1

An Overview

Learning Outcomes

After reading this chapter, you should be able to:

- Define maintenance and explain its importance from a strategic business perspective;
- List the three main aspects of maintenance;
- Provide a classification of engineered objects;
- Describe reliability and non-reliability performance measures of engineered objects;
- Describe the factors that affect performance degradation;
- Recognize the consequences of poor maintenance;
- Describe the main categories of maintenance costs;
- Explain that there is a trade-off between preventive maintenance effort and maintenance costs;
- Explain that there are maintenance decision-making problems at the strategic, tactical, and operational levels;
- Describe the evolution of maintenance over time and the new trends;
- Understand the structure of the book.

Introduction to Maintenance Engineering: Modeling, Optimization, and Management, First Edition.
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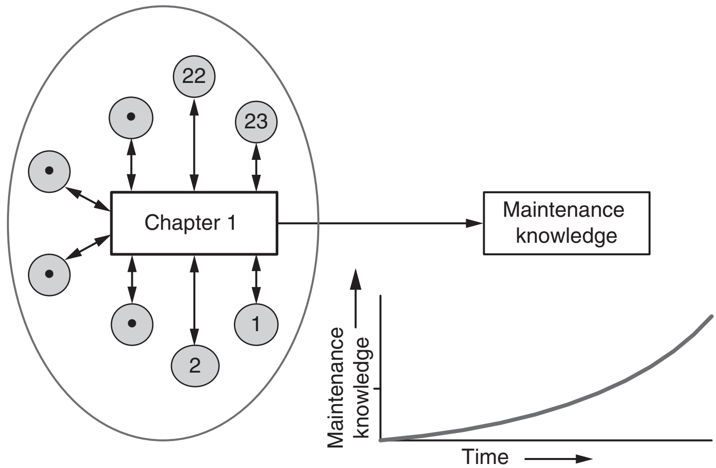

1.1 Introduction

Modern societies use a range of engineered objects for many different purposes. The objects are designed and built for specific functions. These include a variety of products (used by households, businesses, and government in their daily operations), plants, and facilities (used by businesses to deliver goods and services) and a range of infrastructures (networks such as rail, road, water, gas, electricity; dams, buildings, etc.) to ensure the smooth functioning of a society.

Every engineered object is unreliable in the sense that it degrades with age and/or usage and ultimately fails. A dictionary definition of failure is "falling short in something expected, attempted, desired, or in some way deficient or lacking." From an engineering point of view, an engineered object is said to have failed when it is no longer able to carry out its intended function for which it was designed and built. Failures occur in an uncertain manner and are influenced by several factors such as design, manufacture (or construction), maintenance, and operation. In addition, the human factor is also important in this context.

The consequence of a product failure may vary from mere inconvenience (for example, a dishwasher failure) to something serious (for example, an automobile brake failure leading to economic and possibly human loss). The failure of an industrial plant or commercial facility may have major economic consequences for a business as it affects the delivery of goods and services (outputs of the business) and the revenue generation. The daily loss in revenue as a result of the product being out of action due to failure may be very high. Rough estimates (circa 2000) for the revenue lost due to engineered objects being out of action are as follows:

- Large aircraft (A340 or Boeing 747) ~ $500 000/day;
- Dragline (used in open cut mining) ~ $1 million/day;
- A large manufacturer (for example, Toyota) ~ $1–2 millions/hour.

> **Definition 1.1**
>
> Maintenance is the combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it may perform the required function (CEN, 2001).

In a sense, maintenance may be viewed as actions to compensate for the unreliability of an engineered object. Building in reliability is costly and is constrained by technical limits and economic considerations. However, not having adequate reliability is costlier due to the consequence of failures. Thus, maintenance becomes an important issue in this context. Table 1.1 shows the maintenance costs (as a fraction of the operating costs) in different industry sectors, as reported in Campbell (1995).

There are several aspects to maintenance and they may be grouped broadly into the following three categories:

- Technical (engineering, science, technology, etc.);
- Commercial (economics, legal, marketing, etc.);
- Management (from several different perspectives – manufacturer, customer and maintenance service provider when maintenance is outsourced).

This implies that maintenance decisions need to be made in a framework that takes into account these issues from an overall business perspective. Figure 1.1 shows the link between maintenance (strategic and operational) and production from a business perspective.[1]

In this book we discuss all of these aspects and this chapter gives a broad overview of the book.

The outline of the chapter is as follows. Section 1.2 deals with the classification of engineered objects and presents some examples that are used in later chapters to illustrate different concepts and issues. The performance of an engineered object degrades with age and/or usage and this is the focus of Section 1.3, where we look at both reliability and non-reliability performance measures. Maintenance consists of actions to ensure the desired performance and this is discussed in Section 1.4, where we look at a range of such types of maintenance, the consequence of poor maintenance, maintenance costs, and so on. Although

Table 1.1 Maintenance as a percentage of operating cost.

Industry sector	Maintenance cost (%)
Mining (highly mechanized)	20–50
Primary metals	15–20
Electric utilities	5–15
Manufacturing processing	3–15
Fabrication/assembly	3–5

[1] The state of an object is discussed briefly in Section 1.3.3 and in more detail later in Chapter 2.

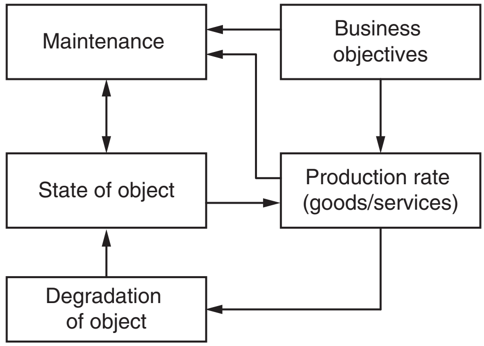

Figure 1.1 Maintenance from a business perspective.

maintenance has been practiced since the dawn of civilization (maintaining shelters to live, stone tools, etc.), the theory of maintenance evolved only recently (in the early part of the twentieth century). Since then it has been growing at an ever-increasing pace and this issue is discussed in Section 1.5, where we look at both the past and future trends. These sections provide the background to highlight the focus of the book, which is discussed in Section 1.6. We conclude the chapter with a brief outline of the various chapters of the book in Section 1.7.

1.2 Classification of Engineered Objects

Engineered objects may be grouped into three broad categories, as indicated in Table 1.2.

Each of these categories may be subdivided, and this is discussed in subsequent sections.

1.2.1 Products

Products may be classified into three groups, as indicated in Table 1.2. Each group may be divided into two subgroups: (i) standard (or off-the-shelf) and (ii) custom-built.

- *Consumer products:* These are mostly standard products (for example, television sets, appliances, automobiles, and personal computers) that are consumed by society at large. (These products are also consumed by businesses and government agencies.) As such, the number of customers is large, with a small to medium number of manufacturers. The complexity of the product may vary considerably, and the typical small consumer is often not sufficiently well informed to evaluate product performance, especially in cases involving complex products (computers, cars, etc.).
- *Commercial and industrial products:* These may be either standard or custom-built (for example, mainframe computers, CNC machines, pumps, X-ray machines, and aircraft), with a small number of customers and manufacturers. The technical complexity of such products and their mode of usage may vary considerably. The products may be either complete units, such as cars, trucks, pumps, and so forth, or product components needed by another manufacturer, such as batteries, drill bits, electronic modules, turbines, and so on.[2]

[2] Industrial products include machines, equipment, tools, and so on.

Table 1.2 Classification of engineered objects.

Products	*Consumer:* Household appliances, automobiles, and so on *Commercial and Industrial:* Also referred to as equipment, machinery, and so on *Defense:* Ships, tanks, planes, and so on
Plants	Collection of several elements*:* Power plant composed of boiler turbine, generators, and so on
Infrastructures	*Discrete:* Buildings, dams, and so on *Distributed networks:* Rail, road, gas, water, and so on

Table 1.3 Classification of plants.

Industry sector	Operations and outputs
Mining	Extracting and enriching raw materials (for example, ore, fuels)
Processing	Converting ore to metal, crude oil to gasoline, and so on
Manufacturing	Converting processing plant outputs to goods
Power	Producing electricity from coal, oil, nuclear fuel, and so on

Table 1.4 Classification of facilities based on sectors.

Health	Provide healthcare in hospitals, nursing homes, and so on
Transport	Help move goods and people by road, rail, sea, or air
Maintenance	Provide maintenance services for a variety of industrial and commercial products (such as elevators, buses, etc.)
Educational	Provide education (such as in schools and universities)

- *Defense products:* These are specialized products (for example, military aircraft, ships, rockets) with a single customer and a relatively small number of manufacturers. The products are usually complex and expensive and involve state-of-the-art technology with considerable research and development effort required from the manufacturers. These products are usually designed and built to customers' requirements.

1.2.2 Plants and Facilities

Plants are used to produce a variety of goods. They may be classified into several categories, as indicated in Table 1.3.

Facilities (such as hospitals, schools, sport centers, entertainment centers, etc.) also use a range of products to deliver different services. We include these under plants.

A facility is a collection of products used to produce different types of services. They may be classified into several categories, as indicated in Table 1.4.

Table 1.5 Classification of infrastructures.

Industry sector	Examples of infrastructures
Transport	Road and rail networks, ferries, airports, pavements, bridges, and so on
Energy	Electricity networks, gas and petroleum pipelines, and so on
Water management	Water network, sewerage network, dams, and so on
Communication	Telephone and mobile phone networks, cable television, Internet, and so on
Others	Public buildings such as school and hospital buildings, and so on

1.2.3 Infrastructures

Infrastructures are physical structures and facilities that provide services essential for plant operation and also to enable, sustain, or enhance societal living conditions. In other words, they are needed for the smooth operation of a society and the effective functioning of the economy. Infrastructures facilitate the production of goods and services and their delivery to customers; they may be classified into several groups, as indicated in Table 1.5.

Infrastructures may be further classified as being (i) distributed (involving a spatial dimension, such as networks) or (ii) discrete or lumped (where the spatial dimension is not significant, such as buildings, dams, terminals, etc.).

1.2.4 Assets and Systems

The term *asset* is often used in the context of maintenance. In financial accounting, assets are economic resources – tangible or intangible with a positive economic value. A business balance sheet records the monetary value of the assets owned by the business. Tangible assets contain various subclasses, including current assets and fixed assets. Current assets include inventory (such as spares and material needed for carrying out maintenance), whilst fixed physical assets (such as buildings, plants, and equipment) are purchased for continued and long-term use to earn profit for a business. This group includes buildings, machinery, furniture, tools, equipment, and so on. They are written off against profits over their anticipated lives by charging depreciation expenses. Accumulated depreciation is shown in the balance sheet.

The term *system* is used to denote a collection of interconnected elements. Thus, a product, a plant, and an infrastructure may all be viewed as a system.

1.2.5 Illustrative Examples

The following examples will be used in later chapters to illustrate the different concepts, tools, and techniques needed for effective maintenance.

Example 1.1 Automobile (Consumer Product)

The automobile is a self-propelled passenger vehicle designed to operate on ordinary roads. Automobiles may be classified into several types based on (i) structure and usage – passenger cars, light trucks, heavy trucks, vans, buses, and so on, and (ii) the primary energy source – gasoline, diesel, electric, hybrid (combination of gasoline and electric) and others such as hydrogen, solar, and so on, which are still in the experimental stages. Individuals buy one automobile at a time whereas a business might buy a fleet, either for use by its staff or for renting out.[3] ■

Example 1.2 Photocopier (Commercial Product)

Photocopying (also referred to as *xerography* – a word derived from two Greek words – *xeros* meaning dry and *graphy* meaning writing) is a dry process for making paper copies of documents and was invented by Chester F. Carlson (an American Physicist) in 1938. The process of xerography involves the following steps:[4]

1. The clean surface of a "photoreceptor" drum (or belt) is coated with a light-sensitive (photo-conductive) material that acts as an insulator in the dark and as a conductor when exposed to light.
2. The photoreceptor material is electrically charged positively through a "corona wire."
3. Light is reflected from the original through a lens on to the drum.
4. The light dissipates the charge on the drum in the areas of the image that are blank. A positively charged image forms on the light-sensitive surface.
5. The negatively charged *toner* (also referred to as *dry ink*) is dusted on the drum and sticks to the positively charged image on the drum. This leaves a "toner image" of the original on the drum.
6. A paper charged positively with the corona wire is pressed against the drum so that the toner image is transferred.
7. The "fuser" heats the positively charged paper for a short period so that the toner is permanently attached to the paper.

The drum surface is cleaned by a "cleaning blade" to remove the remainder of the toner and transferred into a waste bin so that the process may be repeated. ■

[3] See http://auto.howstuffworks.com for a discussion of the principles of how the different subsystems work.
[4] For more details, see Bruce and Hunt (1984). See also, http://www.howstuffworks.com/photocopier.htm.

Example 1.3 Diesel Engines (Commercial/Industrial Product)

A diesel engine (also known as a compression-ignition engine) is an internal combustion engine (ICE) that uses the heat of compression to initiate ignition to burn the fuel, which is injected into the combustion chamber. This is in contrast to spark-ignition engines such as a gasoline engine (petrol engine) or gas engine (using a gaseous fuel as opposed to gasoline), which uses a spark plug to ignite an air–fuel mixture. The engine was developed by Rudolf Diesel in 1893.

Diesel engines are manufactured in two- or four-stroke versions. Since the 1910s they have been used in ships, and their use in locomotives, trucks, and electricity-generating plants followed later. Since the 1970s, diesel engines have been used in on- and off-road vehicles.[5] ■

Example 1.4 Thermal Power Stations (Plant)

A power plant generates electrical power. At the center is a generator, a rotating machine that converts mechanical power into electrical power by creating relative motion between a magnetic field and a conductor. The energy source used to turn the generator varies widely and sources include: (i) burning fossil fuel such as coal, oil, and natural gas, (ii) fission in a nuclear reactor, and (iii) cleaner renewable sources such as solar, wind, and hydroelectric power.

A thermal power station is a power plant in which the prime mover is steam-driven. Water is heated, turns into steam, and spins a steam turbine which drives an electrical generator. After it passes through the turbine, the steam is condensed in a condenser and recycled to where it was heated. Some thermal power plants also deliver heat energy for industrial purposes, for district heating, or for desalination of water as well as delivering electrical power. ■

Example 1.5 Oil Refineries (Plant)

An oil refinery is an industrial process plant where crude oil is processed or refined to produce useable products such as gasoline, kerosene, diesel fuel, heating oil, and asphalt base. The process is very complex and involves both chemical reactions and physical separations, as the crude oil is composed of thousands of different molecules. Mixtures of molecules are isolated according to the mixture's boiling point range (gasoline molecules boil in the range 90–400 °F and kerosene in the range 380–520 °F) through a separation process called *distillation*. These fractions are mixed or blended to satisfy specific properties that are important in allowing the refined product to perform as desired in an engine. To have an effective and efficient operation, process optimization and advanced process control are used to run a refinery. ■

[5] Currently the world's largest diesel engine is a Wartsila Sulzer RT96-C with 108 920 hp (81 220 kW) output.

Example 1.6 Dragline (Industrial Plant)

A dragline is a moving crane with a bucket at the end of a boom. It is used primarily in coal mining for removing the dirt to expose the coal. The bucket volume varies around 90–120 cubic meters and the dragline is operated continuously (24 hours/day and 365 days/year) except when it is down undergoing either corrective or preventive maintenance actions. A performance indicator of great importance to a mining business is the yield (annual output) of a dragline. This is a function of the dragline (bucket) load, speed of operation, and availability. Availability depends on two factors – (i) degradation of the components over time and (ii) maintenance (corrective and preventive) actions used. Degradation depends on the stresses on different components and these, in turn, are functions of the dragline load. As a result, availability is a function of the dragline load and the maintenance effort. Availability decreases as the dragline load increases and increases as the maintenance effort increases. This implies that the annual total output is a complex function of dragline load. ■

Example 1.7 Rail Transport (Infrastructure)

Rail transport involves wheeled vehicles running on rail tracks. Tracks usually consist of steel rails installed on sleepers and ballast on which the rolling stock (wagons and carriages), fitted with metal wheels, moves. Rolling stock in railway transport systems has a lower frictional resistance than vehicles on highways and roads and is coupled to form longer trains. In some countries the rail transport is public (owned by the government) and in others it is private (owned by private businesses) or jointly private and public. The two major subsystems are (i) infrastructure and (ii) rolling stock. The infrastructure is managed by the track operator (often a publicly owned company or agency) and the rolling stock is managed by rolling stock operators (may be either public or private). Together, they provide transport between train stations (for passenger and freight transport) and between two terminals (for freight) – such as a mine or manufacturing/processing plant and a port. Power is provided by locomotives which either draw electrical power from an electrical network or produce their own power (usually using diesel engines). Most tracks are accompanied by a signaling system to ensure smooth and safe operation of trains. ■

Example 1.8 Road Transport (Infrastructure)

Road transport involves wheeled vehicles (automobiles, buses, trucks, etc.) moving on roads. Road infrastructure consists of pavements (or roads) and other items such as traffic signals, signs, and so on. There are two types of pavement – rigid and flexible. Rigid pavements consist of a thick concrete top surface. Flexible pavements have a flexible layer on top of the surface. The infrastructure may be owned and managed by a public entity (Federal, State, or Local government) or by a private agency under some form of private–public partnership. In contrast to rail transport, many types of vehicles use roads and they provide transport between different points of the road network. Most roads are accompanied by a signaling system to ensure smooth and safe movement of vehicles. ■

Example 1.9 Pipe Networks (Infrastructure)

Pipeline infrastructures have been employed as one of the most practical and low-cost methods for large oil and gas transport for decades. Pipeline networks for water distribution and sewage systems are everywhere and they pose critical management and maintenance problems. Aging infrastructure and replacement costs are major challenges for municipal water utilities. With populations increasing and available freshwater resources decreasing, water and wastewater distribution pipelines need to be maintained to prevent water loss and damage to the surrounding environment. Since replacements are certain to become more costly over time, the burdens, if shifted to the future, are bound to get heavier.

America's drinking water systems face an annual shortfall of at least \$11 billion to replace aging facilities that are near the end of their useful life and to comply with existing and future federal water regulations. This does not account for growth in the demand for drinking water over the next 20 years. Leaking pipes lose an estimated 7 billion gallons of clean drinking water a day. ■

Example 1.10 Concrete Structures (Infrastructure)

Reinforced concrete is the world's most important structural material due to its versatility and relatively low cost. A large part of its worldwide appeal is that the basic constituent materials – cement, sand, aggregate, water, and reinforcing bars – are widely available and that it is possible to construct a structure using local sources of labor and materials. Massive concrete structures include multi-story buildings, dams, bridges, and so on. Although most of these structures have high durability, they are susceptible to deterioration due, for instance, to corrosion of bars, which may lead to a reduction in the strength, serviceability, and esthetics of the structure. As such, proper inspection, monitoring, and timely maintenance interventions may reduce the massive investment sometimes needed to restore the deteriorated structure. For example, chloride-induced corrosion is a progressive problem and if it is identified before or just after initiation, treatment is far simpler and cheaper than if the structure is permitted to degrade further.

According to the ASCE 2009 Report Card for America's Infrastructure, \$2.2 trillion needs to be invested over five years to "bring the nation's infrastructure to a good condition." ■

1.3 Performance of Engineered Objects

The performance of an engineered object is a complex entity involving many dimensions and it depends on the perspective – manufacturer or customer – and is best characterized through a vector of variables, where each variable is a measurable property of the object. These measures may be divided broadly into two categories: –non-reliability performance and reliability performance measures.

1.3.1 Non-Reliability Performance Measures

The non-reliability performance measures include technical, operational, economic, environmental impact, and so on. They are specific to the engineered object. Table 1.6 lists a few of the non-reliability performance measures for four of the illustrative examples discussed in the previous section.

1.3.2 Reliability Performance Measures

Some of the reliability measures used in the designing of products and plants are as follows:

- *Interval reliability:* The probability of no failure over a specified interval.
- *Interval availability:* The fraction of the time in which the product or system is in the operational (non-failed) state over a specified interval.
- The number of failures over a specified interval.

1.3.3 Degradation of Performance

The *desired performance* is the starting point for the designing and building/manufacturing of every engineered object. The design process is complicated, starting with components and materials and then building/manufacturing to produce the object. Since performance depends on usage (mode, intensity, etc.) and operating environment, the design process involves selecting components and materials to ensure the desired performance for some nominal values (or ranges) for usage and operating environment.

The performance of the object degrades due to the degradation of the material and components of the object. These are functions of age and/or usage and are influenced by operating environment. The degradation phenomenon is discussed in more detail in Chapter 3.

Table 1.6 Non-reliability performance measures for some engineered objects.

Engineered object	Type	Performance measures
Automobile	Consumer product	Fuel efficiency (km/l) Economic efficiency (cost/km/kg) Quality of ride Emissions (PPM)
Photocopier	Commercial product	Quality of image Throughput (copies/min)
Oil refinery	Plant	Efficiency Downtimes Emissions
Rail network	Infrastructure	Train delays (min/wk) Ride quality (noise, vibration, etc.)

1.4 Maintenance

Maintenance involves actions to (i) control or prevent the deterioration process leading to failure of an engineered object and (ii) restore the object to its operational state through corrective actions after a failure. The former is called *preventive maintenance* (PM) and the latter *corrective maintenance* (CM).

Maintenance is the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it may perform its required function.

1.4.1 Consequences of Poor Maintenance

We illustrate the consequences of poor maintenance through two examples.

Example 1.11 Vehicle Maintenance

Head gaskets: The head gasket in an automobile engine seals the cylinder head of the engine to the engine block. There are coolant and oil passages that transfer the oil and coolant from the engine to the head and back. The reason for these passages is for the oil to lubricate the valve train and the coolant to remove heat from the cylinder head. The other job of the head gasket is to seal the top of the cylinder to keep the compression contained. Head gasket problems arise generally due to poor maintenance of the cooling system. Acidic coolant may begin to eat away or erode the sealing area of the coolant passages in the gasket. This may cause a weak area and a leak may start to form. The head gasket leakage may travel either internally or externally. An external leak is visible outside the engine; an internal leak means that coolant may seep into oil passages or erode the compression sealing ring in the head gasket, allowing coolant to enter the cylinder or compression to enter the cooling system. This is what is called a *blown* head gasket.

Brakes: A coach driver and his business partner were jailed for the manslaughter of a couple who died in a road crash in the UK. An investigation by police concluded that the cause of the crash was acute brake failure due to poor maintenance. At the Crown Court, the coach driver was sentenced to five years and three months in prison after he admitted charges of causing death by dangerous driving and gross negligence manslaughter. His business partner, who pleaded guilty to gross negligence manslaughter, was jailed for three years. This resulted in a warning to all drivers who ignore vehicle maintenance warning signs – particularly in relation to tire and brake wear – that could result in a fatal road crash and land themselves and their bosses in court. ■

Example 1.12 Rail System Operations

An investigation by the Rail Accident Investigation Branch (RAIB) into a passenger train that overshot a station in East Sussex, UK by almost two-and-a-half miles revealed that it was because of poor maintenance. The report said that the train did not deposit sand (needed to assist the braking process) when the driver braked because the leading sand-hoppers were almost empty. Maintenance procedures did not ensure the sand-hoppers were refilled despite there being information that the sand was low. ■

1.4.2 Maintenance Costs

The costs of maintenance may be divided into two major categories:

- *Direct costs:* These costs are incurred due to maintenance and repair actions, broadly represented by the cost of labor, the cost of material and spare parts, the cost of contractors, and the costs of infrastructures used and related tax (service tax, etc.). Often, these are the costs which may be tracked down easily in account books.
- *Indirect costs:* These are costs resulting from the consequences associated with failure or unplanned maintenance actions and include loss of revenue due to the production stops owing to maintenance and repair actions, cost of accidents, demurrages, insurance policies, and so on.

The maintenance costs shown in Table 1.1 are the direct costs. The indirect costs are, in general, higher and depend on the engineered object. These indirect costs are difficult to measure but, in general, they are roughly equal to or greater than the direct costs The maintenance costs increase with time due to the aging effect and increasing labor costs. This implies that maintenance is a significant issue for businesses and government agencies.

1.4.3 Preventive versus Corrective Maintenance

As mentioned earlier, there are two types of maintenance: preventive (PM) and corrective (CM). Carrying out maintenance involves additional costs to the owners (individuals, businesses, and government agencies). As the level of PM effort increases, the PM costs increase and the CM costs decrease, as shown in Figure 1.2.

The total cost (PM and CM costs) has a convex shape, indicating that there is an optimal level of PM effort.

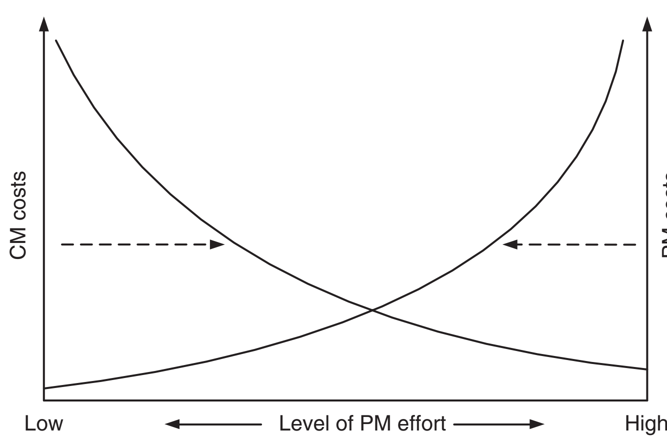

Figure 1.2 PM and CM costs versus PM effort.

1.4.4 Maintenance Management

Maintenance management deals with maintenance-related decision making (for example, recruiting of skilled labor, resource allocation, and scheduling of resources, etc.) at the strategic, tactical, and operational levels, and then initiating actions to implement the decisions.

Businesses and government agencies need to make decisions relating to maintenance of engineered objects at three different levels: strategic, tactical, and operational. Figure 1.3 lists some of the decision problems at each of these three levels.

Proper maintenance with periodic in-service inspections of an engineered object has a positive influence on the technical state of the object and may extend its lifetime considerably. A proper framework is required for planning and executing the decisions, with data playing an important role. Figure 1.4 shows the sequence of activities for implementing the decisions at the operational level.

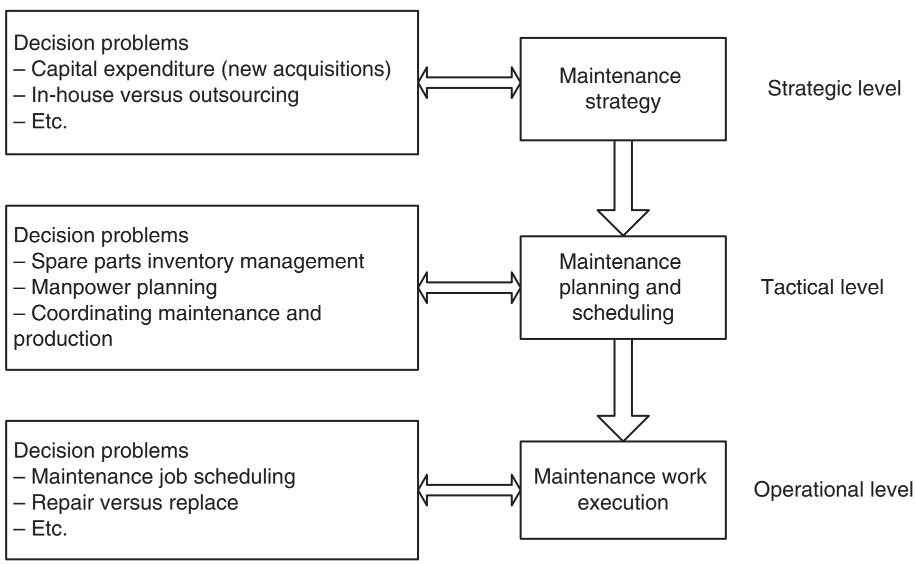

Figure 1.3 Decision problems in maintenance.

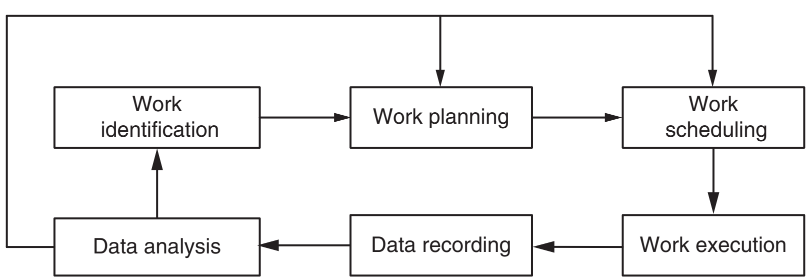

Figure 1.4 Implementation of decisions at the operational level.

1.4.5 Role of Science and Technology

Every object consists of several elements and each of these is comprised of one or more components. An understanding of the degradation process at the component level is critical to understanding the degradation of the object. Reliability science (discussed in the next chapter) deals with this topic. Technology has played an important role in assessing the degradation through the use of sensors. Both of these have played an important role in more effective management of maintenance.

1.5 Evolution of Maintenance

The approach to maintenance has changed significantly over the last century. In this section, we give a very brief historical overview of the evolution[6] as well as current trends in maintenance.

1.5.1 Historical Perspective

Until about 1940, maintenance was considered an unavoidable cost and the only maintenance used was corrective maintenance. When equipment failed it was the task of a specialized maintenance workforce to return the failed item to its operational state. Maintenance was not addressed during the design of the system, nor was the impact of maintenance on system and business performance recognized.

The evolution of Operations Research (OR) from its origin and applications during the Second World War to its subsequent use in industry led to the widespread use of preventive maintenance at component and higher levels. Since 1950, OR models for maintenance have appeared at an ever-increasing pace. The models examine many different maintenance policies and the optimal selection of the parameters of these policies. The impact of maintenance actions on the overall business performance is not addressed.

Starting in 1970, a more integrated approach to maintenance evolved in both the government and private sectors. New, costly defense acquisitions by the US government required a life cycle costing approach, with maintenance cost being a significant component. The close link between reliability and maintainability formed the basis for this change. The term "R&M" began to be used more widely in defense acquisitions to denote reliability and maintainability. This concept was also adopted by manufacturers and operators of civilian aircraft and formed the basis for Reliability Centered Maintenance (RCM) in the USA.

In the RCM approach, maintenance is carried out at the component level and the maintenance effort for an item (component or higher level) is a function of the reliability of the item and the consequence of its failure under normal operation. The core of the RCM philosophy is that maintenance will be performed only after evaluating the consequences of failures (safety, economic, operational, and environmental) at component level. In other words, it deals with optimization of preventive maintenance activities considering failure consequences. The RCM approach is system-oriented and may be implemented free of a company's organizational culture.

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[6] For a more detailed discussion of the evolution of maintenance, see Pintelon and Parodi-Herz (2008).

At the same time, the Japanese evolved the concept of Total Productive Maintenance (TPM) in the context of manufacturing. Here, maintenance is viewed in terms of its impact on the manufacturing (or production process) through its effect on equipment availability, production rate, and output quality. In TPM the focus is on autonomous maintenance through involvement of all employees and is a human- and employee-centered maintenance approach.

Both RCM and TPM are now widely used in various industrial sectors and many variants have been developed to extend their original functions and/or facilitate their application. Many businesses use elements of both as part of their maintenance strategies.

Since the late 1970s and early 1980s there has been a trend toward Condition Based Maintenance (CBM). This became possible with developments in sensor technologies which enabled PM actions to be based on the condition (or level of degradation) as opposed to age and/or usage.

Maintenance needs to be viewed from a long-term perspective. It needs to take into account the commercial aspects (which determine the load on components), the science aspect (to model the effect of load on equipment degradation), the socio-political aspect, demographic trends, and the capital needed. It needs to address issues such as in-house versus outsourcing of maintenance and their impact on the overall costs of maintenance and the associated risks. This requires an approach where maintenance decisions are made from a strategic perspective using a framework that integrates both technical and commercial issues in an effective manner from an overall business perspective.

1.5.2 Trends in Maintenance

Engineered objects are becoming more complex to meet the ever-increasing demand of customers. Detecting failures and faults is becoming harder and more time-consuming. The cost of labor to carry out maintenance has also been increasing. As a result, maintenance will continue to evolve and the two main drivers for this are (i) technology and (ii) management.

1.5.2.1 Technology Trends

Many different types of technologies are beginning to impact on maintenance. These include:

- *Sensor technologies:* These are used to monitor the condition of an object and to decide on maintenance based on the condition.
- *Information and communication technologies* (*ICTs*)*:* These technologies are used to access, store, transmit, and manipulate relevant information for maintenance decision making.

1.5.2.2 Management Trends

Maintenance is no longer viewed as a cost but as a function which creates additional value in the business process. The focus has shifted from fail-and-fix to root cause elimination, and from functional thinking to a process-oriented approach with the end customer being the focus. Trends include:

- *A risk-based approach to maintenance:* The focus is to reduce the business risk.
- *Maintenance outsourcing:* Here, a business outsources some or all of the maintenance actions to an external agent under a maintenance service contract.

1.6 Focus of the Book

Maintenance of engineered objects requires finding and implementing the solutions to a wide range of decision problems. The starting point is the list of business objectives. These determine the production rates and they, in turn, impact on the state of the asset which degrades with age and usage. Maintenance strategies need to take these issues into account. Formulating effective maintenance strategies requires (i) proper data collection and analysis and (ii) models to assist the decision-making process. This, in turn, requires a proper understanding of many different concepts, tools, and techniques. Figure 1.5 (from Murthy, Atrens, and Eccleston, 2002) shows the key elements and the linking between them.

A proper understanding of maintenance requires a comprehensive framework. There are many different definitions of a framework and the one that is appropriate in the context of the book is the following:

Definition 1.2

A framework is a logical structure that identifies key concepts, the relationships among the concepts to provide a focus, a rationale, and a tool for the integration and interpretation of information relevant to a decision problem. The structure serves as a starting point for developing models for solving the decision problem.

The framework needs to deal with one or several of the following issues depending on the maintenance problem under consideration:

- Use of scientific methods to understand the degradation processes;
- Proper collection and analysis of relevant data;
- Use of models for decision making;

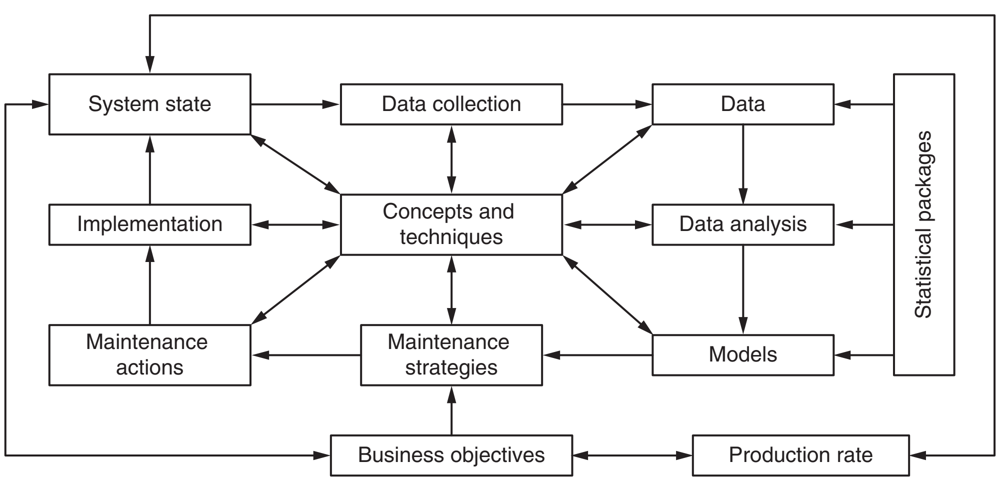

Figure 1.5 Solving maintenance decision problems.

- Use of appropriate technologies;
- Effective maintenance management.

The focus of the book is on introducing students to a comprehensive framework that looks at maintenance from a "big picture" perspective, combining the above elements in a unified manner including the latest trends in maintenance.

1.7 Structure and Outline of the Book

The book is structured in five parts (Parts A–E), each containing one or more chapters, and Part F with five appendices. For Parts A–E, the logical linking between chapters and appendices is given below.

Part A: Maintenance Engineering and Technology
This part consists of the following six chapters:

- Chapter 2: Basics of Reliability Theory
- Chapter 3: System Degradation and Failure[7]
- Chapter 4: Maintenance – Basic Concepts
- Chapter 5: Life Cycle of Engineered Objects
- Chapter 6: Technologies for Maintenance
- Chapter 7: Maintainability and Availability

Chapter 2 looks at basic concepts from reliability theory, since they are needed for a proper understanding of maintenance. Chapter 3 deals with system degradation and failure. A proper understanding of failure mechanisms is crucial to effective maintenance planning. Basic maintenance concepts are covered in Chapter 4, including types of maintenance actions, maintenance requirements of different engineered objects as complexity increases from product to plant to infrastructure, and the important elements of effective maintenance. To be effective, maintenance needs to be viewed from a life cycle perspective, and this is discussed in Chapter 5. Chapter 6 deals with maintenance technology, as technology plays a crucial role in maintenance in terms of data collection, transmission, and processing. Technology also plays a key role in CBM. The final chapter (Chapter 7) in this part of the book is devoted to maintainability, since designing engineered objects for ease of maintenance and efficient use of resources may reduce a good proportion of maintenance costs and enhance the performance of the engineered object in terms of its reliability and availability.

Part B: Reliability and Maintenance Modeling
This part consists of the following five chapters:

- Chapter 8: Models and the Modeling Process
- Chapter 9: Collection and Analysis of Maintenance Data

[7] A system is a collection of interconnected elements. As such, products, plants, and infrastructures can be viewed as systems.

- Chapter 10: Modeling First Failure
- Chapter 11: Modeling CM and PM Actions
- Chapter 12: Modeling Subsequent Failures

Models play an important role in understanding and solving maintenance problems. Models and modeling issues, including the steps of the mathematical model-building process, are discussed in Chapter 8. Chapter 9 deals with maintenance data and information. Types and sources of maintenance data, data collection, and preliminary analysis of data (which requires concepts from the theory of statistics) are among the issues presented in this chapter. Chapter 10 discusses probability models for time to first failure. Important issues discussed include different probability distributions, their properties, parameter estimation methods, and model validation. Chapter 11 deals with modeling maintenance actions which affect subsequent failures. The modeling of subsequent failures is the focus of Chapter 12 and this requires an understanding of point processes because failures occur as random points along the time axis.

Part C: Maintenance Decision Models and Optimization
This part consists of the following four chapters:

- Chapter 13: Optimal Maintenance
- Chapter 14: Maintenance Optimization for Non-Repairable Items
- Chapter 15: Maintenance Optimization for Repairable Items
- Chapter 16: Condition-Based Maintenance

Building on the knowledge gained from Part B, Part C deals with various replacement, preventive maintenance, and condition maintenance models. Chapter 13 looks at the process needed to build models for the optimal maintenance of an item. Chapter 14 deals with models for the optimal maintenance of non-repairable items, while Chapter 15 deals with similar issues for repairable items. Chapter 16deals with condition-based maintenance, building on Chapter 6.

Part D: Maintenance Management
This part consists of the following six chapters:

- Chapter 17: Maintenance Management
- Chapter 18: Maintenance Outsourcing and Leasing
- Chapter 19: Maintenance Planning, Scheduling, and Control
- Chapter 20: Maintenance Logistics
- Chapter 21: Maintenance Economics
- Chapter 22: Computerized Maintenance Management Systems and e-Maintenance

Chapter 17 deals with maintenance management issues ranging from maintenance strategic planning to maintenance control and the two well-known and commonly used methodologies – RCM and TPM. Maintenance outsourcing is a strategic maintenance issue discussed in Chapter 18. Chapter 19 is devoted to the important issue of maintenance planning and scheduling. Maintenance logistics, the supply chain, and spare parts management issues are presented in Chapter 20. Chapter 21 deals with maintenance economics and includes life cycle costing methods and capital replacement models. Maintenance performance measurement is a key to continuous improvement and computerized maintenance management systems (CMMSs) are vital for storing, processing, and producing timely reports and information required for informed decision making. These issues are the subject of Chapter 22 along with e-maintenance, an area where technology plays a key role in gathering and delivering information where it is needed.

Part E: Case Studies
This part consists of the following chapter:

- Chapter 23: Case Studies

The chapter looks at two real cases that illustrate the linking of concepts provided in the various chapters of the book.

Part F: Appendices
Part F consists of the following five appendices:

- Appendix A: Introduction to Probability Theory
- Appendix B: Introduction to Stochastic Processes
- Appendix C: Introduction to the Theory of Statistics
- Appendix D: Introduction to Optimization
- Appendix E: Data Sets

Review Questions

1.1 What is maintenance?

1.2 What are the consequences of product failure? Give examples.

1.3 Explain the following statement: "Building in reliability is costly. However, not having adequate reliability is costlier."

1.4 What are the three main aspects of maintenance?

1.5 What is an adequate classification of engineered objects?

1.6 How is the performance of an engineered object measured?

1.7 What are the factors that affect performance degradation?

1.8 What are the different types of maintenance costs?

1.9 What is the effect of PM effort level on CM and PM cost and what are the implications?

1.10 What are some of the maintenance management decisions at the strategic, tactical, and operational levels?

1.11 What are the main historical developments in maintenance up to the present day?

1.12 What are the new trends in maintenance?

1.13 What is the main focus of this book?

Exercises

1.1 Describe the operations and list some non-reliability performance measures for the following engineered objects:
   (a) Room air-conditioner.
   (b) Commercial refrigerator in a restaurant.
   (c) Back-up generator in a large hospital.
   (d) Elevators in an underground mine.
   (e) Food-processing plant.
   (f) Pipe networks in an urban area.
   (g) Railway infrastructure (tracks, bridges, power supply, communication system).

1.2 Comment on the following statement: "Building in reliability is costly but the consequences of not having adequate reliability are costlier" in the context of the following engineered objects:
   (a) Aircraft.
   (b) Nuclear reactor.
   (c) Implant in a human (for example, a heart pacemaker).

1.3 Discuss how production (output in the case of plants and throughput in the case of infrastructures) and maintenance affect each other in the context of the following:
   (a) Road network in a region.
   (b) Manufacturing plant.
   (c) Power station.
   (d) Pipe network distributing water to an urban area.
   (e) Railway bridges and tunnels.

1.4 Many consumer products need regular maintenance. Make a list of a few products and discuss the maintenance (preventive and/or corrective) requirements for each of these items.

1.5 Explain in a paragraph the relevance of each of the topics listed below from a maintenance perspective:
   (a) Sustainability.
   (b) Risk.
   (c) Economic impact.
   (d) Societal impact.
   (e) Product quality.
   (f) Product reliability.

1.6 Individuals may lease automobiles and other household objects (such as refrigerators, televisions, etc.) as opposed to buying. List the reasons and the advantages and disadvantages of leasing.

1.7 Buildings (large complexes and apartments) need regular maintenance. List the different types of maintenance activities that are needed.

1.8 Explain the link between maintenance and production from a business perspective using Figure 1.1.

1.9 Explain, using Figure 1.5, why a proper understanding of maintenance requires a comprehensive framework that requires making use of several disciplines.

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