Useful life <of an item>

- time interval, from first use until user requirements are no longer met, due to economics of operation or maintenance, or obsolescence (IEC 60050(192))
- time interval from first use until the instant when limiting state is reached. The limiting state may be a function of failure rate, maintenance support requirement, physical condition, economics, age, obsolescence, changes in the user´s requirements or other relevant factors. (EN 13306)

Whole life cost (WLC)

- total costs incurred over the lifetime of the item. WLC is often used a synonym for LCC. In some applications (see e.g., Nato guide, 2007), WLC consists of all elements that are part of total cost of ownership plus indirect, fixed, non-linked costs and WLC covers all costs or expenses that are attributed to the systems.

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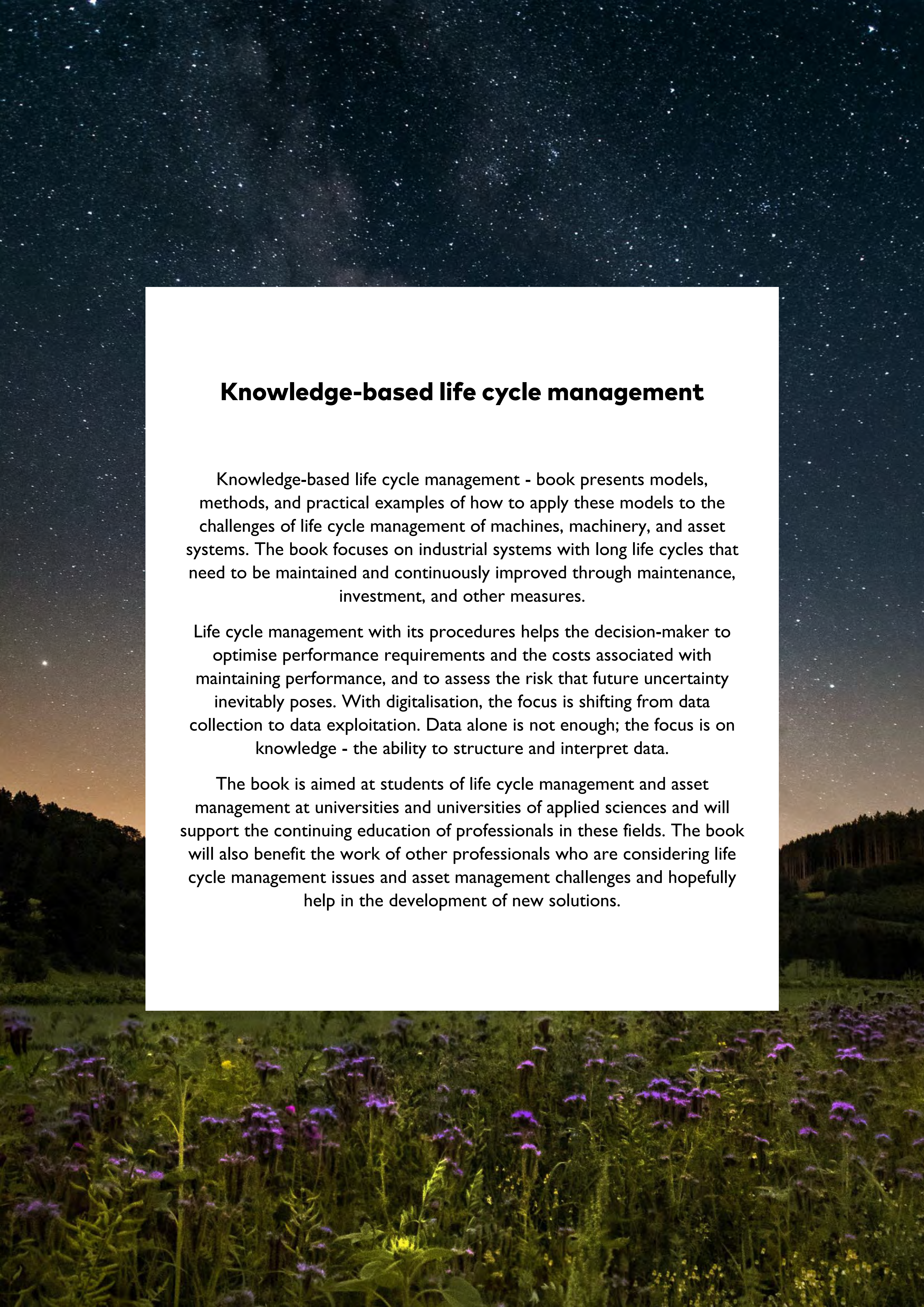
Tero Välisalo, Research scientist, M.Sc.(Environmental Engineering), tero.valisalo@vtt.fi , VTT Technical Research Centre of Finland. Tero Välisalo has worked at VTT for more than 25 years developing safety and reliability of machines and systems in various fields. Asset management and life cycle cost assessment are also among his areas of expertise. His current research interests focus on ensuring safety and reliability of new technologies and energy sources, including hydrogen-powered systems and wave energy generation. The development of maintenance and maintainability is an important part of his work.



Knowledge-based life cycle management

Knowledge-based life cycle management - book presents models, methods, and practical examples of how to apply these models to the challenges of life cycle management of machines, machinery, and asset systems. The book focuses on industrial systems with long life cycles that need to be maintained and continuously improved through maintenance, investment, and other measures.

Life cycle management with its procedures helps the decision-maker to optimise performance requirements and the costs associated with maintaining performance, and to assess the risk that future uncertainty inevitably poses. With digitalisation, the focus is shifting from data collection to data exploitation. Data alone is not enough; the focus is on knowledge - the ability to structure and interpret data.

The book is aimed at students of life cycle management and asset management at universities and universities of applied sciences and will support the continuing education of professionals in these fields. The book will also benefit the work of other professionals who are considering life cycle management issues and asset management challenges and hopefully help in the development of new solutions.