

1

Introduction

This chapter provides an introduction to electric power grids as strategic infrastructures (Section 1.1); introduces asset management (AM) as an approach to optimize performance versus efforts (Section 1.2); provides an overview of maintenance concepts with their underlying philosophies and under which conditions they are preferred (Section 1.3); and finally discusses incident management (IM) (Section 1.4). The purpose of this chapter is to describe the context of the statistical methods discussed in this book.

1.1 Electric Power Grids

In 1880 Joseph Wilson Swan started to provide electricity to a residence in Rothbury, UK and in 1882 Thomas Edison's Pearl Street Station power plant generated electricity for homes in Manhattan. Edison envisaged: 'After the electric light goes into general use, none but the extravagant will burn tallow candles' [1]. This statement evolved into: 'We will make electricity so cheap that only the rich will burn candles'. Interestingly, these statements refer to three themes that are important to AM: performance (electric light versus candles), general use (utility) and price (extravagant, rich).

In many countries electricity lived up to this expectation and became a dominant energy carrier, not just for lighting, but also for industrial machines, transportation, many household functionalities and more. Electric power networks grew, were integrated and expanded to continental grids and larger. Interconnections have been developed, such as the 580-km NorNed submarine cable that enables hydropower reservoirs and consumption in Norway to act as energy storage for, for example, a surplus of wind power generated out of the German coast. That energy can be transmitted through the Netherlands' grid and transmitted through this NorNed cable or connected to other grids in Europe and beyond. The 130-kW power plant of 1882 has been succeeded by GW power plants installed by State Grid, China. Nowadays, developed countries depend to a great extent on a reliable supply of electric power, which makes electric power grids very strategic infrastructures. The growing environmental awareness and focus on sustainable energy led to initiatives like the German '*Energiewende*' (in English: energy transition, namely the shift from fossil and nuclear energy to sustainable energy), which only adds to the importance of electric power grids with electricity as a convenient energy carrier.

A power grid consists of many assets, but it is much more than a collection of components. The assets depend on each other to such an extent that they form clusters and connections which can be treated as units. For instance, a cable system consists of a cable termination and cable sections that are linked with cable joints. In addition, this cable system combined with primary components like switchgear, measuring transformers (current, voltage), a power transformer and a rail forms a circuit. Two parallel circuits can form a redundant connection, and so on. The components and connections are often controlled and protected by secondary systems. All those systems together form the network or grid.

Utilities are responsible for the performance of these networks. The assets that together form the grids need to be designed for their function, supervised, maintained, repaired and finally replaced. The network as a whole must fulfil its duty of collecting, conducting and supplying energy. It must be robust and cost-effective, and moreover must be safe and blend well into the environment. Planning and decision-making to meet these requirements is the core of AM. Mature AM is based on lessons learnt from the past and present philosophies. It works with assumptions and predictions to optimize decision-making. There are different styles of AM and of decision-making with IM, but they all take great benefit from statistical techniques. This book aims at providing the essential background for applied statistics to be used in AM and IM.

1.2 Asset Management of Electric Power Grids

Since electrical energy started being transmitted and distributed through power networks, the electric power supply has changed modern society, but society in turn has also changed the electric power supply. Starting out as more or less a gadget offered by inventors, entrepreneurs and technical engineers, many countries nowadays have ministries of energy or economic affairs to develop strategies for energy supply. Political choices set the targets of the performance and conditions that utilities have to meet. The expectations have to be fulfilled through an infrastructure composed of many components and connections that form the networks or grids. The physical components are the tangible assets that together shape this infrastructure. The question is how to reach the requested performance and added values at the lowest price. Value and price do not necessarily concern merely financial or economic concepts, but can also involve other business values like safety, power quality, security of supply, and so on.

AM is the collective term for the structured decision-making and execution of plans to reach an optimized balance between performance, efforts and risk with the utilization of assets. This includes all aspects that are relevant to the performance of the grid, such as the strategy, operations, finance, regulations, information, value and more. An AM system is an organized set of systematic and coordinated activities to stay in control.

Standards have been developed for common practice in AM. The Institute of Asset Management (IAM), together with the British Standards Institute (BSI), developed the Publicly Available Specification 55 (PAS 55) [2]. This standard led to the ISO standards 55000, 55001 and 55002 entitled ‘Asset Management — Overview, Principles and Terminology [55000]; Requirements [55001]; and Guidelines on the Application of ISO 55001 [55002]’, which are generally applicable for the purpose of managing physical assets [3–5]. ISO 55000 defines an asset as ‘an item, thing or entity that has potential or actual

value to an organization. The value will vary between different organizations and their stakeholders, and can be tangible or intangible, financial or non-financial'. AM then translates the organization's objectives into asset-related decisions, plans and activities, using a risk-based approach. Effective AM is not just an activity, but rather an integrated system that must be implemented organization wide and combine all related disciplines including managerial, financial and technical in order to create optimum value during the complete asset lifecycles.

Considering all aspects there will be conflicting interests, which urges organizations to find optimum balance. For instance, keeping assets in service as long as feasible is a way to postpone investments, but also increases the risks associated with unplanned outage by failing assets. The optimum between postponing investments and preventing damage due to failures touches the interest of not only various organizational departments, but also of stakeholders including employees, clients, investors, legislation and even people passing by a substation (for safety). AM therefore requires a comprehensive system to provide an integral approach. The treatment of such a system is beyond the scope of the present book, but the matter is very well introduced by a free document provided by the IAM (see also 'Asset Management – An Anatomy' [6]). Various AM subgroups (Table 1.1) are distinguished. Most of these subgroups use data that is processed to provide information. This involves descriptive statistics as well as inferences to analyse scenarios and carry out forecasting that is used for planning.

Section 1.3 elaborates further on the essential aspects of AM, namely maintenance styles (part of 'Lifecycle delivery activities' in Table 1.1) in relation to failure behaviour

Table 1.1 AM subject groups (for a detailed description, see [6]).

AM subject group		
1.	AM strategy and planning	Core activities to develop AM policy into plans. Based on organizational strategy, organization and people enablers and AM decision-making, giving input to the lifecycle delivery activities.
2.	AM decision-making	Framework for decision-making on the optimum blend of activities to achieve specific objectives. It is based on asset knowledge enablers as well as organization and people enablers. Balancing cost and value as well as strategies related to ageing assets are part of this subject.
3.	Lifecycle delivery activities	The lifecycle comprises acquisition, operation, maintenance and disposal of assets. It is based on AM strategy and planning, asset knowledge enablers as well as risk and review. Incident response is part of this subject.
4.	Asset knowledge enablers	Data, information (data in a context) and knowledge (experience, values, information, insight combined as basis for decision-making). The knowledge comprises a SWOT analysis (strengths, weaknesses, opportunities and threats) related to the assets. This subject also concerns what and how information is collected and used in the organization.
5.	Organization and people enablers	Concerns contract and supplier management, as well as leadership, structure, culture, competence and behaviour within the organization.
6.	Risk and review	Among others, assessment of criticality and risk management of performance monitoring and accounting.

versus preventive measures. In the light of these maintenance styles, asset health and risk are also discussed. The purpose is to provide a focus on the relationship between these concepts and statistical failure behaviour.

1.3 Maintenance Styles

Managing the grid assets requires decision-making about the whole lifecycle of assets. This starts with the design and specifications of the local grid and the way compliance is tested. It ends with disposal of the assets when operation of that part of the grid is no longer needed. In between, the assets are part of the operational grid. As the performance, condition and properties of the assets that build the grid may change over time, maintenance is required to keep the grid fit for purpose. There are various policies that can be followed when managing (systems of) assets to remain in operation. In the following sections, the maintenance activities are divided into:

- inspections
- servicing
- replacement.

Inspections are activities to check the functionality and other properties of the asset. In case of a transformer, this can be visual inspection of the housing to check for oil leakage, testing the quality of bushings, monitoring the properties of the oil, and so on. Servicing the asset concerns all preventive or corrective activities that aim at prolonging operational life and improving the condition of an asset, like replacing contacts in switchgear or cleaning insulator surfaces. Repair, refurbishment and overhaul also fall into this category. Replacement means ending the operation of one asset or subsystem and installing another asset or subsystem to take over the required functionality. The collective term of ‘maintenance style’ is used for the combination of inspections, servicing and replacement.

Maintenance styles are rooted in the AM system. AM decisions will generally balance various aspects. Examples of such aspects are listed in Table 1.2, where the aspects are grouped in the categories ‘Licence to Operate’, ‘Resources’ and ‘Financial’. In reality, the

Table 1.2 Examples of aspects to be balanced with asset management.

Licence to operate	Resources	Financial
<ul style="list-style-type: none"> • Being in control • Safety • Security of supply • Power quality • Politics • Permits • Public relations • Image of social responsibility • In compliance with law • ... 	<ul style="list-style-type: none"> • Reliability and availability of grid assets • Access to expertise • Availability of qualified and skilled personnel and contractors • In-time delivery of services and parts • Stock of spare parts • Local circumstances • ... 	<ul style="list-style-type: none"> • Capital expenses (new equipment) • Operational expenses (maintenance costs, etc.) • Compensation (damage, non-delivery, right of way) • Hiring personnel • Income through tariffs • Public investment • ...

AM systems embrace many more aspects and categories, but Table 1.2 illustrates the variety of aspects that are balanced with AM. For instance, the utility earns its licence to operate the grid by adequate performance, which includes securing the power supply and power quality (a set of characteristics of the voltage like amplitude and frequency stability, low disturbance in the form of harmonics and transients, etc.) in a safe and affordable way.

In order to earn this licence, the utility needs access to resources that enable the construction, operation and control of the grid. Resource aspects concern reliability and availability, including personnel, parts and market partners like manufacturers, contractors, and so on. It may require that reliable equipment can be bought from at least two different manufacturers in order to secure the supply of products in case one manufacturer faces problems in production. Power supply is important, but must also be financially balanced. Financial expenses are generally divided into capital expenses (CAPEX) and operational expenses (OPEX). CAPEX involves all investments in the construction of new and/or replacement assets; OPEX refers to all costs of operating assets such as inspections and servicing.

Historically, the maintenance style developed with the role of electric power in society, characteristics of assets, political views, technological breakthroughs, environmental circumstances and the role of information technology, to mention a few. The role of electric power developed from a luxury article replacing candles to a commodity article that significantly improved health and working conditions (cf. [7–9]). The importance of reliability and availability of the electric power supply shifted from it being a luxury item to basically a necessity of life. Whatever the degree of dependence, the power system must fulfil its task. This is the role of AM, and the AM boundary conditions will determine what maintenance styles are preferred.

Though many variations in maintenance styles exist, four main styles can be distinguished, as described in the following sections:

1. corrective maintenance (CM)
2. period-based maintenance (PBM)
3. condition-based maintenance (CBM)
4. risk-based maintenance (RBM).

For each style, implications are discussed with respect to inspections, servicing and replacement, and when this style is typically applied. The term ‘hazard rate’ is used in the discussion on maintenance styles to express the danger that an asset fails. For the moment, this qualitative concept does not need to be explained further. However, Chapter 2 discusses the hazard rate as one of the basic statistical functions (see Section 2.4.5).

1.3.1 Corrective Maintenance

CM aims at mitigating situations with defective assets (i.e. failed, insufficient functioning or unacceptably damaged). No preventive action is carried out until the moment the asset becomes defective. Another name for this style is run-to-fail. This may look like a rather careless type of maintenance, but there can be very good reasons to apply this style. Figure 1.1 shows the concept of CM.

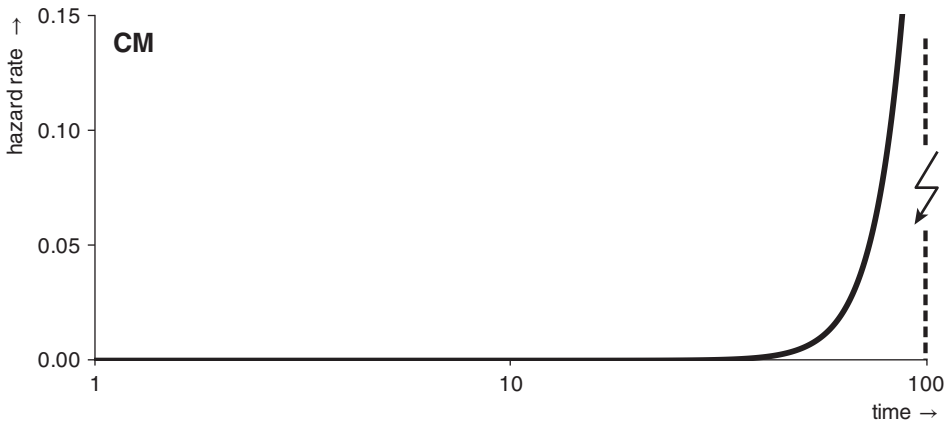


Figure 1.1 The concept of CM: the asset is left to operate without preventive maintenance. Repair or replacement is carried out after failure.

A familiar example of domestic CM is generally applied with lighting. Lamps at home will be used without maintenance until failure and are then replaced.

1.3.1.1 CM Inspections

If inspections are carried out, this is mainly to check whether the asset is still functioning well. It may also include determining whether the local environment is suitable. For example, it may be concluded that vegetation should be cut if it threatens the asset. If an asset has a task to fulfil in one way or another, it must be considered how it will become apparent that corrections must be carried out (i.e. when the asset has stopped working).

1.3.1.2 CM Servicing

CM avoids servicing. If the asset under consideration is not able to fulfil its task, it must be repaired or replaced. Therefore, CM restricts maintenance to corrective actions after an asset fails. Usually it is evaluated whether repair or replacement of the asset is preferred.

1.3.1.3 CM Replacement

Replacement means removing the old asset and installing a new one. The CM maintenance style will probably influence the specification of the asset. For instance, if an asset will be employed in a remote or otherwise hard-to-access place where servicing requires unreasonable efforts, then CM may be the only realistic option. In order to optimize the performance, the specification of the asset may prescribe a long life without servicing. In contrast, another maintenance style may be preferred over CM in accessible locations where convenient servicing procedures exist. The serviceability would then most likely appear in the specifications.

1.3.1.4 Evaluation of CM

CM is particularly applicable in situations where:

- (a) OPEX is considerably larger than CAPEX (i.e. it is significantly cheaper to replace than carry out preventive maintenance). Large parts of cable networks are

managed by this style, although monitoring and diagnostic systems are increasingly employed.

- (b) Maintenance initiates failure behaviour. In such cases the relevant phrase is ‘as long as it works, don’t touch it’. A typical example used to be generators, which had a bigger chance of failing after maintenance and recommissioning than when they ran without human interference. This changed when sensors were developed that could indicate the adequate moment for maintenance (CM then turns into CBM, see Section 1.3.3).
- (c) The asset life cannot be extended by maintenance, because of its properties. A lamp is a typical example; with most lamps there is very little that can be done to improve their condition by servicing (other than sometimes, e.g. if dirt can be removed to avoid overheating).
- (d) The asset cannot be maintained because it is out of reach, which may apply to remote unmanned stations, satellites in space, assets in harsh environments, and so on.

CM is sensible in various situations, but it needs to be checked whether situations allow CM and indeed, if not, whether the situation can be adapted to become suitable. For instance, it may be unacceptable that a complete system goes down after failure of a single asset in the system. A solution to that situation is to introduce redundancy (see Section 7.4) and emergency plans. Examples are double lights on a car, quick repair (e.g. due to quick access to spare parts – lights in a house, cable splices and terminations in a storage facility; see also Section 8.5) or providing an alternative like allowing a manual override if a control system itself is subject to CM.

An important issue mentioned above is whether a failed asset is detected in a timely manner. An insulation failure results in a breakdown which is usually readily observed, but if the contacts of a circuit breaker or disconnecter are welded together on closing the contacts, malfunction may only appear at the moment that the circuit breaker needs to break a current but is unable to do so. Again, redundancy is the general solution to that, which translates into switching equipment in series with circuit breakers.

Overall, CM has the advantage of low OPEX and taking advantage of the full technical lifetime of the asset. But it is not always true that the expenses of CM mainly consist of CAPEX. A failure or interruption of service may also be solved by refurbishment. Keys to successful CM are timely detection of malfunction, fast response, flexible workforce and robustness of the grid after asset failure and/or matching asset lifetimes with system lifetimes (e.g. with non-serviceable systems).

1.3.2 Period-Based Maintenance

PBM is also referred to as ‘time-based maintenance’, ‘use-based maintenance’ or ‘periodic maintenance’. This style aims at preventing asset failure by timely preventive actions with fixed intervals (periods) in between (see Figure 1.2). These intervals can be periods in terms of calendar times, but can also be operational hours, number of switching operations, and so on. So, ‘period’ does not necessarily refer to time. For that reason, the term ‘period-based maintenance’ is preferred over ‘time-based maintenance’. Typical examples are routine visual inspections at a substation (calendar periods), replacement of turbine blades after fixed running hours (usage or operational hours), servicing switchgear after a fixed number of switching actions, or maintaining

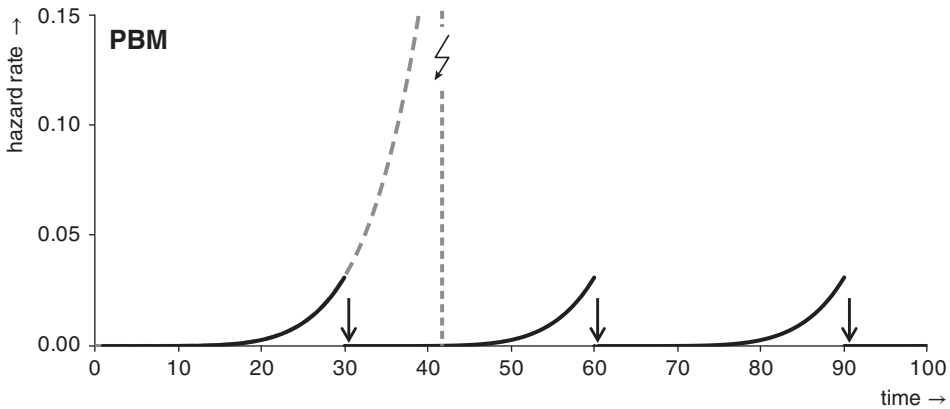


Figure 1.2 The concept of PBM: the asset is periodically maintained to reduce the hazard of failure expressed in terms of the hazard rate (Section 2.4.5). The dotted line shows the development without PBM and the solid lines show maintenance with PBM to extend the operational life of the asset. *Note:* In practice, the reset of the hazard rate is not perfect (cf. Section 9.1.1.4).

a car after a prescribed number of driven kilometres/miles. Traditionally, this style has been (and still is) used in grids to keep the system in optimum technical condition. Because of its high costs, however, it is increasingly replaced by CBM (see e.g. Sections 1.3.3 and 9.1.1).

1.3.2.1 PBM Inspections

Inspections with PBM are according to a plan with fixed periods in between, irrespective of the asset condition. As mentioned before, these periods can be defined in terms of calendar time, but also running hours, number of rotations, switching actions or lightning strikes, and so on. Various inspection cycles may be employed simultaneously (e.g. visual inspections at a higher frequency and more labour-intensive deeper investigations at a lower frequency). Because the planning will be comprehensive, there is a high probability that all assets are inspected in due time and a good, up-to-date overview of the asset states can be available at any moment. Inherent to PBM is that it tends to be labour-intensive and most inspections are carried out without the need for follow-up actions.

1.3.2.2 PBM Servicing

Servicing with PBM involves planned cleaning, overhaul or refurbishment. Whereas CM acts on asset failure, PBM plans to prevent these failures. This means carrying out servicing before failure might occur. Overall, a grid that is maintained by the PBM style tends to be in very good technical shape at relatively high cost. The advantage is that the grid suffers fewer failures, faces fewer emergencies and becomes more predictable. The disadvantage is that equipment may be serviced too often, equipment may be more frequently planned out of service and resources may be unnecessarily spent. Some assets may be vulnerable to excessive servicing, with the danger of introducing child mortality (i.e. unexpectedly early failures) into the equipment caused by maintenance, which produces the reverse of what is aimed for. However, these disadvantages may be overcome by employing a larger period/lower frequency for PBM.

1.3.2.3 PBM Replacement

Applied to replacement, PBM means replacing assets after a fixed period, which could be calendar time, operational time or other measures of deployment. The advantages of PBM are high reliability of the assets in use due to timely replacement, having time to wait for the right price to acquire assets and receiving assets in time. The disadvantage is that valuable remaining life of the assets is sacrificed (cf. Section 9.1.3). In some particular cases, child mortality may appear in the new assets, which does not increase but rather decreases grid reliability. Another concern is that frequent replacement means taking parts of the grid temporarily out of operation, which limits the operational flexibility in the grid. Although PBM may give insight into the development of the early stages of ageing, it also prevents the build-up of experience with actual asset lifetimes because every asset is replaced before failing. This effect can be reduced by analysis of removed assets to evaluate the likelihood that the asset would have failed in the near future or by testing assets on remaining life after taking them out of the grid.

1.3.2.4 Evaluation of PBM

PBM requires a planning, register and progress monitoring system. It will have relatively high OPEX due to frequent preventive actions, irrespective of the asset condition, and also relatively high CAPEX because of early replacements to keep the failure probability low. On the other hand, the periodic servicing may extend the operational life of assets.

Situations where PBM is particularly applicable are where:

- (a) Assets are of such strategic value that relatively high OPEX and high CAPEX are justified.
- (b) OPEX is a worthwhile investment compared to CAPEX, when servicing is known to prolong operational life and/or is more cost-effective than a higher level of redundancy. So, the depreciation of the assets is lower (e.g. regular visual inspection of a (sub)station is a fairly cheap way to detect problems such as oil leaking out of transformer coils or surface deterioration of insulators). Being able to detect problems at an early stage enables timely plan servicing. This helps to prevent early failure and replacement.
- (c) The ability to plan maintenance and replacement provides significant profits compared to the required flexibility for ad-hoc mitigation with CM.

PBM is particularly favoured in a technology-driven environment and where uninterrupted performance is required. However, the assets must be suitable for periodic check-ups. If inspections require the asset to be temporarily taken out of operation, the system as a whole must allow that interruption. Again, redundancy may enable that situation.

Overall, PBM is usually associated with a high degree of reliability, but also with relatively high OPEX for frequent inspections and maintenance and high CAPEX for timely (early) asset replacement. Keys to successful PBM are assets with a predictable lifetime, readily observable quality, good planning and access for inspections, servicing and replacement.

1.3.3 Condition-Based Maintenance

CBM or also reliability-based maintenance aims at a compromise between CM and PBM by using smart technologies and knowledge rules. The concept is that preventive

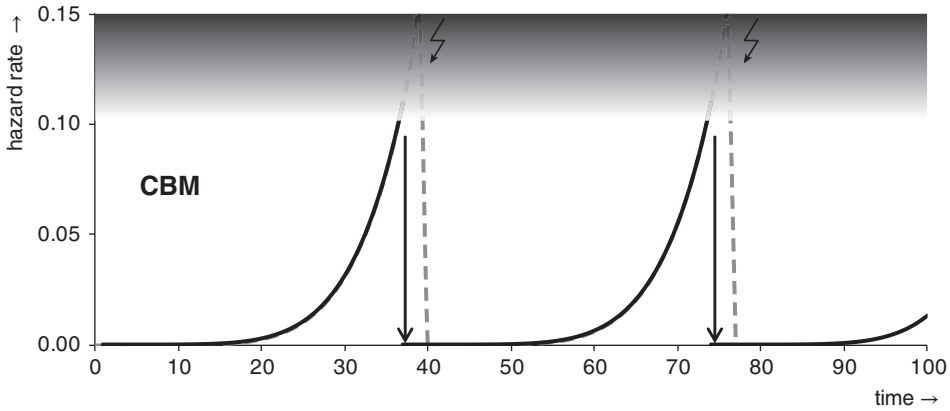


Figure 1.3 The concept of CBM [11]: the hazard of failure can be detected by diagnostics and expert rules on remaining life. This is depicted by the dark band. The dotted line indicates that a failure would occur if no preventive action is taken. The arrows show that maintenance or replacement reduces the hazard rate, which is the essence of CBM.

actions are avoided until the final stages of ageing reveal themselves through a diagnostic technique, in combination with adequate failure forecast of remaining life based on knowledge rules. CBM leans heavily on the ability to detect the early stages of failure or a (side) effect that correlates well with the hazard of failure (see Figure 1.3), as well as on the correct interpretation of the observations by expert rules that translate the observations into an adequate diagnosis. With proper diagnostics and expert rules, CBM aims at timely interventions when the hazard of failure becomes significant. Expert rules are also called knowledge rules.

For instance, cables and cable terminations may break down due to electrical treeing that precedes the actual breakdown. Depending on the specific situation, like materials and circumstances, this electrical ageing process develops in weeks up to even years and is driven by partial discharge (a kind of sparking within the insulation without being a full breakdown). These partial discharges can be detected by sensors and signal processing systems, that may even allow the partial discharge location to be pinpointed. A condition monitoring system (CMS) may be in place to monitor the occurrence of partial discharge. If experience is built up about the correlation of partial discharge and remaining life, partial discharge monitoring can generate alerts for imminent breakdown. Preventive measures can then be taken in time [10]. This is a typical CBM approach.

The style gained importance after utilities were forced to operate at lower cost. Cutting back on PBM was a first reflex, but generally the lack of maintenance did not meet the expected cost reductions and – even worse – jeopardized the security of supply. As mentioned above, PBM is planned irrespective of the asset condition, but that does not mean that all maintenance can be reduced without damage. The efficiency of maintenance could be improved if inspections and servicing could target assets that require attention, while leaving healthy assets unattended.

Investments in cost-effective, smart technologies became essential. The success of CBM was partly due to new sensitive detectors, but also due to knowledge rules that effectively translated observations and expert opinions into meaningful alerts.

A domestic example is a smoke sensor that reveals the early stages of fire. Another example is inflating bicycle tyres after they appear too soft and the hazard of damaging the tyre by riding the bike is deemed unacceptable (or too uncomfortable).

1.3.3.1 CBM Inspections

One of the first achievements of CBM was to reduce the number of periodic inspections by using inspection results to forecast whether the next planned inspection might or might not be skipped. For instance, if insulators are found to be in a very good state on inspection and the local circumstances are mild to the equipment, it may be practically certain from past experience that the next inspection also (as planned with PBM) would not urge the crew to take any corrective actions. So those inspections might be skipped as well. In the line of CBM the frequency of inspections can be reduced, which reduces OPEX without increasing CAPEX. If, on the other hand, the asset does not require immediate attention, but the condition seems to deteriorate, then the next inspection should be carried out as planned or even earlier. Such smart planning and alerts require expertise to be laid down in knowledge rules. With the automated processing of inspection findings, development of sensors and smart monitoring techniques, the inspection frequency can thus be optimized. Of course, there has to be a sound balance between investing in CMSs and reduced inspection costs.

1.3.3.2 CBM Servicing

CBM servicing involves methods to determine the condition and then be able to timely plan overhaul and repair the asset (just) before it fails. An alert that an asset is reaching possibly dangerous levels of degradation can be obtained from diagnostic programs or inspections (by CBM or PBM). Often inspections (even with PBM) contain elements of CBM, because if unacceptable situations are observed, then also with PBM such situations are normally mitigated immediately. The CBM style responds to triggers that call for servicing just-in-time.

1.3.3.3 CBM Replacement

Condition-based replacement aims at deploying assets until their last stages of operational lifetime. In that way asset depreciation is minimized and most benefit is taken from CAPEX. The definition of end of life may not just be time until technical failure, but alternatively the time until end of economic life. For instance, once the rate of inspection and servicing costs exceed the depreciation of new equipment, the conclusion can be that economic life is over and it is more cost-efficient to replace the asset than to keep it in operation. This interpretation of condition and operational life tends towards RBM, but stays close to the focus of managing the condition of assets and could therefore be regarded as CBM.

1.3.3.4 Introduction to the Health Index

A method that enables a convenient overview of the condition of the assets in a grid is provided by the so-called health index (HI). It is particularly helpful in evaluating populations of assets and can be extended towards groups of different assets such as connections consisting of linked assets and (sub)grids. The concept rates the condition of each asset in terms of the HI. It is an indicator for the urgency to service or replace an asset. The HI concept is presented in Figure 1.4 (cf. [12]) and explained below.

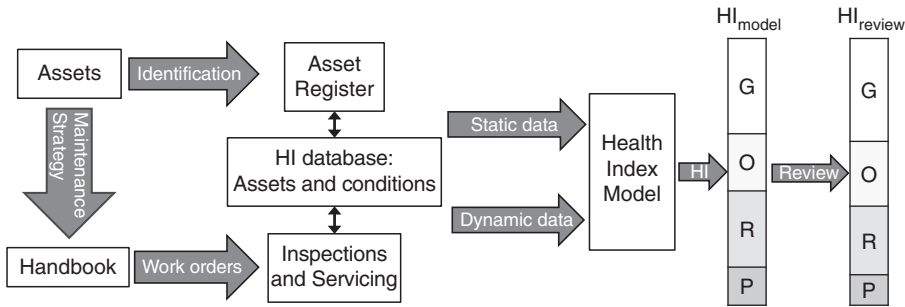


Figure 1.4 The concept of the health index [12]. Based on the asset type (static data) and observations (dynamic data), a HI model calculates the HI_{model} , which may be checked and adjusted to yield the HI_{review} . The cell heights in the columns (right side of the flow chart) reflect a percentage of the asset population. The codes in the cells mean: G = green (OK, no action required); O = orange (fair, but action required to return to G); R = red (suspect, investigation required, plan for repair or replacement); P = purple (urgent attention required).

Assets with their identification (ID) and characteristics like location, year of installation, and so on are stored in an asset register. These are the so-called static data. The assets are subject to a certain maintenance strategy, which is described in a handbook (which can also be an electronic document or interactive website) and induces orders for inspections (condition assessment) and servicing. The results from the condition assessment and servicing are observations which are translated into condition indicators (CIs). These findings are the so-called dynamic data. The static and dynamic data are stored in a HI database and used as input to the HI model.

This model consists of knowledge rules that are used to assign a HI_{model} based on the static and dynamic data. The HI_{model} reflects the probability that the asset will fail in a defined upcoming period. This HI_{model} is generally a score on a certain scale (which can be 1–10 or 1–100, etc.). This mark is often also translated into some colour code (as in Figure 1.4). Four colours may be used, but three or two are also practiced. Typically, the colour scheme follows the traffic-light convention, possibly extended with an additional colour (green = good; orange/yellow = fair, but action required and possible to return to green; red = suspect, plan for replacement or refurbishment; and purple = urgent attention required). A group of assets will have a certain percentage of each colour, which gives the HI_{model} colour distribution shown in Figure 1.4. As the HI_{model} is calculated by a model and the actual situation may be somewhat different, the results should be checked, which leads to a HI_{review} . Ideally, the HI_{model} and HI_{review} will be the same, but in the stage where the knowledge rules still need to be developed there may be significant differences. This is a learning cycle that should improve diagnostics, knowledge rules and the HI model, and possibly lead to considering other CIs. Even after many years, issues with new information may come up that urge updates of the HI method. Some scatter will usually also occur due to differences in assets, observations and circumstances.

The HI_{review} of the individual assets is input to planning of servicing or replacement. The collective HI_{review} gives insight into the condition of the total asset base in the grid and can be used to plan maintenance and replacement of assets. The HI of assets that together form a connection or even (sub)grid can be integrated into a combined

health index (CHI), which can be used to evaluate the state for those integrated systems.

After discussing statistical techniques to evaluate the state of assets and grids, the HI is discussed in greater depth in Section 9.2 and further.

1.3.3.5 Evaluation of CBM

CBM assumes the ability to fully assess the condition and adequately alert for imminent failure. This full assessment is of course an ideal situation, but in an imperfect reality, CBM can still be very effective. CBM is built on diagnostic methods and knowledge rules that provide an estimate of failure moments based on the observed and perceived condition of the asset. The quality of the forecasts leans heavily on the quality of the observations and of course on the validity of the knowledge rules. These are the greatest challenges within CBM.

Situations where CBM is applicable:

- (a) On the one hand, assets are of such value and/or failure has such an impact that CM is not acceptable but on the other hand, effective PBM is too expensive. CBM is a good compromise granted that condition assessment is possible, reliable and sufficiently cost-effective.
- (b) Condition assessment techniques are feasible and cost-effective.
- (c) The organization is able to work with a flexible planning, keep an overview of the system and has access to both human and material resources for timely servicing and replacement.

CBM is particularly favoured in an advanced technological environment where automated systems can process monitoring data and planning can be adjusted according to the needs of the moment and near future. Besides adequate diagnostics and knowledge rules, key to successful CBM is organizational flexibility to respond to alerts in a timely manner. Of the three discussed maintenance styles, CBM requires the most expertise on signals that correlate with failure mechanisms.

1.3.4 Risk-Based Maintenance

The previous three maintenance styles – CM, PBM and CBM – focused on the assets and their condition. RBM takes into account that events (e.g. failures) impose risks to many more aspects than just technical functionality. In daily conversation the term ‘risk’ is often used for the probability that a certain danger will become reality. However, risk has another meaning in RBM. Risk comprehends both the likelihood of an event occurring as well as the impact of the event with respect to business values like safety and security of supply. Risk is therefore often defined as the product of probability and impact or effect:

$$risk = probability \times impact \quad (1.1)$$

A similar definition is:

$$risk = occurrence\ rate \times consequence \quad (1.2)$$

Whether risk should be defined exactly as the mathematical products in Eq. (1.1) or (1.2) is debatable, nevertheless AM systems often employ a so-called risk index (RI) as

a measure of risk for prioritization that scales with both probability and effect on both occurrence rate and consequence.

For example, some cable terminations may build up pressure and subsequently fail with a blast. If such a termination is next to a place where people reside, the problem of an operational interruption after a blast may be secondary to the safety issues involved. The failure of the very same type of termination in a remote or shielded area will cause the same operational nuisance, but safety may not be an issue in that case. The failure probability is the same, but the risk with respect to safety is much higher in the first case.

The concept of RBM is that the mitigation of situations with a higher risk level gets a higher priority. It may mean that a high risk urges an asset to be taken out of service earlier than would be done with CBM. In that case the loss of operational life is weighed against the violation of other values. On the other hand, if a local grid is sufficiently redundant (so a single failure will not interrupt energy supply) and other consequences of failure are acceptably small, then mitigation urgency is lacking and RBM may lead to postponing replacement until a convenient moment for action is found. RBM aims at optimizing the total performance with respect to the various corporate business values (CBVs).

The difference between CBM and RBM is that CBM focuses on the integrity of the asset and RBM focuses on the performance of the utility in all its aspects (see Figure 1.5).

1.3.4.1 Corporate Business Values and the Risk Matrix

RBM evaluates the risk of events by combining the occurrence frequency and the impact with respect to business values. It depends on the utility with which values will be involved in risk assessments and how each of the risks is weighed.

Some commonly used CBVs are:

- (a) performance
- (b) safety
- (c) finances
- (d) reputation

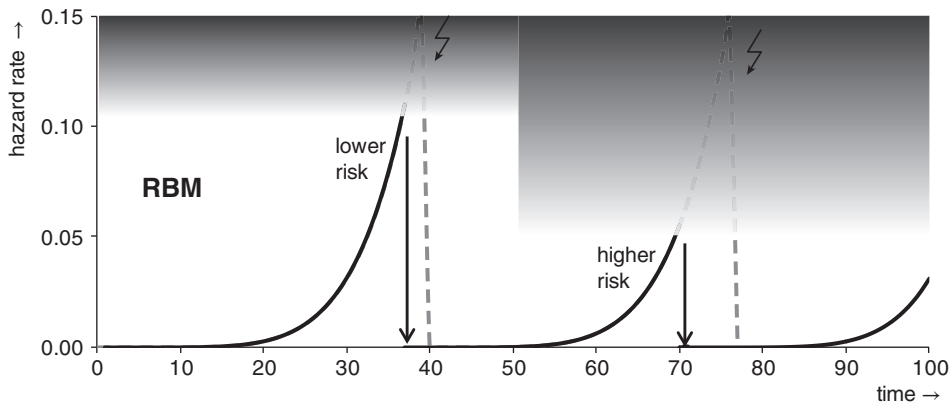


Figure 1.5 With RBM not the asset condition, but the risk in terms of corporate business values determines the priority of mitigation: the higher the risk of violating corporate business values, the lower the hazard rate that triggers treatment of an asset.

- (e) customer satisfaction
- (f) environment
- (g) compliance
- (h) social responsibility
- (i) ...

These CBVs will normally be defined quantitatively by a reference level. For instance, for CBV 'safety' the standard might be: 'nobody gets hurt'. If an incident occurs where someone gets bruised or his arm broken or worse, then the CBV is violated. The levels of violation are normally categorized according to their impact gravity.

In case of an undesired event, one or more CBVs may be violated. For instance, if a termination or a bushing fails with an explosion the value 'performance' of the grid is locally jeopardized, but the blast and the bits that are propelled from the termination, as well as the possible fire following the failure, will also endanger people in the near vicinity of the termination. So, the CBV 'safety' can also be violated. Another example is oil leaking from a transformer or oil-pressure cable, where the CBV 'environment' can be violated.

With RBM risk analysis is used for prioritizing the mitigation of issues. There are various challenges to overcome. One challenge is how to evaluate the risk based on the likelihood of an event and the impact it imposes with multiple risks. Another challenge is how to compare the violation levels of different CBVs.

A traditional way is to translate impacts into money, which may lead to the awkward duty of estimating the financial value of human life, of pricing operating within the law versus damage to the environment. From the viewpoint of simplicity, it is appealing to just calculate the cost of damage compensation, but the CBVs may be valued much higher than financial compensation alone. The frequency of CBV violation can be established through statistical inference, as will be shown in the coming chapters. Since inflation and deflation influence the value of money, the option of translating CBVs into money must be continuously adapted with the financial markets. However, even financial impacts themselves may be weighed differently. For instance, the same amount in CAPEX, penalties to be paid, interest, asset book value or loss of income may have a very different weight. Probably formulas can be drafted that overcome such differences, but in the end it may be concluded that the financial balance is not such a convenient value after all.

An alternative to translating CBVs into only money is provided by a risk plane or more popular, in its discrete form, the so-called risk matrix (RM). This is illustrated in Figures 1.6 and 1.7. Here shades of grey are used, but normally colours indicate the acceptability of the risk (which inspired the cover design of this book). Those colours do not relate directly to the colour scheme of the HI (see Section 1.3.3.4). The idea of a risk plane is to scale the impact with respect to CBVs by a number that can be translated into terms of 'minor' to 'extreme' impact. In this way most of the CBVs can also be evaluated regardless of the cost. CBVs with a financial impact can be adjusted to the corporate financial strength independent of non-financial CBVs like safety. Again, the frequency of CBV violation can be established through statistical inference. The combination of frequency and impact leads to two-dimensional coordinates in a risk plane, as in Figure 1.6.

Usually not a scale but a range of impact categories is designed through interviews with the stakeholders, including the management board. Also, the frequency may be

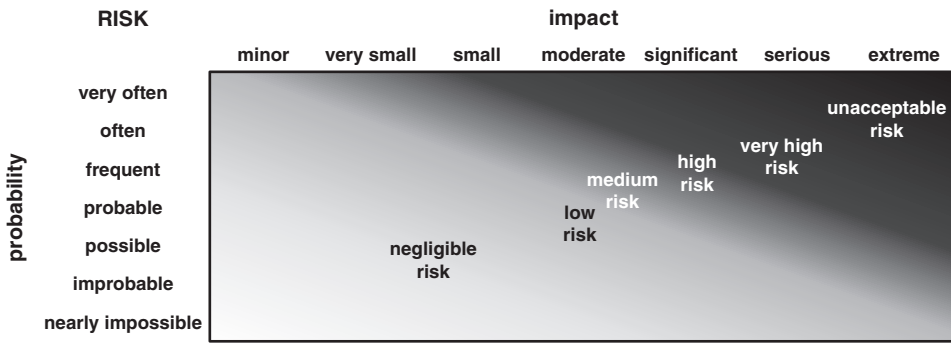


Figure 1.6 Risk is a combination of the quantitative occurrence and impact of the event. The risk for an evaluated business value has coordinates in this risk plane. A strategy can be to mitigate all risks from and above a certain level (e.g. the medium risk level).

RISK		impact						
		minor	very small	small	moderate	significant	serious	extreme
probability	very often	low	medium	high	very high	unacceptable	unacceptable	unacceptable
	often	negligible	low	medium	high	very high	unacceptable	unacceptable
	frequent	negligible	negligible	low	medium	high	very high	unacceptable
	probable	negligible	negligible	negligible	low	medium	high	very high
	possible	negligible	negligible	negligible	negligible	low	medium	high
	improbable	negligible	negligible	negligible	negligible	negligible	low	medium
	nearly impossible	negligible	negligible	negligible	negligible	negligible	negligible	low

Figure 1.7 Risk is often discretely categorized, which yields the risk matrix. The risk for each evaluated CBV is assigned a cell in this risk matrix [12].

categorized. This leads to the discrete representation of the evaluation results in a risk matrix (see Figure 1.7). With the discretization some information gets lost, but it may be easier to harmonize risk evaluations of different inspectors and reduce scatter.

The HI may not be a good indicator for value-violating frequencies. The frequency of an event (like failure with an explosion) is not necessarily the frequency that belongs to a certain risk (like putting people in danger). For instance, if at some point a termination is estimated to fail once per 5 years, the frequency for interrupted power supply will be 0.2 per year (in case of no redundancy). If the termination is properly shielded, or people rarely come into the vicinity, say 1% of operational time, the estimated frequency of human exposure to a termination explosion may then be 1% of 0.2 per year, so 0.002 per year (the assumption here is that the explosion and the presence of people are independent). Following that line, the frequency for CBV safety is also one-hundredth of the frequency for performance. So, in this case the same event yields different frequencies for different CBVs.

For each CBV the risk evaluation leads to coordinates in the risk plane or a cell in the risk matrix. The risk plane and risk matrix replace Eqs (1.1) and (1.2). One method is to

use the equations for each business value and then take the highest as the criterion for mandatory mitigation. After a positive decision to add the issue to the portfolio of issues (the 'to-do list'), normally still a single risk index like the weighed risk is constructed to allow an unambiguous priority ranking.

Another method is to first weigh each CBV risk, compose a weighed risk index (cf. Section 9.1.4.2) and then apply a criterion to add the issue to the portfolio or not. The difference between the two methods is that in the first case each single CBV can trigger action, while in the second case a good or bad score on certain CBVs may reduce respectively advance the mitigation on the other CBVs. If all CBVs are weighed equally, the above listed CBVs would each add 12.5% to the risk index, but usually different CBV weighing factors are used in priority ranking for risk mitigation (see also Section 9.1.4).

One may wonder why the weighing is applied while the risk matrix might be adapted as well. However, the risk matrix is used to qualify events for the mitigation portfolio, while the weighed risk index is used for prioritizing only the issues that made it to the portfolio.

1.3.4.2 RBM Inspections

RBM applied to inspections means that the inspection regime is tuned to the identified risks. For example, not only the asset condition may be inspected, but also whether the surroundings changed such that the risk increased. For example, inflammable products may be placed in the near vicinity of the assets, which could increase the impact in case of a failure. Particularly the frequency of inspections or monitoring of specific aspects may be intensified if the circumstances require so. RBM may or may not lead to lower OPEX than CBM, but the aim is primarily to prevent violations of the utility CBVs. It requires not only the smart planning of CBM, but also an evaluation method to estimate the impact on CBVs. As this is applied to all assets, many risk evaluations have to take place and a practical rather than a very precise risk evaluation system may be developed. For example, a geographical information system may be used to evaluate whether assets are close to a populated area that would make the asset more likely to be a safety risk. Assets in an environmentally sensitive area like a nature park, in a populated area or of extraordinary strategic value may be inspected more frequently with RBM.

1.3.4.3 RBM Servicing

RBM servicing, similar to RBM inspections, is based on estimated risks, which requires knowledge of both condition and impact with respect to the CBVs. Depending on the estimated risks and anticipated scenarios, the preferred option can also be to replace rather than carrying out maintenance. Similar to risk-based inspections, assets in an environmentally sensitive area like a nature park, in a highly populated area or of extraordinary strategic value may be serviced more frequently because of the RBM policy.

1.3.4.4 RBM Replacement

RBM replacement aims at replacing assets when the risk in terms of one or more of the CBVs becomes too high and preserving the CBVs can be directly reflected in the investment plan. The overall performance of the utility is thus optimized in this way. Again, assets in an environmentally sensitive area like a nature park, in a populated area or of extraordinary strategic value may be replaced earlier with RBM.

1.3.4.5 Evaluation of RBM

RBM not only assumes the ability to assess the condition and to forecast imminent failure like CBM, but also assumes the ability to assess the impact that asset failure has on CBVs. It requires more complicated evaluations, but the overall performance of the utility may benefit from this approach.

Situations where RBM would typically be used are where:

- The focus is on utility performance measured in CBVs rather than only asset survivability. For establishing the likelihood of failure events, the prerequisites for CBM have to be fulfilled.
- RBM may be selectively applied to replacement and investments while any other maintenance style might be applied to inspections and/or servicing.

RBM is particularly favoured in an advanced technological environment and setting where utilities are evaluated for their performance in a broader sense. RBM may resemble CBM for forecasting events, but it aims at better tempering the adverse effects where the stakes are higher. Keys to successful RBM are diagnostics, knowledge rules that can adequately forecast imminent failure, organizational flexibility to respond to alerts in a timely manner, methods to measure CBVs are in place and the ability exists to quantify the risks. Of the discussed maintenance styles, RBM has the broadest scope.

1.3.5 Comparison of Maintenance Styles

The maintenance styles discussed in previous sections are summarized in Table 1.3. The first rows show the differences in strategy, focus and consideration that lead to the respective maintenance style. In short, CM in its most extreme form leaves the asset unattended until failure. This style employs assets to the very last moment. PBM aims at a prescheduled lifecycle, which makes this style the most predictive in CAPEX as long as the scheduled lifetime is shorter than the technical lifetime. However, the technical life may be prolonged with dedicated servicing efforts. The periods between servicing should be optimized. CBM aims at keeping track of the asset's condition. This alternative to PBM usually employs diagnostics and knowledge rules that must then adequately forecast imminent failures. The focus of CBM is on the asset. RBM primarily aims at the best performance in terms of CBVs, rather than focusing on the asset alone. Of course, failure ends operation of each asset and RBM will most probably never produce a longer lifetime than CBM, but it may prevent the worst violations of CBVs from happening.

The two following rows in Table 1.3 show typical asset features and action. The maintenance styles are split into inspection, servicing and replacement. Inspection consists of checks, servicing consists of preventive measures or refurbishments, and replacement consists of removing the existing (possibly failed) asset and installing another one instead.

The answer to the question of which maintenance style is the most cost-effective very much depends on the balance between various aspects like CAPEX, OPEX, required operational life, predictive value of condition monitoring and the weight of CBVs (safety, compliance, etc.). Each maintenance style can be the best option depending on the circumstances.

In many cases the maintenance styles are not used in their purest form, but rather blended. For instance, inspection may follow a PBM regime for ease of planning, servicing may follow a CBM regime, while replacement may follow an RBM regime. If

Table 1.3 Characteristics of maintenance styles.

Maintenance style aspect	CM	PBM	CBM	RBM
Strategy	Run to fail	Periodic preventive action	Timely action based on asset condition	Timely action based on CBVs
Focus	Maintenance-free	Scheduled plan	Asset condition	Utility performance
Consideration	Solving failure outvalues preventive actions	Preventive action outvalues solving failure	Condition monitoring outvalues periodic preventive and corrective action	Utility performance based on managing risks in terms of CBVs
Typical asset feature	Non-serviceable or disposable	Cost-effective servicing or very strategic	Able to be monitored	Able to be monitored and fail impact to be estimated
Typical action	Inspection and/or maintenance impossible or unwanted	Cost-effective preventive servicing	Cost-effective condition monitoring	Measures to control mixed and weighed risks
Inspection	Ability to detect failure	Periodic as scheduled	Indicated by perceived condition	Indicated by risk in terms of CBVs
Servicing	Not preventive, possible alternative to replacement after failure	Periodic as scheduled	Indicated by perceived condition	Indicated by risk in terms of CBVs
Replacement	After detected failure	After scheduled operational life; before significant failure probability	Indicated by perceived condition	Indicated by risk in terms of CBVs
Typical needed statistical information	Average lifetime Warranted minimum lifetime CAPEX per lifetime Asset operational availability	See CM + OPEX per action Optimum cycle	See CM + OPEX per action Success rate of monitoring Predictive window of monitoring	See CBM + Utility performance Likelihood and estimated impact

maintenance costs are relatively high and the risks associated with failure are low, CM may still be a good option in the early stages of operational life, while replacement may still follow an RBM regime.

The last row in Table 1.3 shows typical information that is used for decision-making and evaluation of AM performance.

1.4 Incident Management

Maintenance styles aim at managing assets in normal operation. Asset managers should, however, be prepared for the fact that usually unusual things happen as well. This is IM. Of particular interest is the evaluation of the extent to which an incident can develop into an emergency situation.

Although IM has various aspects in common with the CM style, there are differences. CM can be a deliberate choice based on a balance between saving OPEX due to not servicing the asset and willingly increasing CAPEX due to earlier replacement, since no effort is undertaken to prolong operational life. Also with CM there will be an expectation of average operational life after which replacement is necessary and with the choice for CM this expectation is apparently acceptable or preferable over other maintenance styles.

However, if assets fail considerably faster than expected, then not only corrective action is necessary. The asset manager may most likely have to evaluate whether the incident is unfortunate, but not worrying on the one hand or on the other hand the situation requires adequate measures to prevent (or contain) an emergency situation and eliminate the possibility of similar failures in the future. One possible reason for early failures is that assets suffer from errors in production and/or installation. Another possible reason is that the operational conditions differ from the specification – like a salty environment that appears more harmful to the assets than anticipated. Repair or replacement will probably not improve the situation if the new assets suffer the same problems or if the condition problems are not solved.

The following issues may typically call for IM:

- (a) *Early failures.* If a group of assets is commissioned, a few unexpected early failures may occur. The question is raised of whether or not these failures are statistically unavoidable and should be accepted. The answer may be challenging because at that stage there are too few events to draw firm conclusions. Forensic studies, in combination with unbiased statistics, may be applied to take optimum benefit from the small data set to evaluate the likelihood of these early failures considering the specifications (see also Section 9.4 and following).
- (b) *Non-compliance.* Early failures may still fall in an acceptable range, but their trend may suggest that the next failures will be too early and that the average lifetime will be considerably shorter than specified. A question is raised over the certainty with which a batch will not comply with the specifications, and when measures must be taken. Again, forensic studies and statistics will be employed in the evaluation (Section 3.6.5 and 3.7).
- (c) *Repair-or-replacement decisions.* Failures may occur near the end of the specified minimum life. Many systems are repairable, but after several repairs asset replacement may be more appropriate. The question is thus whether the latest failures are incidents that can be resolved with repair or whether a wave of failures can be expected, and replacement of the entire batch is appropriate (see also Section 9.4.2).
- (d) *Adjustment of maintenance style.* Maintenance styles should be selected based on circumstances, but if the circumstances deviate from expectations, then the maintenance style may have to be adjusted. This may be the cause when failures encountered with CM could be prevented with minor preventive servicing indicated by

PBM or CBM. Another example is that servicing based on CBM assumes successful forecasting, but if this appears not possible, then a PBM style may be a better approach. Aspects of maintenance styles are also discussed in Section 9.1.

Statistical description, together with forensic studies, often provides insight into the actual situation and statistical inferences are often used for prognosis and decision-making.

1.5 Summary

Electrical energy systems started as luxury features to replace candles by electric light. Within a century, electric power supply gained a dominant position in modern societies. The role of electric power supply is still growing. Transmission and distribution networks consist of a large number of assets like transformers, cables that are integrated into subsystems like circuits and stations which are integrated into the networks that build the grid. Utilities are responsible for the performance of these networks.

AM is the collective term for the structured decision-making and execution of plans to reach an optimized balance between performance and efforts with the utilization of the assets. This includes all aspects that are relevant to the performance of the grid, such as the strategy, operations, finance, regulations, information, value and more. AM also determines the way the assets are maintained. The maintenance activities are subdivided into inspection, servicing and replacement.

Though many variations in maintenance style exist, four styles are described here: CM, PBM, CBM and RBM. Each aims at optimizing the balance between OPEX, CAPEX and performance including risk control.

CM aims at mitigating situations with defective assets while avoiding preventive inspections and servicing. The advantage is low OPEX, but since no effort is put into prolonging asset life, CAPEX may be higher. PBM is based on planned actions. Preventive activities take place whether or not the asset requires attention. The disadvantage is that OPEX is generally relatively high. Life may be prolonged by preventive actions, but asset replacement is also planned, whether or not operation could have been continued. CBM aims at both avoiding unnecessary preventive actions and still carrying out maintenance in a timely manner based on the asset condition. CBM leans heavily on the ability to detect the early stages of failure or a (side) effect that correlates well with the hazard of failure. CM, PBM and CBM all focus primarily on asset functionality.

RBM resembles CBM in assessing the likelihood of failure events, but additionally assesses the impact of events as violation of a set of CBVs (like safety and compliance with regulations). Risk is defined by a combination of event likelihood and impact on CBVs. Prioritization is based on the (usually weighed) risk index. RBM is not necessarily cheaper than the other maintenance styles, but aims at a better overall performance in terms of all CBVs involved. The focus of RBM is therefore on utility performance rather than merely technical performance of the assets.

Two methodologies in support of maintenance are the HI and the RM that may produce an RI. The HI enables a convenient overview of the condition of the assets in a grid. It rates the confidence in the asset health. A colour code reflects the HI and the urgency to undertake preventive or corrective actions. The RM is a plane or matrix that is useful to assess the risk for violation of CBVs. On the vertical axis the occurrence frequency

is rated in line with the HI. On the horizontal axis the impact of a failure event on the CBVs is rated. The position in the RM determines the gravity of the risk. For instance, an event that will happen very often in combination with an extreme impact would be an unacceptable risk, while a nearly impossible hazard in combination with a minor impact is a negligible risk. Other combinations of occurrence frequency and impact would be risks that rate between negligible and unacceptable.

Apart from the organized AM and maintenance styles, unusual things usually happen as well. This is taken care of with IM. Both AM and IM require fact-finding and decision-making. Descriptive statistics is used in fact-finding and inferential statistics is used for exploring scenarios and making decisions. The coming chapters discuss methodologies for both types of statistic.

Questions

- 1.1 Categorize the following cases in maintenance activities (inspection, servicing, replacement) and styles (CM, PBM, CBM, RBM). Explain your choices.
- New transformers are installed. The utility wishes not to rely merely on commissioning tests and decides to install equipment that detects hydrogen gas. This gas is associated with fast degradation. These systems are kept in place for 5 years and then removed. Up to 30 years of age, visual inspections and oil analysis is regularly carried out annually. After 30 years, equipment for on-line gas-in-oil analysis is installed on the transformers in order to detect various gases that signal imminent failure.
 - Transformers are installed in a remote area. Annually the transformers are checked visually and oil quality is measured. After 15 years the nearby city expands and the station becomes located in a newly developed urban area. Soon residents start to complain about transformer noise. The utility starts to monitor the acoustic noise from the transformer, which appears to be within legal limits. Additional research is carried out that points to the possibility of constructive interference (i.e. the houses are built in such a way that at some place the noise is amplified, which leads to complaints). Although compliant with the regulations, the utility wants to protect its reputation of social responsibility and takes measures to reduce noise and schedules installing new, silent transformers.
 - Cable terminations are components that can be built in a ceramic housing. Normally such components hardly require maintenance, but occasionally the oil level is checked. In theory these components can build up pressure and ultimately explode, propelling sharp porcelain fragments over a distance of tens of metres. After an actual incident with an exploding termination the utility decides to install screens near terminations to block possible fragments flying from exploding terminations. Furthermore, in residential areas and near roads, the utility starts to exchange such terminations by terminations with polymer housing, because these are safer due to less violent rupture and absence of sharp fragments. Later the rest of the terminations are exchanged as well.

- 1.2 Recommend maintenance strategies based on the provided information for the following assets and cases. If information is lacking, state a reasonable assumption and proceed.
- a. A cable circuit consists of two accessible terminations (one at the beginning and one at the end), various lengths of direct buried underground cable that are connected by joints. The cable is planned to last for at least 40 years. Three failure breakdown modes are considered by their initiation:
 - i. External damage mainly to cable and joints due to digging activities of third parties. Except for regulations for third parties to consult, there are no countermeasures taken.
 - ii. Discharge breakdown (i.e. electrical insulation failure after various partial discharge phenomena, e.g. kinds of internal or external electric sparking but not yet a full breakdown); at the time of installation no on-line monitoring system had been developed for that voltage class. Incidental partial discharge measurements are possible at the cost of about 1% of the cable system price.
 - iii. Thermal breakdown (i.e. electrical insulation failure after overheating of the insulation). This cable system contains a glass fibre sensor to monitor the temperature of the complete cable length with a resolution of typically a few metres. This can be used as a warning for imminent thermal breakdown, after which the load can be reduced in a time manner to prevent actual failure. The fibre may deteriorate after 20 years and cannot be replaced. Additional costs for installing a thermal monitoring system and communications amount to about 2% of the cable system, with 5% operating costs per year.
 - b. Surge arrestors capture overvoltages on the high-voltage systems (e.g. after lightning strikes). They are used amongst other countermeasures to protect transformers that typically cost a hundred times more than a surge arrestor and are regarded as strategic in the grid. The surge arrestors can withstand a certain number of strikes and transients. The arrestors do not have a remote monitoring system, but a counter is attached to keep track of the history. The counters occasionally appear not to work well.
 - c. Various types of high-voltage equipment at an open-air substation near the ocean coast are placed on insulators. These insulators are to prevent flash-over from the high-voltage conductors to earth and must therefore remain in good condition for about 30 years. However, sea salt may be deposited on the insulator surface and may lead to flash-overs after typically 2 years. After 10 years of operation there are two options to be considered: continue the annual cleaning of the insulators at a cost of 2% of the equipment or exchange the insulators for new insulators featuring self-cleaning surfaces. With annual cleaning there is still a 5% probability that equipment will fail. Doubling the cleaning frequency would reduce the failure probability to 1%. Exchange of the equipment would mean a depreciation of 20 years.

