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Asset Management for Infrastructure Systems

Energy and Water

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Preface

The implementation of competition in the area of infrastructure has often led to the consequence that within utilities, new decision-making and organizational structures were developed and installed. Here, the term ʺAsset Managementʺ has been established in recent years, particularly in the area of technical as well as economic considerations. Globally considered, the essential task is to optimize the financial and operational tasks of an infrastructure system. In this context, the examples presented in this book often refer to the area of the electric power supply, but this should be considered only exemplary, as all considerations can be applied to other infrastructure sectors (gas, water, telecommunications, etc.). The principles and examples, which are presented in the following sections, essentially have two different sources, which in turn refer to the international discussion in companies, organizations, and associations:

- The Department of ʺElectrical Power Systemsʺ at Darmstadt University of Technology (Technische Universität Darmstadt) dealt intensely the past 20 years with questions and solutions concerning asset management, with the aim of optimizing the maintenance from the viewpoint of the supply reliability. The results of this work are expressed in many publications and dissertations that were published during this period. At this point, we would like to thank the employees for their work.
- The suggestions from the experience of an appropriate organization were received by the EnBW AG, Karlsruhe, who has with their subsidiary Netze BW GmbH, one of the largest distribution network operators in Germany. The implemented structure of asset management, which was developed and expanded with the help of a national and international exchange of other network operators, is used as a basis for discussion of the operational content. Organizational models, established procedures, and the system landscape in information technology are of crucial importance.

Since this whole process is not yet completed while in permanent change and continuing development, particularly against the background of the political and regulatory framework, methodologies and results of this book represent the current state of both the research discussion and the current operating implementation in those companies which possess an appropriately developed organization.

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Exemplary, the predetermined conditions in Germany (legal and regulatory requirements, standardization, etc.) have been used. It is assumed that there are similar conditions in all countries and thus the described approaches can be transferred to other regions.

Darmstadt
Karlsruhe
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1 Introduction

The advanced infrastructure of a country is one of the main drivers behind its economic development and the most important factor for successful global development in the world. Whereas developing countries have to build primarily new infrastructures, the task of industrialized countries is to renew existing infrastructure after once it reaches the end of service life. In the meantime, this challenge is exacerbated in the power sector by the changing characteristics of the transmission network. The original grid designed to transmit energy from large power plants to the load end user has now changed into a power grid which incorporates, along with energy consumers, centralized and decentralized power producers.

In recent years, the term “asset management” became accepted in the area of utilities business, and the basic task is to optimize the management of grid infrastructure assets by using clear defined procedures [3] and to define the development of infrastructure along emerging or new challenges.

1.1 Basis of the Asset Management

A good infrastructure is one of the basic requirements for the growth of country’s economic strength as it facilitates investments from various industries and increases prosperity of the population, thus resulting in higher living standard. In general, the term infrastructure can be applied to different areas, such as:

- Energy networks (electricity, gas),
- Water, sewage,
- Roads,
- Rail network (trains, trams), and
- Telecommunications.

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The main characteristic of the above areas is that the construction of the necessary network is highly capital intensive in long term, so that wrong decisions at the beginning of the investment phase will have negative effect over decades and will need considerable efforts to correct. Investment management as it is described by a holistic approach has the goal to ensure the optimal development and maintenance of infrastructure by utilizing comprehensive planning criteria.

The largely uninterrupted capability of infrastructure to maintain its functionality and fulfillment of the customers' expectations is essential in the areas of energy and water supply so that situations leading to "traffic jams" or "busy signals" should be minimized. This book exclusively focuses on the description of asset management methodology for infrastructure in the areas of energy (electricity, gas) and water supply. According to [5], the investment in networks in Germany for expansion or new construction had the following amount in the year 2010:

- Electricity: 3.8 billion €
- Gas: 1.1 billion €
- Water: 1.3 billion €

In addition to these values, new studies demonstrate that specifically in the German distribution network, an investment is needed in the range of 30–40 billion € priori to 2030 [11]. These figures underscore the importance of correct decision making regarding the optimal timing for these long-term investments in order to conserve and save available resources to then extent possible. Additionally, it has to be taken into consideration that many utilities are not monopolies like in the past, and at the present time, all decisions have to be made under competitive conditions. This means the presence of maximum revenue caps for the investments and maintenance expenditures in the network infrastructure as prescribed by regulators, enforced by legislators and evaluated using efficiency benchmarks. The basis for this approach is the Energy Act [12] published as essentially a fundamentally new document in 2005, and the most important parts for the asset management aspects are as follows:

- § 1: Purpose of the Act

  (1) Purpose of the Act is the most secure, cost-effective, consumer friendly, efficient, and environmentally sustainable supply of electricity and gas to public transmitted via network lines.
  (2) The regulation of the electricity and gas distribution network will be aimed at ensuring effective and fair competition in the supply of electricity and gas while maintaining long-term performance and reliable operation of energy supply networks.
  (3) …

- § 11: Operation of power supply networks

  (1) Operators of energy supply systems are required to operate a safe, reliable, and efficient power grid in a non-discriminatory manner, to maintain and to expand as needed, where it is economically feasible.

- § 49: Requirements for energy installations

  (1) Energy installations shall be constructed and operated in a manner that ensures system technical security. In subject to conformance with other laws, the generally accepted rules of technology have to be respected.
  (2) …

From guideline of the Energy Act, it can be deduced that the duty of a power company is to construct and operate networks in such a way that a safe and reliable supply is provided in economically feasible manner. This means that the two basic additional criteria:

- technical condition and
- economic condition

have to be evaluated in each case against each other, whereby the technical conditions can be represented by the quality of supply. In the new energy world, not only the consumption (load) side but also the production (generation) side has to be considered and taken into account at all voltage levels. The considerations have to include two aspects:

- On the one hand, the required network development driven by changing conditions, such as load growth, additional construction of distributed generation, and development of electric mobility, needs to be considered. This aspect is addressed by network development and planning assumptions.
- The second aspect represents the needs associated with replacement of network components due to their end of life. These have increased influence on the reliability of supply according to the failure probabilities.

The following analysis focuses on the second aspect, as the issues related to the network development will be addressed in appropriate detail in a later chapter. A solution of this issue is now performed by a widespread established “asset management” in the field of the supply companies, and not only different processes are defined but also the organizational structures are changed accordingly at the same time. This process is also influenced by the “unbundling,” which means that the various functions of the formerly vertically integrated energy supply companies, from production through distribution to transportation and distribution, have to be transferred into legally independent corporate structures, such as wires companies, system operators, and privately owned generating companies.

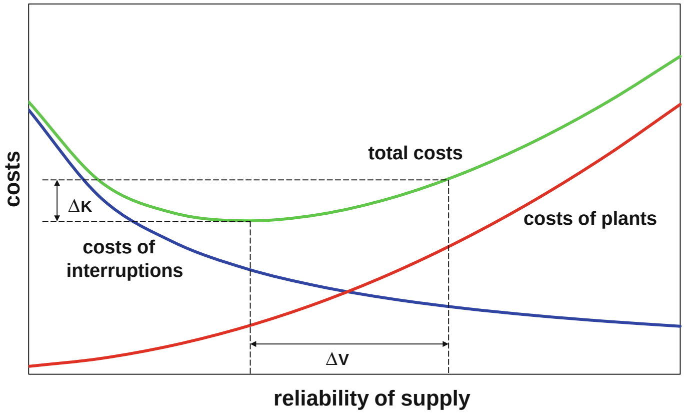

Fig. 1.1 Evaluation of the optimum of costs and reliability of supply

The two represented boundary conditions (technical and economic) are each influenced by the maintenance and the investment in new equipment. However, results from this calculation have a reciprocal influence on the cost of the overall system. The fundamental relationship between the cost and reliability of supply is exemplary presented in Fig. 1.1.

The relationship between the cost and quality of maintenance can be derived as follows:

- Costs of supply interruptions decrease with increasing reliability of supply, as the number of interruptions is reduced and hence the costs of repairing faults will decrease (repair costs, cost of not delivered energy, etc.).
- Costs of the assets increase with rising reliability of supply, as a larger expenditure on maintenance and new investments is required in order to achieve a better reliability.

Basically, according to Fig. 1.1, it can be calculated analytically, which financial effort is required if a certain reliability of supply should be achieved. This, however, requires knowledge of the exact dependency, which would only be achieved in practice if the exact time of a fault is predictable so that quality assurance measures are possible in time. The role of asset management consists of deriving the optimum reliability of supply, which of course must meet the legal requirements.

1.2 Development of the Investment Management During the Last Decade in Europe

A brochure of Cigre Group 37–27 published in 2000 shows the result of a survey of the members of this working group regarding the age distribution of installed high-voltage assets [9]. The result of the age distribution is shown in Fig. 1.2.

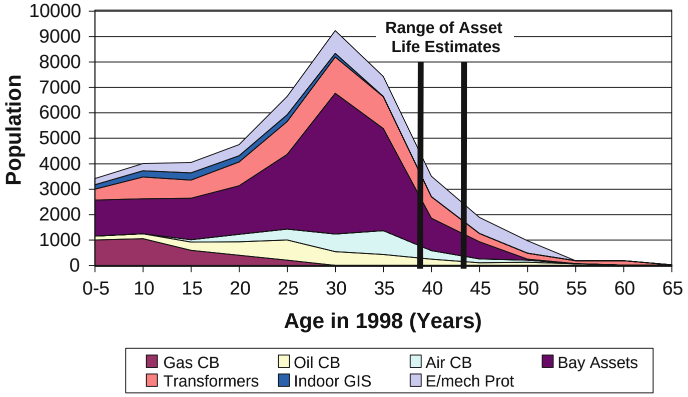

Fig. 1.2 Number of assets and age distribution (status 1998) [9]

The age distribution according to Fig. 1.2 illustrates the impact of different technologies in the asset category of circuit-breaker (CB). In recent years, a significant technology change took place from air blast circuit-breaker (Air CB) via the minimum oil (oil-CB) to SF_6-type circuit-breakers (Gas CB). Moreover, at the end of the 60s, the first encapsulated switchgear (GIS) has been installed, which today represents the state of the art if—due to the space and environmental limits—open-air technology cannot be used. The high growth in particular in Central Europe after the Second World War meant that the power grids were significantly expanded in the 50s and 60s. This trend was reinforced in the so-called years of economic miracle. Growing load requires further expansion, so that on the one hand many existing devices had to be replaced before the end of their technical life by new devices with higher technical capability and new technology, and on the other, new networks were built. This situation can also be seen in the age distribution shown above back-calculated from 2000 showing high investments in the 60s and 70s and the subsequent flattening of the curve in later years. Meeting of customer needs required rapid expansion of infrastructure during that period. Consequently, there was no need for an optimized investment management process.

In contrast to this, a lower load growth is assumed in the decades to come. Therefore, it makes sense to take advantage of the already existing resources and to use the installed component up to the end of their technical life. On the other hand, the structure of the energy supply—particularly in the electricity and gas market—will change to many small power generation units. If the average age of equipment is assumed to be 40 years, it is clear that in the coming years the existing infrastructure is expected to integrate many of such installations. New technologies are developed and deployed to control the reliability and security of the energy supply. The so-called "Smart Grid" has become very important in the development of infrastructure systems and is all the time presented as a solution for all future energy supply problems. Assuming that the transmission networks are already relatively "smart" due to their good observability by the control centers of the transmission system operator, distribution networks' "Smart Grid" means the increased use of information and communication technology but also the utilization of completely new components, for example, controllable power transformers feeding low-voltage systems. This aims to operate and to control safely the low-voltage systems due to many challenges, such as the volatile supply of renewable generation units (especially wind and solar), a presumably increasing volume of distributed storage systems, the volatile energy prices, and variable market-driven loads. The resulting "investment avalanche" as described before will strongly affect the humans as well as the financial resources of the utilities because of its expected capital-intensive and long-term investment pattern.

1.3 Motivation for an Investment Management

The long-term guarantee of a reliable network infrastructure is required according to the Energy Act [12] and therefore is an important objective of asset management. In addition, the entire approach of the asset management process is mandatory even though it excludes considerations for different influences and targets of various stakeholders. Consequently, the main task of asset management considers in the long term revenue optimization with simultaneous high supply reliability while being subjected to acceptable risks. Based on the various definitions and fields of activity of the asset management process, participants can select between various types of models regarding the operational realization. Moreover, an integrated and linked information flow and decision-making process are essential components necessary to enable such a consistent asset strategy for the whole network.

1.3.1 Legal Issues

Markets for conducted energy (gas, electricity) have been opened in Germany by the Energy Law [7] in 1998. Until that time, the utilities had a monopoly in their supply areas, which was in line with the competition laws. Further legal provisions were made by the Energy Law Amendment 2003 [6] regarding free access of third parties to the network in order to facilitate competition.

The transition from the negotiated to regulated network access came into force as the Energy Law on July 13, 2005 [12]. The key aspect of this was that proceeds are no longer negotiated between the groups involved in the market but are specified by legal requirements (regulatory) [10].

The regulations requires unbundling of the system operators in a competitive electricity market so that market participants have to operate in separate legal entities with exceptions for smaller utilities. Figure 1.3 shows the time evolution as a result of the transition from an integrated utility to a confederation of various parts, where different entities can operate separately depending on their expertise and area of business.

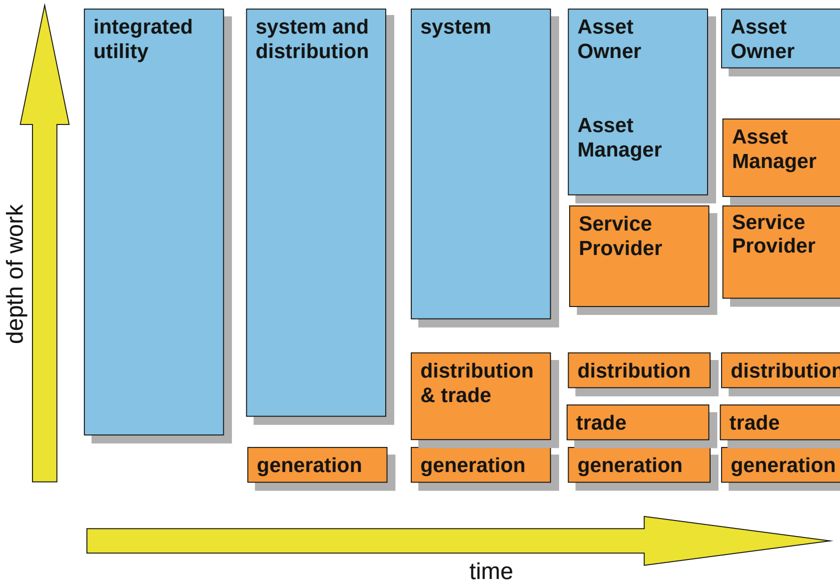

Fig. 1.3 Temporal evolution of utilities

Starting with a vertically integrated company which covers all areas of generation, transmission and distribution, today the different functions are operated by well-defined entities which could be categorized as follows:

- Network transmission,
- Network distribution,
- Metering and billing,
- Sales,
- Trade, and
- Generation.

Furthermore, the internal organization of the network business area can be subdivided into three main functions in the sense of a role model:

- Asset owner,
- Asset manager, and
- Service provider.

Because of the above changes in the legal requirements, new business models with appropriate management processes and control functions are being developed to reflect the new accounting framework.

1.3.2 Impact of Regulation on Infrastructure Companies

In the past, allowable revenues of a utility being a monopoly were based on a calculation of all identified cost factors (capital and operating costs), including a reasonable amount for the capital employed. Revenue caps were set by the transition to the incentive regulation [10], which have to be applied by the company. The reason for the use of the incentive regulation was, in the eyes of politicians, generally to increase productivity as monopolies lacking efficiency cost-optimizing incentives since all the expenditures associated with the network activities were fully reimbursed.

The incentive regulation was thus used to introduce competition into a monopoly market, which is generally a natural monopoly market due to technical conditions because it makes no economic sense for new competitors to first build and then operate a parallel infrastructure.

After becoming effective on January 1, 2009 [6], the first regulatory period lasted five years and the second regulatory period started on January 1, 2014. The essential component of the regulation is a revenue cap which defines the total allowable revenue of a system operator. This revenue cap is determined by Eq. (1.1), where the influence of a quality element Q_t is implemented in further regulatory periods:

$$\mathsf{EO}_t = \mathsf{KA}_{dnb;t} + \left(\mathsf{KA}_{vnb;0} + (1 - \mathsf{V}_t) \cdot \mathsf{KA}_{b;0}\right) \cdot \left(\frac{\mathsf{VPI}_t}{\mathsf{VPI}_0} - \mathsf{PF}_t\right) \cdot \mathsf{EF}_t + \mathsf{Q}_t \tag{1:1}$$

The various parameters in Eq. (1.1) are defined as follows:

EO_t	revenue caps of system charges
$\mathsf{KA}_{dnb,t}$	permanent non-influenceable costs
$\mathsf{KA}_{dnb,0}$	temporary non-influenceable costs
V_t	factor for the reduction of inefficiencies
$\mathsf{KA}_{b,0}$	controllable costs
VPI_t	overall consumer price index of the year t of the regulation period
VPI_0	overall consumer price index (Federal Statistical Office) of the base year
PF_t	productivity factor
EF_t	expansion factor
Q_t	surcharges and discounts to the revenue cap (quality element)

A detailed description of some values is essential to assess which costs in Eq. (1.1) are of interest to the asset manager:

- Permanent non-influenceable costs, e.g.:
  - Legal purchase commitments and payment obligations,
  - Concession fees,
  - Operating taxes,

  - Expenditure of the approved investment budget; this includes capital investment, which are necessary for the stability, the integration into the overall system or grid, or a tailored expansion of the power grid,
  - Required use of overlaid voltage levels,
  - Reimbursement of decentralized power generation,
  - Education and training, etc.

- Temporary non-influenceable costs: These costs are calculated as part from the total costs, if the network operator can claim special challenges with respect to its task.
- Influenceable costs: These are costs that cannot be assigned to the two parts of costs defined above; for example, this includes the repair and maintenance costs of the network assets.

The expenditures for the maintenance of supply system assets represent a major cost variable which can be influenced by the asset manager. In theory, it is possible to reduce the maintenance costs by increasing the maintenance cycles, but this may lead to a deterioration of the service reliability and shortening of the assets' lives. A quality element ([10], § 19) is included in the incentive regulation to ensure a sufficient system reliability. The security and reliability of supply and the ability of the operator to manage disturbances should be guaranteed by the introduction of the Q-element, as the system operator has ability to request more revenue to address the compliance with reliability of supply and the power quality requirements. The evaluation of network reliability can be performed by the following criteria ([10], § 20):

- Duration of the of supply interruptions,
- Frequency of supply interruptions,
- Amount of not delivered energy, and
- Amount of not supplied load.

If these criteria are exceeded or not met based on the average for the total supply, the revenue cap can be increased or reduced by the regulator (Q_t).

Despite the multitude of regulatory requirements, it should be noted that generally, the system operator has the ultimate responsibility for the network operation in a private market structure.

1.4 Challenges of Transmission and Distribution System Operators (TSO and DSO)

As a consequence of the legal requirements and a wide range of technical and social conditions, the transmission and distribution system operators have to solve a number of key challenges which will have a strong influence on the infrastructure. These include the following:

- Maintaining the reliability of supply,
- Integration of decentralized power generation,
- Integration of offshore wind farms,
- Unbundling of different areas,
- Introduction of incentive regulation,
- Compliance with regulatory requirements,
- Ensuring a cost-effective power transmission,
- Optimization of the revenue and earnings,
- Optimization of maintenance activities,
- Proper use of existing resources,
- Control of replacement investments for components at the end of technical life,
- Integration of information and communication technologies for the networks control and for instruments monitoring, and
- Target network planning.

The main criterion is that different trends are superimposed, and a solution has to be selected from which the above objectives can be served. Among these trends are the following:

- Increased competition,
- Increasing need for investment in the coming years,
- Integration of renewable electrical energy sources (wind, sun),
- Increased energy storage requirements, and
- Volatile load control due to the electricity pricing signals.

The above tasks impose significant additional stress on the available resources, including both human resources and financial resources of the companies.

Basically, there is no need for companies to deal with all the above issues internally. The ability to do that depends on the available skills which therefore have to be kept on a high level. In some cases, it makes better sense to outsource some of the services to external parties in order to maintain competitive framework.

1.5 Activities of the Asset Management

The term “asset management” describes all activities of the entire process in terms associated with sustaining and adding to the existing infrastructure, whereas the “asset manager” is only responsible for the activities mentioned in the following under “asset manager”.

The development, management, and optimization of technical facilities of a utility are conducted by a decision process which involves a model with three major participants playing the following roles, the so-called role model [2, 4, 8].

- The “asset owner” performs the function of the economic owner of the equipment/plants, which could also be made possible via leasehold models. Asset owner sets the basic requirements for quality, acceptable risks, supply reliability, the substance of assets (which means total value of the plants in relation to the used part of their life), and financing, so that the basic strategies could be then defined. Asset owner also is the contact entity for the regulator and also has to handle the regulatory management. The asset owner, therefore, governs the asset manager and approves the overall budget for different network levels.
- The “asset manager” defines individual technical strategies based on the requirements specified by the asset owners, mainly in the fields of system development, investment, and maintenance. Asset manager is, therefore, responsible for the implementation of the asset owner’s guidelines into a work plan in order to meet the defined targets. The asset manager identifies the necessary measures and arranges their implementation on the basis of technical standards which are also within his mandate. Finally, asset manager must set up appropriate actions for controlling the use of money and the reliability of supply, to determine the effectiveness of the measures and to undertake corrections if required for the policies and standards. Therefore, the role of the asset manager is to find the optimum solutions for the following problems: acceptable business risk, required network availability, and financing sustainment of system. He commissions a service provider for the operational implementation.
- The “service provider” carries out all services involving network operations and projects on behalf of the asset manager. There are two distinct types of service providers:
  - “Support service providers,” who provide the general services, such as financing, procurement, and information technology.
  - “Asset worker”, who is responsible for the technical processes such as operation of the network, design, and construction execution.
- In addition, many basic services (e.g., documentation, maintenance of databases and statements) and the determination of conditions and needs must be provided in order to derive the budget.

The working group of the TF 23:18 of Cigre carried out a survey among its members regarding the responsibilities of stakeholders within the decision-making process in 2000, as defined above. Sixteen different companies participated; the results of the survey [4] are shown in Fig. 1.4.

From the illustration, it can be seen which party is involved in the various tasks (score between 0 and 100 %) and it is possible that multiple parties could be involved in the same task. The role of the asset owners is seen primarily in the determination of policy and financial targets (budget and revenue). The responsibilities of the “service provider” are divided between internal and external service providers and asset workers (operation).

Based on the responsibilities in the domain of asset management as it is shown in Fig. 1.4, a “pyramid of the asset management process” can be derived, which represents

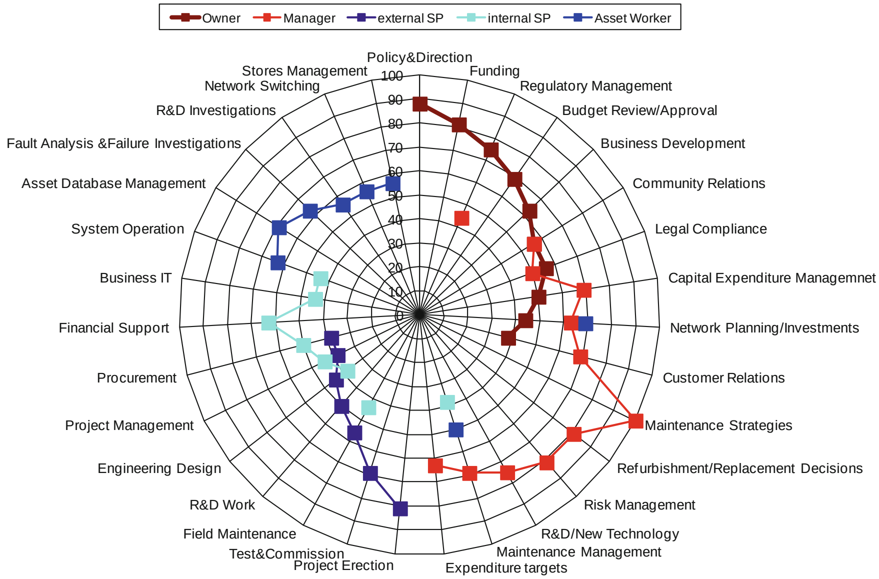

Fig. 1.4 Divisions of responsibilities in the area of asset management [4]

both: the process of decision making and the flow of information needed for this purpose (Fig. 1.5). In reference to the survey of the different companies, some fields of activity can be clearly associated with one of the three functions (asset owners, asset managers, and service providers), whereas others overlap depending on the particular corporate structure.

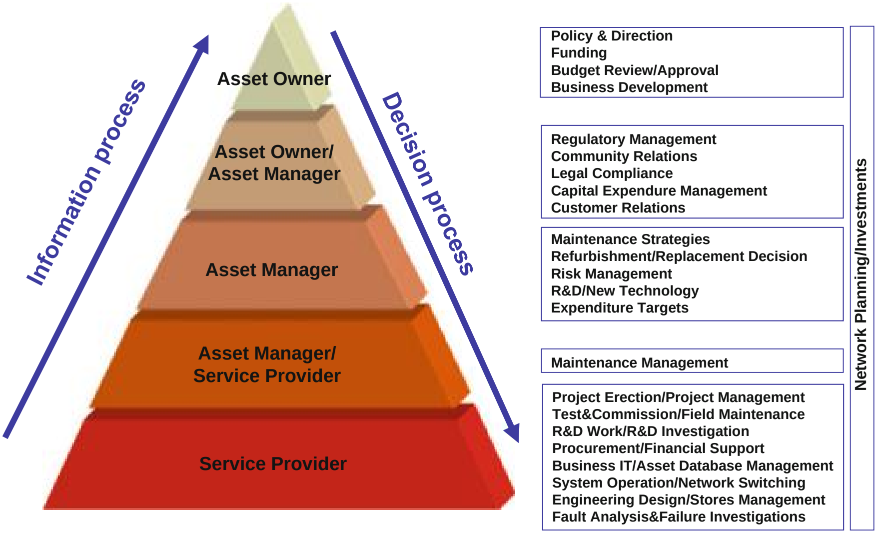

Fig. 1.5 Pyramid of the asset management process [1]

While the flow of information concerning the condition of the equipment goes from the bottom to the top of the company, the decision process is applied in the reverse order. The asset manager takes over the coordination and implementation tasks at the interfaces between the asset owner and the service provider and, thus, has a central function between information process on the one hand and decision-making process on the other hand.

Within the asset decisions process (system development, renewal, and maintenance) by the asset manager, the consideration of the asset lifetime includes various partly competing outcomes.

The choice of strategy at the beginning of the total asset management process has the greatest influence on the financial success and optimized development of the network technology. This includes the long-term strategic asset planning and system development, project planning, implementation planning, commissioning, and the operation or the renewal. Technical conditions, such as voltage stability, reliability of supply, emission values, and current capabilities/ratings of components, have to be kept in mind during the consideration of the planning. This forms the basis for deciding on the most economical way to deal with considered asset groups or systems.

In many cases, asset simulations are used to support the decision-making process of the asset owner as well as the asset manager; the goals of these simulations can be defined as follows:

- Development and optimization of the strategy,
- Reduction of costs (to be deduced from life cycle curves of the equipment),
- Assessment of system risks (impact and deriving the consequences),
- Evaluation of the maintenance activities,
- Determination of the required annual budget,
- Control of the strategy on the basis of a given budget, and
- Implementation of required activities.

The benefit of the asset simulations is for example:

- Clear and transparent basis for the decisions,
- Efficient use of scarce resources,
- Evaluation of the greatest impacts, and
- Documentation of the internal and external communications.

The precise tasks within the asset management process and the consequences resulting for the organization of the company are described in detail in Chap. 4.

1.6 Conclusion

As a result of the new framework, which has changed over the last several years fundamentally utilities business processes, there is a clear structure of the decision-making process required to maintained existing infrastructure over a long term. While the asset owner is primarily responsible for business development and the provision of financial resources, the task of the asset manager is the implementation of the strategies based on the stipulated asset owner's requirements. In contrast, the service provider carries out various activities specifically defined by the asset manager.

In consequence of this structuring, clear interfaces are defined between the various competencies so that a decision-making process can be properly mapped. This should lead to the optimal development and maintenance of the infrastructure.

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Tasks of the Asset Management

2

Different tasks have to be defined to meet the objectives pointed out in Sect. 1.5 which can be reached in the area of asset management. In this context, the development of the strategy and the necessary resources are essential for their implementation. This chapter describes the various tasks in detail.

2.1 Development of Strategies

The asset management tasks defined by Sect. 1.5 can be divided into different sub-tasks, making it possible to define appropriate work steps. For this reason, it is useful to keep this order during processing, as it reflects the sequence of the decision process according to Fig. 1.5 [13].

- Step 1: Determining the overall strategy for all pieces of equipment

The overall system costs are calculated with the help of a long-term analysis, so that both investment and operation costs can be derived for a longer period (e.g., 10 years). This happens taking into account different maintenance strategies on the one hand and other conditions on the other, such as the total energy not supplied or the number of disturbances at certain system nodes, but also issues such as economic development, customer cogeneration, electric mobility, and general political boundary conditions (renewable energy law, financial support for home ownership, etc.). Due to the unpredictability of particular developments, it is useful to apply a framework of scenarios with appropriately defined premises. Results of this process are the long-term needs of the network and the derived annual budget for the development, renewal and maintenance of assets, tasks which fall under the responsibility of the asset manager.

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The procedures for these sub-tasks are described in Sects. 2.1.8 (renewal strategy) and 3.4 (asset simulation).

- Step 2: Implementation of the overall strategy and derivation of particular asset decisions on equipment level

Based on the results of the financial environment, which are determined in the first step, there is a selection of assets that have to undergo a maintenance or renewal activity. The determination is based on the condition of the equipment and the importance for the entire system.

In this context, the RCM strategy is often used in practice (Sect. 1.2).

- Step 3: Selection of the appropriate maintenance activity

After the selection of the unit, which has to be maintained, a decision has to be taken in this step which maintenance activity (e.g., replacement or revision) should be applied taking into account the consequences that are caused by a potential outage of the unit. Here, risk assessment may be helpful, which is described in detail in Sect. 3.2.6.

- Step 4: Optimal maintenance activity of the asset

While the first three steps are related to the assets in the overall system, in this step, the decision is exclusively related to the equipment level. Using the FMEA (failure mode effect analysis), the optimal maintenance of the equipment can be determined taking into account failure statistics and the consequences of failure for the entire unit.

The FMEA method is exemplarily described in Sect. 3.2.6.

In practice, the processing of various strategies in the area of asset management will be carried out under consideration of pre-defined Key Performance Indicators (KPIs, Sect. 3.3) based on the benchmark results from internal and external service providers. The different superior asset management strategies can be divided into different areas with the associated individual tasks:

- System development:
  - Preparation of the strategic planning concept by continual adaptation,
  - Definitions of system planning assumptions,
  - Determination of the limitation in power flow capacity,
  - Consideration of customer needs during the planning stage,
  - Consideration of decentralized active components (generation, storage, etc.), and
  - Identification and commissioning (specifications) of particular projects.
- Maintenance
  - Definition of maintenance cycles,
  - Condition assessment of assets,
  - Decision regarding the procedure in case of outage of equipment,

  - Definition of the scope of work for maintenance,
  - Allocation of resources (material, finance), and
  - Commissioning of the implementation (asset service).
- Renewal:
  - Definition of strategies,
  - Determination of the renewal time of assets including the volume of assets,
  - Decision regarding the used technology,
  - Provision of resources (finance, specifications, suppliers), and
  - Commissioning of the implementation.

With the results of the above-mentioned activities, it is possible to fulfill the tasks of the asset management and to optimally operate infrastructure networks.

According to [29], all measures which are necessary during the life cycle of a maintenance object to maintain its functional condition or return to these, so that the required functions are fulfilled, are summarized in the term “maintenance activities” (including management).

2.1.1 Overview of Maintenance Strategies

Maintenance strategies are applied for equipment of infrastructure facilities including also the replacement or the exchange. The choice of strategy for an asset group depends on various boundary conditions that must be considered in a case-by-case. These boundary conditions are exemplary:

- Outage behavior of equipment,
- Consequence in case of an outage,
- Comparison of maintenance costs related to the investment costs,
- Replacement of the entire equipment,
- Repair time resp. interruption time of operation,
- Availability of spare parts,
- Technology, and
- etc.

Fundamental distinctions of the different strategies are presented and compared below.

2.1.1.1 Definitions

The maintenance of equipment has the task of ensuring the availability and performance of network components over the total life. Basically, each piece of equipment has a certain availability level which can be influenced by appropriate maintenance actions.

But it must be pointed out that it has to be distinguished between availability of a component and a network node, to which the consumers are connected. While the maintenance will directly affect the condition of the equipment, and thus its failure rate, availability of network nodes will be further influenced by additional criteria, for example:

- network topology, network structure,
- operational mode of assets,
- redundancy,
- type of equipment,
- stock of spare parts, and
- availability and reaction time of the staff,

so that the maintenance is only one way to affect the availability of a network. With what measure the desired target can be achieved thus depends on the individual circumstances of a network and the philosophy of the system operator. According to the pre-standard VDE 0109-1 "Maintenance of installations and equipment in electrical supply networks—Part1: System aspects and procedures" [27], the following terms are defined. Similar definitions are listed in [23, 24].

To ensure the operability of the equipment, the selection of a maintenance activity is to find an optimal balance between the consequences and the frequency of supply interruption. Different maintenance strategies had been applied in the past depending on the equipment and the boundary conditions, which are applied in different ways. These different strategies are explained in the following sections, namely:

- Corrective maintenance (Sect. 2.1.1.3),
- Time-based maintenance (Sect. 2.1.1.4),
- Condition-based maintenance (Sect. 2.1.1.5),
- Priority-based resp. reliability-centered maintenance (Sect. 2.1.1.6), and
- Risk-oriented maintenance (Sect. 2.1.1.7).

The maintenance strategies, which are presented in Sects. 2.1.1.4 and 2.1.1.5 (time and condition-based), can be called as preventive maintenance.

Maintenance activities

In principle, the entire maintenance of equipment or a network can be subdivided into various tasks, which are described in detail in the following sections. These are as follows:

- inspection,
- service, and
- overhaul,

and sometimes as a separate activity

- improvement.

Inspection

Inspection is a maintenance activity which is exclusively applied to identify and assess the current condition of equipment, including the causes of wear. As a consequence of the inspection, the necessary maintenance activities are derived, which allow the further use of the equipment. The inspection can be performed by different activities depending on the equipment or plant:

• Site inspection	The site inspection is the simplest possibility to perform an inspection. The objective in this case is to detect the current condition of equipment by a rough visual inspection with respect to the overall condition. In case of overhead lines, the site inspection can be conducted by helicopters
• Visual inspection	In contrast to the site inspection, the condition of a particular asset will be assessed in case of the visual inspection by human senses. In this case, characteristic values describing the condition will be recorded, so that obvious defects can be detected, e.g., pollution, traces of wear-out problems
• Function control (functional test)	The function control of equipment ensures that the required main functions are fulfilled, such as the protection triggering of in case of a short circuit
• Condition determination	The aim of this measure is to allow a deeper assessment of the current condition of the equipment. In general, the condition determination should be performed by measurements (diagnosis) and these actual results can be compared with previous measurements The parameters of a measurement depend among other things on the asset type, the operating conditions, and the operating experience of the user Furthermore, the condition determination can be performed by a nondestructive test
• Condition assessment	Assessment of the condition of a maintenance object by certain measures (site and visual inspection, function control, and condition determination) to derive a maintenance strategy

The above-mentioned measures (site and visual inspection, function control, and condition determination) are combined with the term “condition detection” or “condition recording.” The condition assessment uses the results of the condition detection and derives the necessary maintenance activities of the considered assets. In the following, the term condition determination will be used.

Service

Service is a maintenance activity for the preservation of the target condition, and this measure should postpone the technical wear. The equipment is usually dissembled during service at least partially, wear parts replaced, if available and needed, and the functionality is ensured, e.g., by ensuring the functioning of moving parts, tightening of bolts, etc.

An indication of the time to perform a service may result from inspection, operating problems, or may even emerge from the last service.

Overhaul

In contrast to a service, the overhaul is an activity to recover the target condition. The defined and specified functionality is reached again after a defect or failure of the equipment itself or a significant component by in-depth repair of the asset, including partial replacement of components.

Improvement

The improvement is the combination of all technical and administrative measures as well as measures to increase the reliability of equipment or plant without changing the required function. Basically, improvements may be appropriate if the operating experience and inspection indicate systematic problems. Improvements are not a separate maintenance activity, and they are usually achieved during maintenance or repair.

2.1.1.2 Basis of Maintenance Strategies

In general, the overall decision-making process can be divided into different targets to develop maintenance strategies (Table 2.1) according to [40]. This could be for example.

The commitment to a fundamental strategy or combination of targets for equipment defines the maintenance strategy in detail.

Table 2.1 Targets of maintenance strategies

Part strategy	Description
• Optimization of the equipment	Operation of the system component with rated values and minor switching off times
• Minimum life cycle costs	Low investment and operational costs during the total life and optimal operation
• Optimization of resources	Maximum operation of the system component with minimal resources (human, finance), monitoring of the operation
• Minimum risk	Compliance of the prescribed risks accepted by the company: staff, operation, availability of supply and finance
• Additional opportunities for further development of equipment	Development of additional opportunities on the basis of the available know-how
• Increasing of availability	Reduction of the hazard rate of equipment and the involved consequences in case of an outage
• Optimization of the entire system	Adjustment of the maintenance activities regarding individual components on the remaining life of the total system (e.g., substation and station)

2.1.1.3 Corrective Maintenance (CM)

The replacement or repair is carried out exclusively after a failure which leads to an outage of the device causing an interruption of the power supply. If the investment cost of equipment is low and at the same time the consequences of a failure are negligible or the cost for a condition assessment is high, this strategy leads to the lowest maintenance costs, as costs occur only after a fault event. Spare parts should be available in short time, the consequences of equipment failure and thus an interruption of supply can be neglected, and this strategy is therefore often used in networks with lower voltages. In addition, another reason for this strategy is that the number of used components is high, so that no other strategy is appropriate due to the scale effect and the economic impact.

In case of this maintenance strategy, the current equipment condition is not systematically recorded by an inspection, because this is economically not efficient due to the limited asset knowledge and is sometimes partially prevented by the general inaccessibility of the equipment. Use of equipment takes place up to the maximum useful life, without liability for the availability of the system. Basically, this maintenance is reasonable accepted, for the causes mentioned above, when the failure rate of the equipment is constant at a very low level and no aging behavior occurs (Sect. 2.1.5.1). Therefore, there is no risk of high unforeseen maintenance expenses.

2.1.1.4 Time-Based Maintenance (TBM)

In this case, inspections and services are carried out after a fixed time interval, and the replacement of equipment is performed after a predetermined time depending on an expected technical life span. The time cycle can be derived from the system operator experience and from the manufacturer recommendation, which are justified by known aging behavior as well as statistics. The scope of maintenance measure is defined in advance, and the fundamental basis of this strategy is to avoid forced outages. This strategy is mainly applied to valuable assets with good results for availability, if the wear of various components is assumed based on the operational experience. Basically, however, this leads to the largest maintenance costs and, as a rule, the assets are not used until their end of life. These costs have to be compared against the avoided costs for recording and assessment of the technical condition in case of the condition-based maintenance (CBM) strategy.

However, the application of the TBM requires a correlation between age or the accumulated stress of equipment (e.g., switching frequency of a component) and the failure rate, so that based on a statistical test, individual components can be replaced before an outage occurs.

This maintenance strategy should be used for equipment according to Sect. 2.1.5.1, if its technical condition cannot be evaluated economically by condition determination or monitoring.

In practice, the TBM has the significant advantage that, for example, complete substations or feeders can be switched off and thus maintenance of all equipment at the same time is possible. On the contrary, for the case of CBM strategy, an individual decision should always be made for each piece of equipment.

2.1.1.5 Condition-Based Maintenance (CBM)

Since in many cases, a strict relationship between the failure rate and the age of the equipment is not available, and thus, the TBM is not effective, this leads to the application of the CBM strategy. In this case, the maintenance and the replacement of the equipment occur as a function of the technical condition. The requirement is that the condition of an asset is detected by monitoring or diagnostic procedures and can be compared with the condition history, which results in additional requirements for the investment in diagnostic systems and staff training. In assessing the life cycle costs related to the use of CBM, it is important to note that the cost for monitoring systems takes place at the time of investment of the equipment, while the avoided failure costs will occur at a later date. The consequence is that the economic benefit is a function of the interest rate and all equipment faults cannot be identified as a trend in advance.

However, the disadvantage of this maintenance strategy is that all assets are to be treated basically in the same manner, regardless of their location or of the importance for the system performance.

This strategy is particularly useful for assets that are automatically equipped with appropriate devices for condition monitoring or if the condition assessment is possible during inspection. Basically, the CBM strategy is useful when an aging process and wear problems are clearly detectable, so that the risk should be reduced.

2.1.1.6 Priority-Oriented or Reliability-Centered Maintenance (RCM)

Generally, in the case of the reliability-centered (priority-oriented) maintenance, the importance of equipment for maintenance activities is selected for regardless of the technical condition. The technical condition is taken into account indirectly via the hazard rate, for example, if the outage probability or the energy not supplied is calculated.

In the opposite, a strategy is understood under the label RCM, which takes both the equipment importance and the equipment condition into consideration. Only the combination of importance and condition leads to an optimal allocation of financial resources regarding the maintenance strategy of assets, which on the one hand have a corresponding influence on the supply and on the other hand are also in a technical condition that justifies an activity.

A detailed description of the RCM strategy is given in Sect. 2.1.2.

2.1.1.7 Risk-Based Maintenance

The risk-based strategy is an extension of the reliability-based maintenance by assessing the risk (= probability of failure × resulting consequences) in the event of an outage of equipment or a supply interruption, Sect. 3.2.6. In the evaluation of a risk-based maintenance strategy, the maintenance costs can be taken into account to avoid the outage. The assessment of the accepted risk factors is extremely important when applying this maintenance strategy.

2.1.1.8 Resultant Assessment of Maintenance Strategies

While the first three maintenance strategies (Sects. 2.1.1.3–2.1.1.5) have many disadvantages in case of valuable assets (e.g., costly, adequate storage, all devices are treated identically), the fourth variant (reliability-centered maintenance, RCM) is recently often applied. The RCM can thus be regarded as a superior maintenance strategy, as shown in Fig. 2.1.

If it is not possible or not useful to determine the importance and the condition of the equipment, the most economic strategy is usually the corrective maintenance (CM) (left branch).

The only reason to implement a TBM strategy is to document the inspection or maintenance activities of a defined period due to the legal (or quasi-legal) requirements. As an example, the requirements of special technical standardization groups can be mentioned (such as air compressors and elevators) to control the safety of the equipment.

If it is economically feasible to carry out a diagnosis and an importance assessment, these automatically lead to the reliability-centered maintenance strategy (RCM).

Finally, a wide range of different assets always exists in infrastructure companies, so that a general statement to implement only one strategy cannot be made. In fact, a decision will be made taking into account the identified criteria and efficiency for several asset groups.

Starting from the RCM strategy, it is possible to transfer again in the three previously discussed maintenance strategies (CM, CBM, TBM) as a function of importance. For example, if a reliability calculation demonstrates that the equipment has no significant influence on the non-availability of electric energy and consequently, the CM could be applied, if a replacement or repair can be conducted in the short term. This means that the introduction of the CM is the result of the consideration of the experience, but can also be caused by a specific calculation of reliability indices.

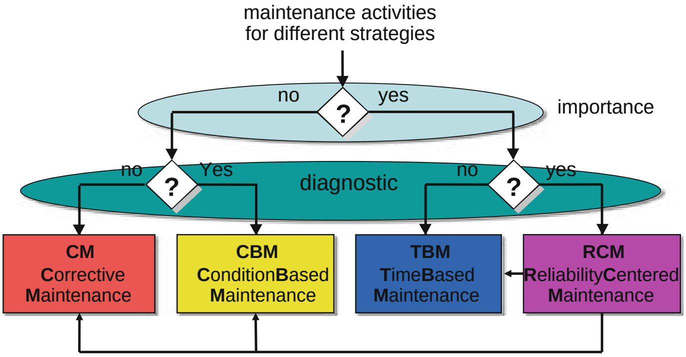


Fig. 2.1 Selection of maintenance strategies

2.1.2 RCM Strategy

Since several years, the RCM is used successfully in many areas [1, 2, 16], with its beginnings in the 60s or 70s in the aircraft industry. In this approach, it is examined in detail which components of the equipment can fail with a certain probability and which consequences can be derived from. The purpose of a RCM is thus a balance between corrective and preventive (time or condition-based) maintenance.

If related to an asset, this procedure is called FMEA (failure mode effect analysis) or FMECA (failure mode effect and criticality analysis). The result of such investigations can be used either for maintenance or for new development of a device (Sect. 2.1.4).

While originally the concept of RCM included only the consequence in case of an outage which leads to a maintenance activity, hereinafter the consideration is extended to the complete decision-making process (replacement, maintenance).

2.1.2.1 Definitions

Basically, there are different ways to apply a RCM strategy:

- Equipment oriented

In this context, the question is examined which component of the equipment loses its functionality and out of which reason. This question is solved by the application of the FMEA method, and the results of this investigation lead to the decision which component to service or to replace. Moreover, recommendations which parts of equipment to optimize for future development can be made.

The basis of these considerations is the reliability of each particular component and the resulting consequences in case of a component failure.

- System oriented

The basis of this approach is to investigate which equipment or plant affects the system availability and performance of the network and thus leads to a supply interruption. This task is achieved by the application of reliability calculations and the evaluation of the energy not supplied or the number of interruptions at certain network nodes. Moreover, it is possible to determine the importance of equipment depending on other criteria. On the contrary to the equipment-oriented approach, the result is which equipment or plant to service or to replace from the system point of view.

Further considerations in Sect. 2.1.2 deal with the system-oriented approach. Application of the described method can be regarded as a higher level approach, so that starting from the system-oriented approach, all other maintenance strategies can be derived, such as corrected, time-based, or CBM strategies (Sect. 2.1.1.8).

2.1.2.2 Procedure

In the case of reliability-centered or priority-based maintenance (RCM), basically two values are assessed: condition of the equipment/plant and importance. This is the basis for the evaluation of the order which equipment to service [3].

The following steps can be derived according to Fig. 2.2:

- Determination of the condition of equipment (condition index c),
- Evaluation of the importance of equipment for the entire system, e.g., the influence of the equipment outage on the reliability of supply (importance index i),
- Combination of this information to evaluate the sequence of the maintenance activities regarding the different assets, and
- Definition of the final maintenance strategy.

While according to Fig. 2.2, a single piece of equipment is evaluated, an evaluation of various components is possible on the same basis, which can be combined into a complete system. In this case, the basic approach can be derived by Fig. 2.16 (Sect. 2.1.3) using the example of a medium-voltage plant [4].

The final condition of the entire plant is determined by a suitable combination of the condition assessment of each piece of equipment. The combination of these interim results to the condition index c is calculated by applying the weighted sum (see condition determination).

The weighting factors for the individual asset groups are determined based on the number of installed equipment and, for example, the investment costs or the consequence on the overall system in case of equipment outage related to the entire installation. Much expertise from the network operation is required for the collection and proper linking of the respective parameters. The transformation is often carried out by intelligent software systems, for example, using fuzzy logic (Sect. 2.1.3).

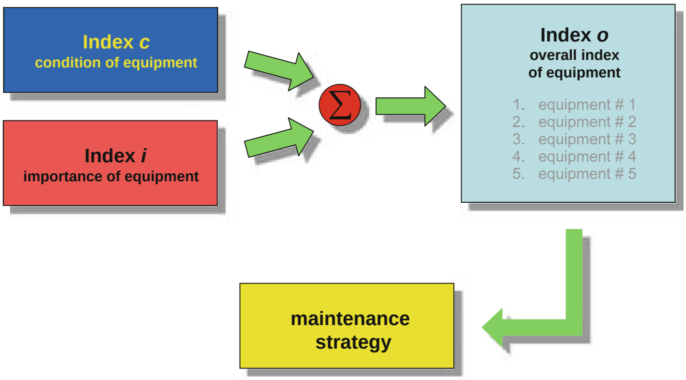


Fig. 2.2 Principle approach of RCM strategy

Finally, the total index o of the installation is derived from the aggregated condition index c and the importance index i.

The development of the two variables (condition and importance) is shown in more detail in the following chapters.

Condition determination

During the condition determination, the pieces of equipment are evaluated separately and compared with each other. In this case, the condition assessment is performed by a suitable combination of the results of selected evaluation criteria. The collection of criteria depends besides the master data (age, technology, location of installation) on comparative measurements, which are carried out in the context of periodical inspections, visual observations, and assessment by the maintenance staff. Furthermore, the evaluation includes the operational experience and the existing technical and economic know-how of the system operator.

As exemplarily presented in Table 2.2, the assessment of the individual criteria of the assets is determined by the selection of pre-defined sets of possible evaluations. The final condition index c is calculated by these individual evaluations as relative weighted sum of these values (weighting). The following rule is applied for the considered equipment: the larger the calculated index c, the worse the condition of the equipment. For $c = 0$, the equipment is in excellent, for $c = 100$ in very poor condition.

Table 2.2 List of criteria for the condition assessment of equipment in case of a circuit-breaker (extract)

Criteria	Scale S		Assessment	Weighting
Age (years)	<20	1		5
	20–35	3		
	26–30	5		
	31–35	7		
	36–40	9		
	>40	10		
Switching operations per year	Normal	1		3
	Medium	6		
	High	10		
Service know-how	Good	1		4
	Medium	6		
	Poor	10		
Results of measurements	Normal	1		10
	Medium	6		
	Poor	10		
Total condition c			(Score)	

In case of the condition determination of the equipment according to Table 2.2, not only the physical condition can be determined, which can be for example derived by measurements or visual observations, as shown above, but also further information is taken into consideration. The additional information might be technology, operational experience, and supply of spare parts or service know-how. The consequence is that an investment control can be performed by this review to replace individual devices or groups earlier, for example, to force a change in technology or implement a new overall strategy. In this case, one would assign "artificially" a poor condition to the asset, so that, for example, an exchange occurs earlier.

In general, it is possible that an assessment of equipment consists of many criteria. A single poor assessment can be perfectly compensated by other assessments, so this poor rating is not noticeable in the overall result. To solve this problem, a message should occur, if a threshold is exceeded so that immediate maintenance actions must be carried out. In addition, it is also possible to apply the evaluation by utilization of fuzzy logic tools. In this case, critical assessments can be weighted separately or knockout criteria are introduced (Sect. 2.1.3).

Importance assessment

The determination of the importance of an asset is always a subjective evaluation; it can be defined by a variety of different criteria, which can also be combined. These criteria may include in case of an electrical system the following items, for example:

- Voltage level (110 kV; 380 kV),
- Location in the network (power station, overhead line bay),
- Investment costs,
- Distance of site from nearest workshop,
- System topology (radial network, meshed network),
- Amount of energy not supplied,
- Number of supply interruptions,
- Hazard rate of equipment,
- Power flow carried by equipment,
- Sociological influence of energy not supplied (hospital),
- Business influence (penalty in case of energy not supplied, loss of revenue),
- Influence on the considered system in case of an outage,
- Interference of the surroundings resp. the environment due to a fault (explosion, leakage of oil), and
- Image damage of the company due to an outage, and
- etc.

Furthermore, the assessment can be weighted against each other and standardized by a combination of different criteria for assessing the importance to obtain a uniform sizing.

These criteria should be selected in case of considering the importance of an entire plant, which can be applied to all components of the plant. This is demonstrated for an electrical substation:

- Voltage level (110 kV; 380 kV),
- Switchgear configuration: single or double bus bar with or without longitudinal coupling,
- Transferred active power, and
- Type of supplied customers: households, commerce, and industry.

While some of the above criteria are related to the particular equipment (e.g., voltage level, hazard rate, and power flow), others are system-oriented (e.g., energy not supplied or not fed in, influence of the disturbance, and supply interruptions). It is quite reasonable to apply the equipment-oriented approach of the importance determination in high-voltage systems due to the system topology and therefore reduced impact of a fault on the complete network, while the system-oriented approach is more appropriate for medium-voltage networks.

It is possible to define a range of importance i between 0 and 100 appropriate standardization. A value of $i = 0$ means that this asset is of negligible importance compared to an asset which has a score of $i = 100$ and thus is considered to be very important. It is essential that the classification is to be seen as relative to similar type of equipment. The final result leads to a prioritization of units within the assets fleet and which maintenance activity has to be applied first.

Interpretation of the results

After determining the scores for the parameters c (condition) and i (importance) according to the procedure described above, it is possible to visualize the results (crosses) in a two-axis coordinate system as in Fig. 2.3. Here, the condition of the equipment is plotted on the ordinate and the importance on the abscissa.

According to Fig. 2.3, a cross in the upper left corner (c * 100, i * 0) represents equipment which is indeed in a poor condition, but whose failure will not have any major impact on the entire system performance as a result of the low importance. In contrast, a cross in the lower right half (c * 0, i * 100) represents a component that is in a very good condition, a failure of which, however, would have significant consequences for the reliability of supply. The technical evaluation parameters c_W and c_E result from the network experience and are specified by the operator [5, 42]. The classification in terms of maintenance measure occurs in parallel to the abscissa i and depends on the condition of equipment, for example:

- Section I: Replacement of equipment,
- Section II: Service activities, and
- Section III: Inspections within the scope of legal possibilities.

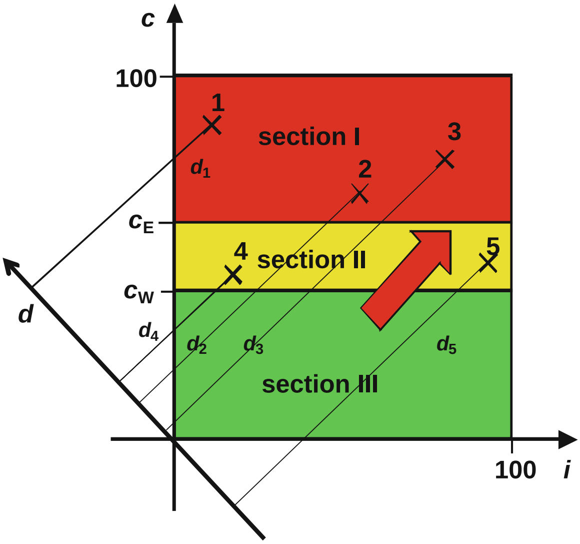


Fig. 2.3 Presentation of the RCM result; c condition of the equipment; i importance of the equipment

The order for a maintenance activity within a section depends on the distance to the line d. If this axis is rotated at an angle of 45° from the y-axis, it means that both criteria (condition c and importance i) influence the decision equally. This means, for example, that the equipment no. 3 in the red section should be replaced first, then no. 2 and no. 1, although the latter has a worse condition. If a conditioned-based maintenance approach is exclusively carried out, which considers only the equipment condition criteria, the exchange should take place in the order 1–3–2, because the importance of the equipment is not included in the selection. The determination of the order, in which the various assets are taken into account in case of the maintenance activity, is illustrated by a red arrow in each of the figures.

All activities in Section II should be carried out in the order 5–4 as equipment 5 has the greatest distance d_5 to the axis d.

According to Fig. 2.3, the d-axis has an angle of 45° relative to the other two axes. Basically, it is possible to have a deviating angular displacement, so that the final assessment of the variables—condition and importance—has a different influence on the decision. If the angle between the axis d and the axis c (condition) is increased to 90°, the CBM is considered, as the distances $d_1 \ldots d_0$ are depend only on the condition of the assets (Fig. 2.4).

If the angle α is described as the angle between the c-axis and the d-axis (Fig. 2.3), the distance to the d-axis is determined according to Eq. (2.1).

$$d_n = c_n \cdot \sin(a) + i_n \cdot \sin(90 - a) \tag{2:1}$$

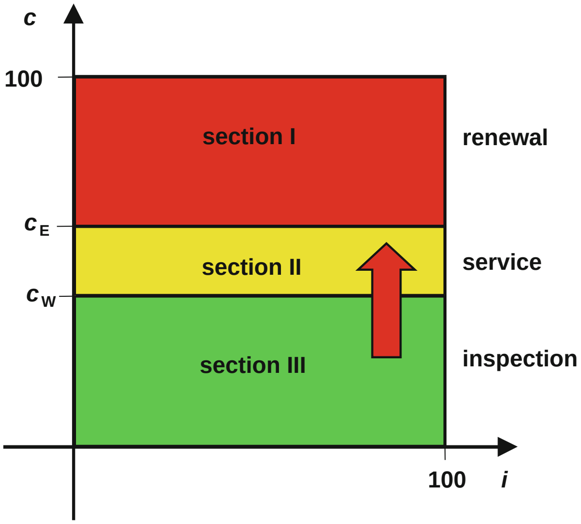


Fig. 2.4 Condition-based maintenance

with index n for the different types of equipment. If the angle is assumed $\alpha = 45^o$, then equation simplifies (2.1) to:

$$d_n = \frac{\sqrt{2}}{2}(c_n + i_n) \tag{2:2}$$

On the contrary, if the d-axis is parallel to the y-coordinate, only the importance is assessed. In this illustration (Fig. 2.5), the pieces of equipment can be divided into different groups so that, for example, a result can look as follows, according to the allocation on the axis of importance i:

- Section I: No service,
- Section II: Service every 10 years,
- Section III: Service every 5 years.

In this case, a replacement of the equipment does not depend on its condition, for example, after a predetermined time, so that either the corrective or TBM can be applied.

In addition to the options shown in Figs. 2.4 and 2.5, different sections can also be combined in different ways, as exemplarily shown in Fig. 2.6. The listed values c and i in Figs. 2.4, 2.5, and 2.6 are characterized by the following properties:

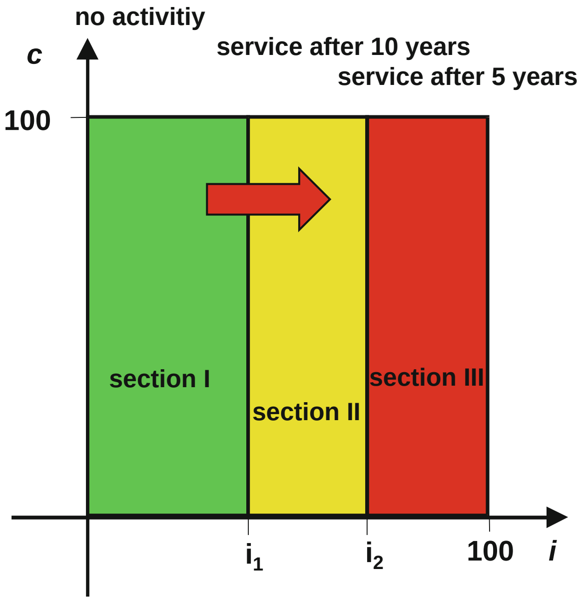


Fig. 2.5 Corrective and time-based maintenance

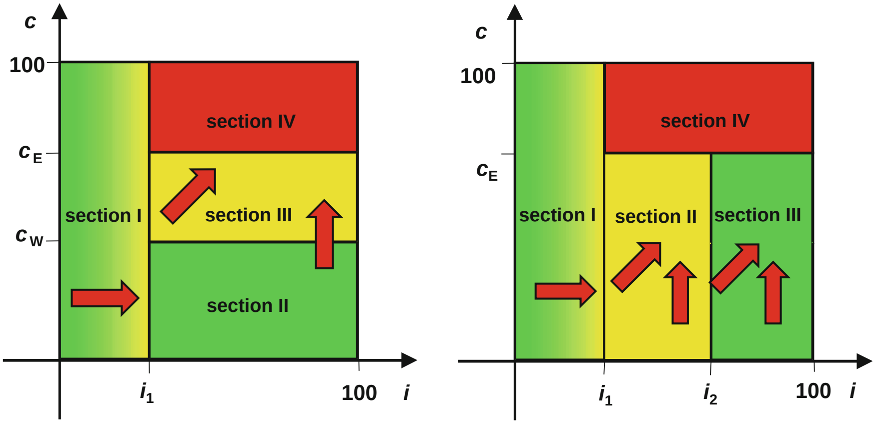


Fig. 2.6 Combination of different maintenance strategies

• c_W	Condition value to which only inspections are useful
• c_E	Condition value from which a replacement of the equipment is recommended
• i_1	Due to the low importance of the equipment for the entire system, the corrective maintenance can be applied
• i_2	As a result of higher importance, different time cycles for maintenance services can be scheduled

This approach can be improved depending on line d and arbitrary combinations of the decision sections. Important, however, are the logical and comprehensible definition and derivation of activities and measures which have to be implemented.

2.1.2.3 Example: Overhead Line Section

This chapter is based on a condition assessment and importance of high-voltage overhead lines, and the need for maintenance activities is derived according to Sect. 2.1.2.2. The description of the example is based on [15]. A possible hazard potential of an overhead line is not taken into consideration to determine the order of maintenance activities, as in any case, this will lead to an immediate maintenance activity.

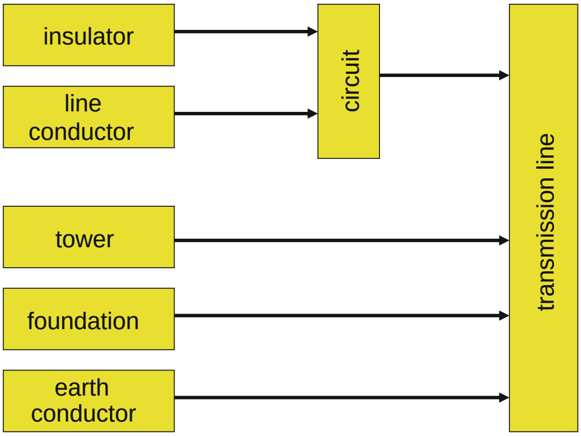
Condition assessment

The condition assessment of a transmission line section is carried out taking into account various criteria that can be defined depending on the operating experience of the system operator and the manufacturer's recommendations. The overhead line components have to be evaluated individually, as a high-voltage overhead line consists of several components (tower, line conductor, earth conductor, etc.). The aggregation is shown in Fig. 2.7.

According to Fig. 2.7, the individual components are evaluated and aggregated as "circuit," which are connected to high-voltage potential, while all components are understood by the term "transmission line." The classification allows to perform a condition assessment of both an electric circuit and the other components in order to subsequently perform a maintenance activity on the basis of the condition assessment.

Various criteria are derived and evaluated for the condition assessment of the individual sub-components of Fig. 2.7. For example, the following criteria can be used for the assessment:

Fig. 2.7 Aggregation of components (HV overhead line)



Line conductor:

- Age,
- Material,
- Design temperature,
- Damages,
- Sag, and
- change, and
- etc.

Line tower:

- Age,
- Material,
- Construction,
- Experiences,
- Type of tower,
- Quality of steel,
- Corrosion protection,
- Corrosion, and
- etc.

Foundation:

- Age,
- Type of tower,
- Damages,
- Design,
- Deterioration, and
- etc.

If the total condition of a circuit has to be determined, consisting of line conductors including terminal connections and mounting sets (c_L) and insulators (c_T), the influence of the various components on the total condition has to be taken into account by weighting factors a_1 and a_2:

$$c_S = a_1 \cdot c_L + a_2 \cdot c_T \tag{2:3}$$

With a value of $a_1 = a_2 = 0.5$, both circuit components will have the same impact on the condition of the entire circuit. A similar assessment can also be derived for the evaluation of the entire transmission line. In principle, the determination of the factors a_1 and a_2 (Sect. 2.1.4.2) can also be performed with the help of a decision matrix with the two criteria are evaluated against each other.

In the case of the condition assessment of an entire transmission line, the results are mean values which are calculated by various criteria of the different components so that extreme values can be canceled out due to the average determination. The consequence is, if a maintenance activity is committed, e.g., refurbishment of the transmission line section, it has to be considered, which component will mostly influence the total condition of the entire overhead line. In this case, the maintenance activity can be applied directly to this affected component.

Importance assessment

A general approach for assessing the importance of a circuit or an overhead line is the calculation of the interrupted energy (e.g., at the end of a transmission line) or the interruption frequency or duration of the outage related to the existing network nodes. These values are influenced by several variables, e.g., the repair time, failure rate of the equipment, the network topology, and load. Which of these values or combinations can be used to assess the importance depends on the boundary conditions in each particular case. The sum of interrupted energy at every system node (customer, power plant), caused by an outage of a line section, is taken into consideration to assess the importance of the overhead line for the example shown here. The interrupted energy is calculated by reliability calculations. It can be distinguished between two options to determine the importance of an overhead line for the entire system:

- energy, which is not available for the supply of customers or for feeding into a downstream system, and
- energy, which cannot be fed in by a power generation plant or by important tie transmission lines.

Which of the interrupted energy is considered (not fed in or not supplied) depends on the task of the system operator. This generally depends on the voltage level of the system; while the not supplied energy is usually used in medium- and low-voltage network, this might be different in high- and extra high-voltage networks.

A reliability calculation is performed to determine the importance of an overhead line in case of the following example by calculating the impact of an outage on the behavior of all system nodes. Data from load flow calculations are used as input data for the reliability calculation, such as network topology, technical data of components and the operating condition (energy generation and supply), and, in addition, the reliability characteristics of the system components:

- Hazard rate λ (1/a),
- Repair time T_r (h).

By means of this reliability data, which can be derived from published statistics or from the records of the user, the effects of the outages on the supply reliability at the network nodes are calculated. Based on this procedure, it is possible to determine the relative contribution of each line section outage to the importance criteria (not fed in or not supplied energy).

Overhead line system

As an example at the discussion above the condition, importance assessment of a 220 kV overhead line network of a transmission system operator (TSO) is shown. The network has a total length of 1145 km and an age distribution according to Fig. 2.8 [15]. It is obvious that most of the 220 kV overhead lines are older than 40 years and the oldest one is 57 years. The last installed transmission lines are designed for a rated voltage of 380 kV, but they are today operated at a voltage of 220 kV.

Result of the condition assessment

According to the procedure outlined above, the assessment of conductors and insulators is performed, which are combined with circuit (Fig. 2.9). The assessment shows that two line conductors are in poor condition compared with the other lines that are in each case the two oldest lines, which were built in 1957. The condition of these lines in a high mountain area may be designated as critical (condition index over 70 according to Fig. 2.9).

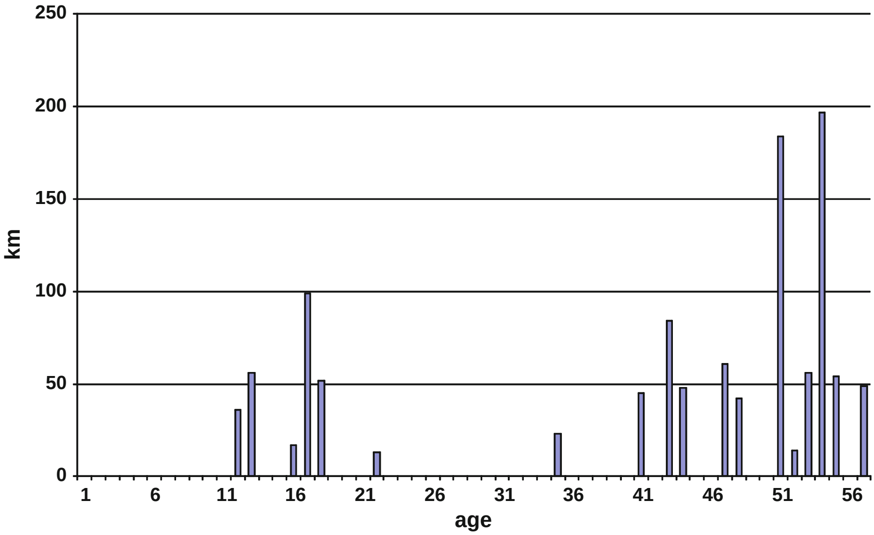


Fig. 2.8 Age distribution of the considered overhead line system (values in km) [15]

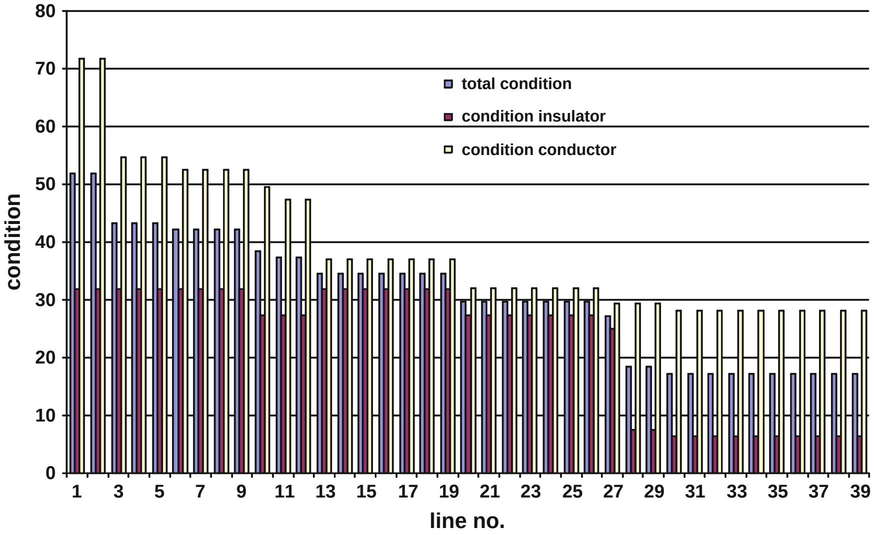


Fig. 2.9 Condition assessment of different circuits [15]

Result of the importance assessment

The calculation of the interrupted energy is carried out for two options, but with different weighting, given by the ratio of the two energies with 1/10 (load: 1, power generation plant: 10). As the importance assessment depends on the particular load situation, different load scenarios are considered, which can be described by the following scenarios:

- Peak consumption winter,
- Minimal consumption winter,
- Peak consumption fall, and
- Peak consumption summer.

Figure 2.10 shows the summary of different importance values for all overhead lines, where the sum of interrupted energy of a line is related to the maximum value of the system which is equal to 100. All load scenarios described above were assessed equally to determine the importance of overhead lines, i.e., the results are, respectively, 25 % of the final result.

The assessment of three main transmission lines with index > 40 of Fig. 2.9 is due to feeding of large power plants into the overhead line network. Less important lines, according to this definition, are located in areas with large consumption which are strongly meshed, so that an outage of one line has less impact on the total supply availability.

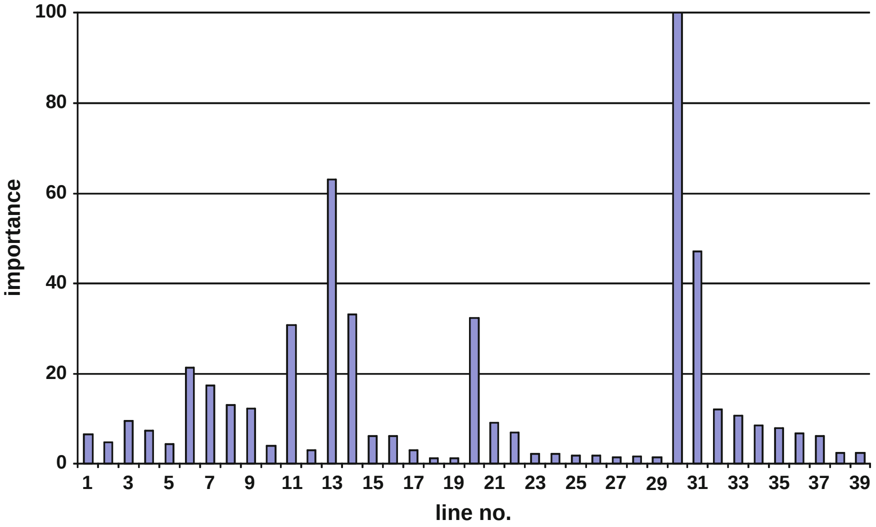


Fig. 2.10 Importance assessment of overhead lines [15]

Resulting assessment

For simplification, the following consideration takes only into account the assessment of circuits to evaluate the maintenance activity. Figure 2.11 shows the total result in a two-axis system based on the assessments according to Fig. 2.3. A mark in the upper left corner of the figure ($c > 50$; $i < 10$) indicates that the corresponding overhead line is in poor condition, but the consequences of failures are almost negligible. On the other hand, a mark (green triangle) in the lower right corner means ($c < 50$; $i = 100$) that the overhead line is in very good condition, but the failure will lead to serious consequences. Figure 2.11 represents a copy of the software program NEPLAN®-Main.

In this case, the assessment diagram will be divided into three different condition sections:

- Green: no measures needed, only inspections, if necessary,
- Yellow: service actions, and
- Red: replacement resp. renewal.

The evaluation shows that the largest proportion of the examined circuits is in good condition, as the majority has a condition index of $c < 40$, while two circuits deviate with a condition index of $c > 50$. If three condition sections are adopted according to Fig. 2.11 for the assessment, as described above, it is obvious that no circuit would have to be replaced due to the condition assessment. However, nine circuits should be subjected to a maintenance activity, while the normal inspection process should be continued for the other lines.

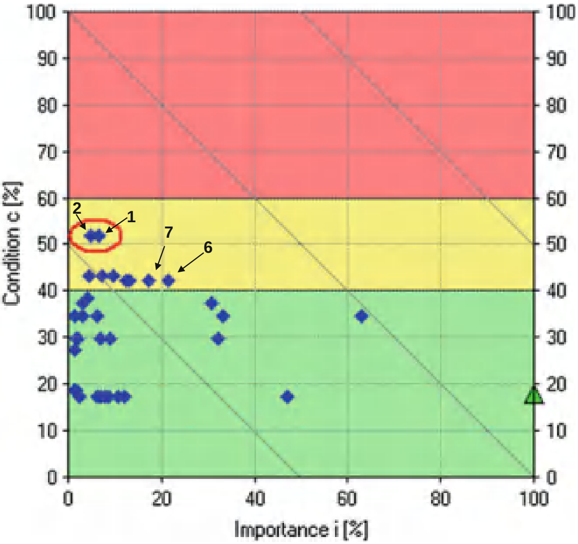


Fig. 2.11 Representation of the total result of the circuit assessment [15]

As a final result, starting from the representation of Fig. 2.11, a prioritization of assets is possible, to determine the order for replacement or a maintenance activity. Here, the distance to a 45° line through the origin is taken as scale. It can be seen that due to the procedure, the lines should be maintained in the order no: 6–7–1–2, etc. (Fig. 2.12a). On the contrary, an inspection should be provided for the lines in the order no: 30–11–13–14, etc. (Fig. 2.12b). The numbering of the lines is according to the identification in Fig. 2.10.

The lines no. 1 and 2 (Fig. 2.11) are in relatively poor condition. However, they have a low importance, so that the priority of these lines for a maintenance activity is low.

2.1.2.4 Assessment of a Maintenance Measure

In general, the decision depends also on the commercial assessment, which maintenance measure, such as replacement or intensive overhaul to shift the replacement, should be carried out, beside technical and regulatory requirements (Sect. 1.3.2). It is usual to calculate the present value of a maintenance measure and compare the result with other options in the context of a life cycle cost analysis. The disadvantage of the present value, comparing different variants, is that technical modifications are not taken into consideration. For this reason, a “System Performance Index” (SPI) is presented [8, 14] which is based on the equipment assessment related to Sect. 2.1.2.2, taking into account the two criteria below:

- Technical modifications caused by the maintenance activity and
- Financial expense caused by this maintenance activity.

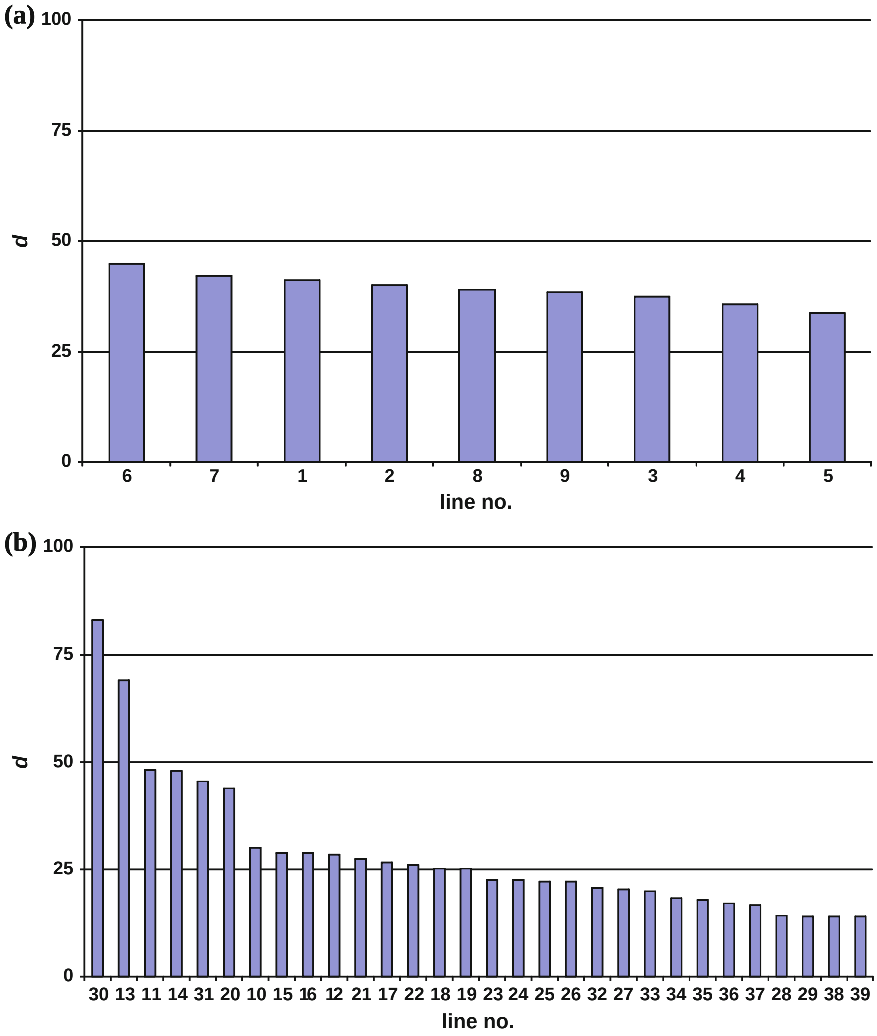


Fig. 2.12 Sequence of the selected line for a maintenance activity [15]. a Circuits in section: yellow according to Fig. 2.11; b Circuits in section: green according to Fig. 2.11

If it is assumed that the condition assessment of equipment leads to the consequence that the equipment should be replaced (marked with E1, Fig. 2.13, $c > c_R$), it is generally possible to shift the replacement by an intensive overhaul (refurbishment), e.g., for 6 years. For better assessment, the technical condition of the entire system must be included in the analysis, as in case of the first opportunity—partial replacement of some components—the old asset is still in use, while in the other case, a new device is in operation with different technology and hazard rate, which would have a different

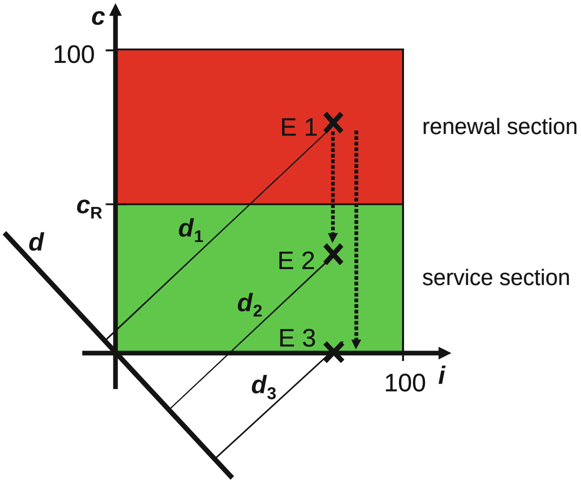


Fig. 2.13 Derivation of the System Performance Index

influence on the system behavior. For this reason, the change of system behavior can be obtained from an overall assessment related to the maintenance costs.

The method can be illustrated by Fig. 2.13. Assuming that the condition assessment of the equipment leads to a value E1, which is described by the condition index c_1 and the importance index i_1, a replacement of the equipment is generally recommended. As a result of the different options of maintenance activities (replacement or intensive overhaul), different assessments of the condition and the importance of the equipment can be evaluated. The new assessments are indicated in Fig. 2.13 by E2 and E3, and in this case, the same importance assessment is considered, if it is assumed that the influence of an outage would not change the system behavior, which is generally not expected in case of a new device. The "SPI" is determined by the following relationship:

$$\mathrm{SPI}_{12} = \frac{d_1 - d_2}{f_M} \quad \text{or} \quad \mathrm{SPI}_{13} = \frac{d_1 - d_3}{f_R} \tag{2:4}$$

with

d_1, d_2 distances according to Fig. 2.13 depending on the maintenance activity
f_M, f_R financial expenses for the replacement f_R or intensive overhaul f_M

The highest SPI value, depending on the maintenance measure, leads to the optimal strategy in terms of network behavior, as the largest "network change" is combined with the lowest financial costs. In a second step, the determined maintenance strategy has to be compared with the outage costs of the equipment. These costs depend on the repair costs in case of failure or an outage, and the costs of energy are not supplied. This approach, however, requires an accurate knowledge of the probable annual costs.

The calculation of the SPI value for the assessment of a maintenance strategy provides a way to evaluate different measures. In practice, risk assessments are often developed, which are described in detail in Sect. 3.2.6.

2.1.2.5 Example to Investigate an Optimal Maintenance Strategy

In the following example, 14 high-voltage circuit-breakers with various technologies are considered [14] to illustrate the application of the SPI approach. The condition as well as the importance assessment leads to the indices c and i according to Sect. 2.1.2.2. The various switching devices have the following characteristics according to Table 2.3.

Twenty-three various criteria are taken into consideration for the condition assessment of the devices, while in this case, the following criteria are used for the importance assessment:

- Voltage level,
- Interrupted active power,
- Hazard rate, and
- Location of the circuit-breakers.

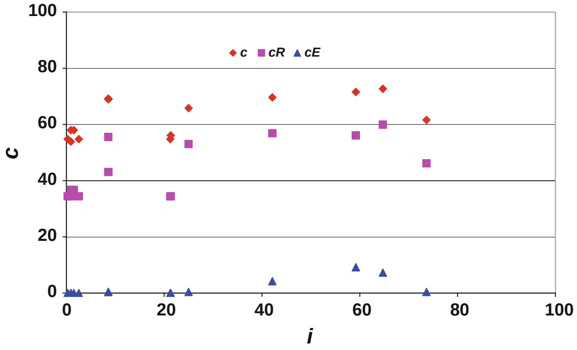
The result is presented in Fig. 2.14 (rhombus). If the replacement of equipment is recommended in case of a condition assessment $c > 50$, the SPI value for this circuit-breaker is derived to determine the order of maintenance measures.

The examination takes places on the basis of the assessment referred to Fig. 2.14, whether an immediate replacement of equipment or an overhaul makes sense to shift the exchange for a time period of 6 years. The change of the condition is used based on the considered maintenance activity for the determination of the SPI value. This means that in a second step, the condition assessment is repeated taking into account an executed overhaul, i.e., the criteria for the condition assessment have to be changed depending on the activity (overhaul) and consequently, new condition indices c_R are evaluated

Table 2.3 Characteristics of assets for the investigation of SPI values

No.	Voltage/kV	Technology
1–6	123	SF_6
7–8	123	Minimum oil
9	123	SF_6
10	123	Air blast
11	245	Air blast
12	420	SF_6
13	245	SF_6
14	420	Air blast

Fig. 2.14 Assessment of HV circuit-breakers; c condition assessment of original circuit-breakers; c_R condition assessment of circuit-breakers after an overhaul; c_E condition assessment after replacement by a new circuit-breaker



(Fig. 2.14 square). The evaluation of a new circuit-breaker for the same location follows the same pattern, c_E (Fig. 2.14 triangle).

The SPI_S ratios are determined taking into account the costs for overhaul according to Table 2.4, and in this case, it is assumed that a replacement of these devices will be delayed by 6 years in case of the overhaul.

Furthermore, the following investment costs (for example) are used to calculate the ratio SPI_E in case of the replacement of a circuit-breaker. In any case, the old circuit-breaker is replaced by a modern SF_6 type:

• Depreciation time		25 years
• Interest rate		6.5 %/a
• Factory price	123 kV	25 k€
	245 kV	75 k€
	420 kV	220 k€

As the financial costs of different maintenance activities cover different time periods, the constant annual costs have to be considered for the total period. The depreciated book value is also taken into account in case of a new investment, so that maintenance costs are comparable.

Figure 2.15 shows the result of the assessment and the values: $\Delta SPI = SPI_E$ (replacement) − SPI_R (overhaul) are listed.

Table 2.4 Costs for overhaul in k€ for different types of circuit-breakers (exemplary)

Type	123 kV	245 kV	420 kV
Air blast	15	25	50
Minimum oil	10	15	30
SF_6	5	10	20

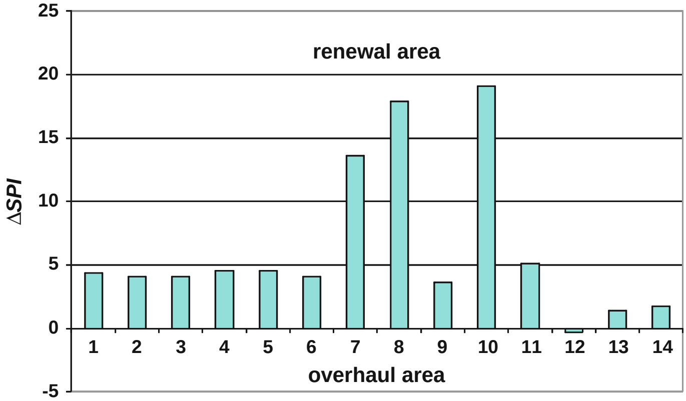


Fig. 2.15 Results of the SPI assessment

A positive value of ΔSPI means that a replacement of the circuit-breaker is recommended against an intensive overhaul to shift the replacement for six years. Finally, the results of the evaluation can be explained as follows:

- The air blast circuit-breakers should be immediately replaced (10: 123 kV; 11: 245 kV; 14: 420 kV).
- The same statement is true for the minimum oil circuit-breakers (7/8: 123 kV) and SF_6 circuit-breakers (1–6: 123 kV; 13: 245 kV).
- An overhaul makes sense for the SF_6 circuit-breaker (12).
- The economic advantage to replace the 123 kV circuit-breakers as soon as possible depends on the low factory price assumed.

By contrast, if only the determination of the present value is used as criteria in case of the considered examples, an overhaul will be the appropriate measure in each case, with the exception of the 123 kV circuit-breakers, which is a consequence of low investment costs assumed.

At the first step, this procedure is based only on the asset “circuit-breaker.” An extended view would also cover the complete 110 kV substation and as a final step, the entire 110 kV system.

2.1.3 Maintenance by Fuzzy Logic

As a result of a condition evaluation, which sequence to maintain the considered assets or components, e.g., service/overhaul or complete replacement. In particular, in case of a renewal measures, the question may arise whether a replacement of individual equipment is worthwhile or the complete bay or substation should be replaced instead. In practice, a clear and systematic answer to this question is often not easy taking into account the economic budget pressures on the one hand and the technical requirements on the other hand. In many cases, the answer depends on boundary conditions that are beyond an objective assessment.

Based on these considerations, it is possible to support the decision with the help of fuzzy logic, if in a specific case, the complete replacement of an entire substation or only the partly replacement of an individual component or equipment is required for technical reasons. As a consequence, this might be the best solution from the economic point of view. The procedure is explained in detail in [7] and is represented here.

Two aspects are taken into consideration in case of the usage of the preventive maintenance resp. RCM strategy as described in Sect. 2.1.2:

- Technical condition of the equipment/plant and
- Importance of the plant for the entire system.

Various different and only component-based criteria are used in case of the condition assessment of the particular equipment. On the contrary, the overall condition has to be evaluated considering the substation or plant. The substation consists of, e.g., different types of assets belonging to the primary system as well as secondary system, building, and auxiliary equipment. The basic procedure is shown in Fig. 2.16 for a substation with different assets which are numbered from 1 to n.

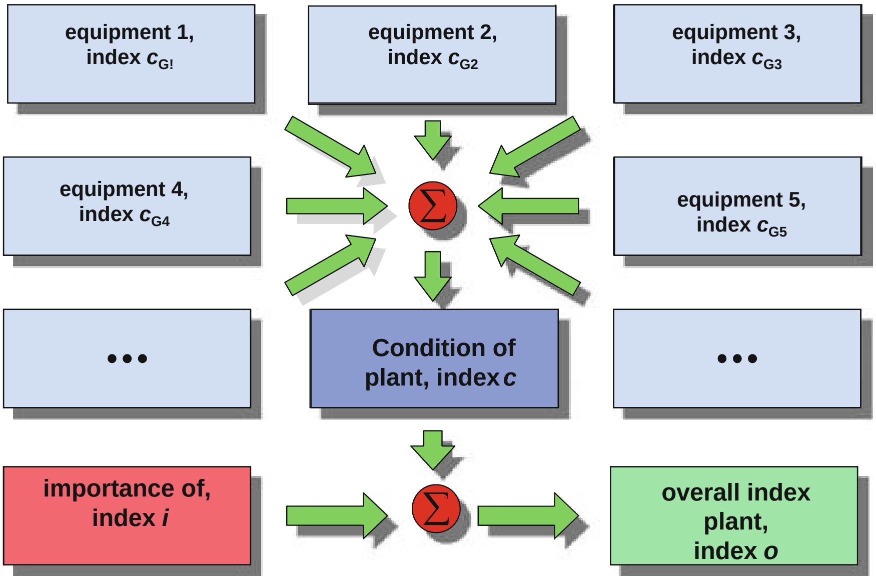


Fig. 2.16 Procedure of maintenance planning of a substation under consideration of the condition and importance of the assets

The overall condition of a substation is determined based on the condition of the single assets by weighting factors. For example, these factors depend on the investment costs for the components or on the impact in case of an outage. Additionally, the number of assets has to be taken into consideration. The result thus represents the average condition value of all assets and gives an indication of the overall health index of the plant.

When determining the optimal maintenance activity, “objective” criteria such as condition and importance are integrated in practice with “subjective” operational experience. The renewal of old installations, for example, may result in a renewal of the surrounding building. Sometimes, there are often good technical and economic reasons to operate old electrical installations inside a renovated building. The decision for or against a partial or complete refurbishment moves in many cases in a gray area and is generally difficult to describe. But even when considering only the electrical installations (e.g., in outdoor installations), the answer to the question—complete replacement or refurbishment—is not always clear. In general, there is an expert assessment, which then leads to a decision procedure. In this case, the human way of thinking to include complex possibilities as well as “fuzzy” issues plays a crucial role to come to a clear “Yes” or “No” decision. The procedure of such decision processes by means of so-called expert systems as well as knowledge-based systems has been intensely investigated and widely used in many different areas successfully. The application of fuzzy logic provides an outstanding opportunity to map these relationships in mathematical functions and to arrive at a systematic reasonable decision.

In Sects. 2.1.3.2 until 2.1.3.5, the aggregation of the condition of different assets is shown to evaluate an overall condition of the plant. It is also possible to combine the conditions of various components to the overall condition of the equipment, and the basic procedure for this purpose is discussed in Sect. 2.1.3.6.

2.1.3.1 Introduction to Fuzzy Logic

When the fuzzy logic is used, the decision process is expressed by verbal (linguistic) fuzzy “If-then” rules, for example:

If component 1 has the condition c_1 and component 2 the condition c_2
then gives the result E

In the context of a maintenance activity of plants resp. substations, this could mean:

If the building is in poor condition and the primary equipment is in poor condition
then a complete refurbishment of the plant/substation is reasonable

The basic approach of the decision-making process with the help of fuzzy logic is shown in Fig. 2.17 and is described in detail in [18, 37].

The particular functional blocks in Fig. 2.17 are described in the following explanations.

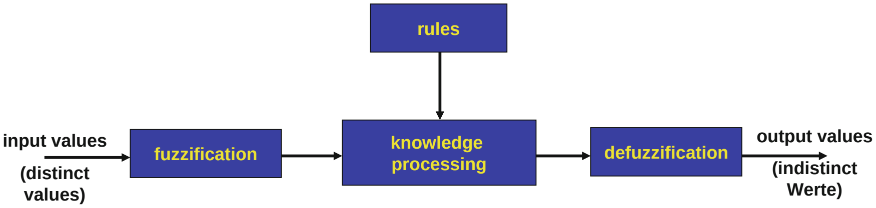


Fig. 2.17 Basic procedure in case of the decision-making process with the help of fuzzy logic [7]

Fuzzification

The purpose of fuzzification is to translate “distinct” input variables into “indistinct” fuzzy variables with the help of so-called membership functions. This means that a current measured value is assigned a certain qualitative variable. Figure 2.18 shows the “technical condition,” which is a distinct variable (a specific numerical value between zero = very good, and one hundred = very poor; see Sect. 2.1.2) of a particular piece of equipment. This “distinct” input variable is represented by three “indistinct” membership functions (good, medium, and poor). The membership functions are expressed in a mathematical form so that the total of the membership function values (ordinates)—in this case 3 values —will be one (1) for every condition value `c` (abscissa). In this example, triangle functions are used; future studies will have to show whether trapezoid functions may be more useful for the “good” and “poor” membership functions.

As shown in Fig. 2.18, in this case, the input variable is the distinct condition value of a piece of equipment that is obtained from a condition evaluation, e.g., according to Sect. 2.1.2. Based on the definition of indistinct quantities, the input variable—here condition `c` of a particular device—can be assigned to one or several membership functions (good, medium, and poor). The following “indistinct” statements (see Fig. 2.18) apply to a “distinct” (specific) condition value of `c` = 70:

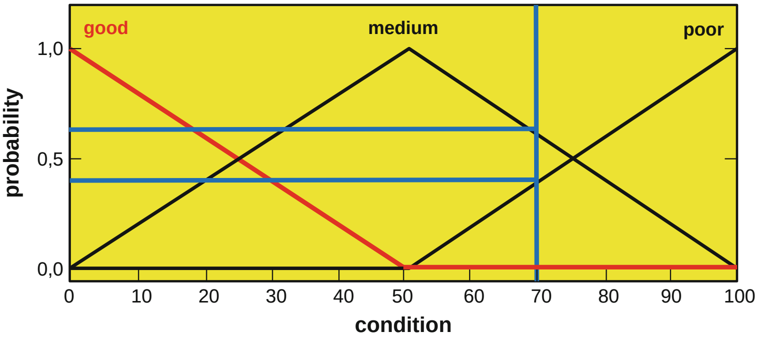


Fig. 2.18 Example of fuzzification [7]

- This value corresponds to 0.0 p.u. of variable “good,”
- This value corresponds to 0.6 p.u. of variable “medium,” and
- This value corresponds to 0.4 p.u. of variable “poor.”

The “distinct” condition values as input variables are thus converted into “indistinct” descriptions, which are afterward combined with the aid of knowledge rules.

Rules

As explained above, the rules, established for the processing of input variables, describe the relationship between the input variables and the output variables. For instance, the rules may be:

- If component 1 is in “good” condition and component 2 is in “medium” condition, the output is “good”;
- If component 1 is in “medium” condition and component 2 is in “medium” condition, the output is “medium”;
- etc.

The “output” or result may be the overall condition of an installation that consists of components 1 and 2. The rules reflect the decision-making process for replacing either individual parts or an entire system. They are based on relevant practical experience, where economic considerations should be included in the decision process. In this case, the number of rules depends on the number of components, which are compared with each other, and the number of membership functions. The maintenance measure can be derived by the degree of the overall condition (defuzzification).

Knowledge processing and defuzzification

In the context of knowledge processing, the indistinct fuzzy variables are logically combined (mainly AND, OR, NOT operations). Here, the operations used are exclusively AND operations (conjunctions). The resulting degree of membership is determined by the minimum of the degrees of membership of various input variables:

- Variable A fulfills requirement 1 at 0.2 p.u., and
- Variable B fulfills requirement 2 at 0.4 p.u.

This means that the appropriate result—based on the requirement “both condition 1 and condition 2 are fulfilled”—fulfills the requirement only at 0.2 p.u. In graphic terms, this may be demonstrated as “cutoff” of the resultant membership function at the point representing the degree of membership of the minimum-fulfilled input membership function (Fig. 2.19).

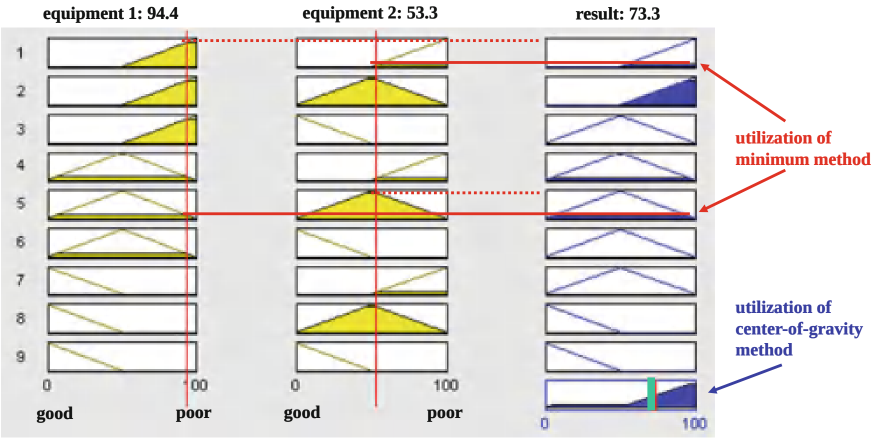


Fig. 2.19 Defuzzification using the minimum method and center-of-gravity defuzzification (simulation MATLAB)

The “minimum method” is only one form of knowledge processing. Depending on the rule basis used, it is also possible to apply the “maximum method” (with pure OR links) or any other method from the fuzzy set theory.

The output variable—in this example, the decision on whether the replacement of the entire system or individual components of the equipment—is computed via center-of-gravity defuzzification of the aggregated membership function, i.e., the center of gravity of the output area is determined. According to Fig. 2.19, two components

- condition assessment component 1: 94.4 and
- condition assessment component 2: 53.3

and in total nine (3 × 3) rules are set up for three different membership functions (good, medium, and poor). The output, in this case: 73.3, is defined by the overlapping of the partial areas and by the computed center of gravity of that covering area. With all non-distinct input membership functions used in practice, the fuzzy output is never exactly zero or exactly one hundred, which is computed with the help of center-of-gravity defuzzification method. This is why the result needs to be normalized, e.g., to one hundred.

The complete pattern of relations between the resulting output function and the condition values of the two given components of the equipment, based on three membership functions according to Fig. 2.18, is illustrated in Fig. 2.20. This example shows that the result is almost constant in case of condition “zero” (equipment 2) if the condition of equipment 1 is located in the range 50–100.

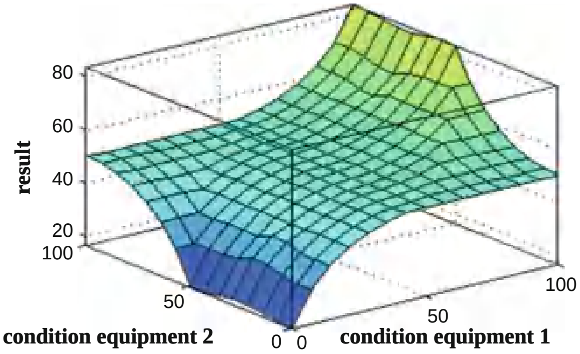


Fig. 2.20 Membership functions of components 1 and 2 in relation to the output (simulation MATLAB)

2.1.3.2 Condition Assessment Procedure with Fuzzy Logic [7]

The presented procedure is used for defining the best suited maintenance activity based on a concrete example: assessment of a secondary substation 10/0.4 kV. A similar procedure would apply to a more complex switchgear installation, e.g., located in a transformer substation or a selective substation of a network node. The condition of a network substation is assessed by applying a number of criteria and by ranking the condition of the following components of assets:

- Bay,
- Transformers (medium, low voltage),
- Disconnector/switch-disconnector/earth switch,
- Instrument transformer (current, voltage), and
- Building/tower.

In case of the condition assessment procedure for a substation, firstly, all components of equipment are evaluated separately according to the specifications (Table 2.2) and grouped to a condition index for the entire station according to their importance for the energy distribution (Fig. 2.16). Consequently, the output is an averaged ranking of the overall substation. For the subsequent implementation of the maintenance task, another procedure is applied where the logic dependencies between the individual items are taken into account (Sect. 2.1.3.3). In this case, the question has to be asked if the overall network station is to be replaced or only a few components.

Starting from the separate assessments, different components of equipment are combined in groups which can reasonably be used for formulating the maintenance strategy for the substation, as it is presented in Fig. 2.21. The aggregation of equipment groups is performed due to the experience that these devices are also treated together in case of a maintenance measure. In this example, current and voltage transformers are combined in one group and disconnectors, switch-disconnectors, and earth switches are combined in another group. After this, these components are combined to constitute the primary equipment when assessing the bays. Finally, the building/tower is included in the

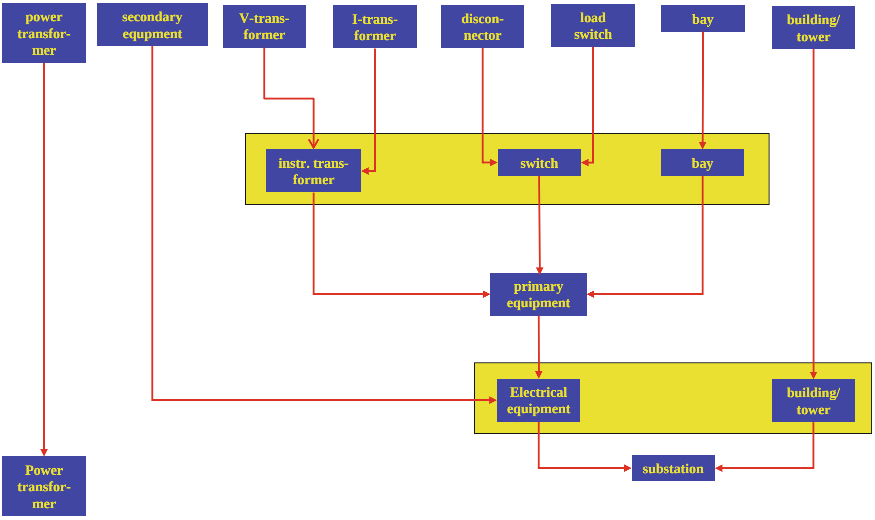


Fig. 2.21 Aggregation of pieces of equipment of a secondary station for the deduction of a maintenance strategy [7]

grouping. The secondary equipment of an installation is normally viewed as a separate group of equipment. But since there is no secondary equipment in this example, it will not be taken into consideration, which shall not limit the validity of the following general findings.

Regarding the implementation of maintenance strategies, it is practically adopted that the MV/LV transformer is exchanged regardless of the condition of the other operational equipment. The technical condition of the transformer therefore does not have any impact on the decision for or against a total rehabilitation of the substation.

The fuzzy logic as described in Sect. 2.1.3.1 is therefore applied to the following decisions:

- Building/tower–primary equipment,
- instrument transformers–switches–bays.

The two levels of the decision process are additionally indicated in Fig. 2.21. Figure 2.22 shows the decision-making tree for implementing the maintenance strategy (without secondary equipment). Starting with the pieces of equipment or units, fuzzy logic is used for identifying whether a total rehabilitation of the substation would be advisable. If this is not the case, a second step helps to decide whether the entire primary equipment should be replaced. If it is found that neither a replacement of the station nor an exchange of the primary equipment is the appropriate approach, the next step is to decide—on the basis of condition c of the individual equipment—how each item is to be dealt with.

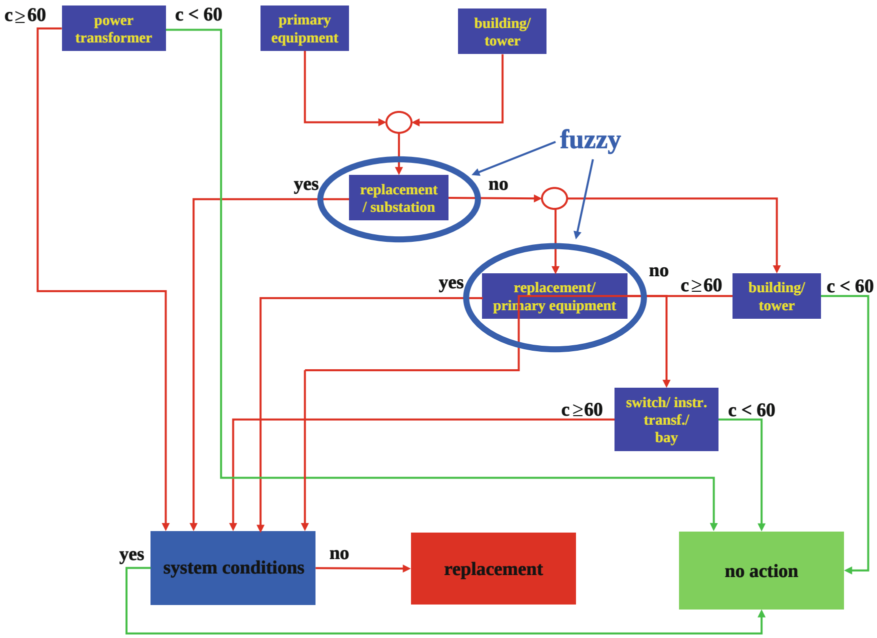


Fig. 2.22 Implementation of a maintenance strategy for secondary substations [7]

Before a final decision on how to proceed with a piece of equipment is taken, it is necessary to find answers to important system issues. The examination is built on five specific questions, which can be extended or reduced depending on the actual application:

- Is the installation/station located adequately, considering the grid losses?
- Are there any plans for making changes in the rated voltage?
- Is the installation/station going to be retrofitted for cable connection in order to replace the overhead line connection?
- Has the location of the installation/station been chosen properly from a public viewpoint?
- Have there been any changes regarding the technical requirements (capacity, reliability, customer requirements, etc.)?

If the answer to one of the above questions is “Yes” for the coming examination period (e.g., the next three years), there will neither be an exchange of the entire installation/station nor a replacement of individual pieces of equipment. As a result of the changed conditions, a new concept is required and a change one by one does not make sense. This systemic issue is identified in Fig. 2.22 by the functional block “system conditions.”

2.1.3.3 Technical Rules for the Knowledge Processing

During the fuzzification process, distinct input variables, which describe the technical condition of pieces of equipment and components, are assigned toward indistinct output variables (Sect. 2.1.3.1). In this context, three fuzzy areas are used:

- Low: good condition,
- Medium: medium condition, and
- High: poor condition.

The allocation of input variables to these areas is described by the triangle membership functions (Fig. 2.18).

The technical rules, which are defined for the decision-making process, take over the indistinct fuzzy variables for further condition assessment in order to meet the decision on whether to “replace the installation” or “replace individual components.” With the rules chosen here, “if-then” conclusions and conjunctions will always be sufficient.

For example: if bay x and instrument transformer y and switch/disconnector z, then the primary part is u. Again, the primary equipment condition (Fig. 2.21) is assigned to three qualitative (indistinct) fuzzy areas L = low, M = medium, and H = high. The areas are described by triangle functions. The same applies to the condition assessment for the building or the tower of a secondary substation.

During the maintenance approach for the entire substation, area L (low) is assigned to the activities “replace individual items” or “no measure.” Area H (high) represents the activity “replace secondary substation” up to “replace individual equipment.” The “medium” area M overlaps both aforementioned fuzzy areas.

Table 2.5 gives some exemplary rules for condition assessment (maintenance activity) for the primary equipment of a secondary substation, consisting of the following pieces of

Table 2.5 Rules for determining the maintenance measures for the primary equipment

No.	Bays	Instrument transformers	Switch / disconnectors	Condition of primary equipment
1	H	H	H	H
2	H	H	M	H
3	H	H	L	M
4	H	M	H	H
5	H	M	M	H
6	H	M	L	M
7	H	L	H	H
…	…	…	…	…
25	L	L	H	M
26	L	L	M	L
27	L	L	L	L

equipment: bay–instrument transformer–switch/disconnector. For $n = 3$ components and $x = 3$ types of conditions, the result is $n^x = 27$ individual rules. Table 2.5 lists the rules for determining the overall condition of a substation, i.e., for the primary equipment and the structural components. In the following, the rules for a medium-voltage substation installed in a cable system are explained. The example is based on the assumption that the substation consists of factory-assembled, type-tested, metal-enclosed bays [26]. The substation does not contain systems with hermetically sealed, gas-filled compartments, where individual items of equipment cannot be replaced. For billing purposes, current and voltage metering transformers have been integrated in a medium-voltage bay.

Explanations for Table 2.5:

- Rule 7: The condition of bays and switchgears is ranked as poor (condition H). This may be due to the following factors: Despite proper maintenance, the admissible contact temperature rise of the switch–disconnectors is clearly being exceeded, even below the rated current; the function of the operating mechanisms is stiff; the bushings in the metal-clad installation point out evidence of partial discharges even at operating voltage levels; the serviceability of bays and switch–disconnectors is clearly restricted, and the exchange of the entire primary equipment (condition H) is indispensable, despite the fact that the current and voltage transformers (condition L) are in good condition.
- Rule 25: The substation has been in operation for about 20 years. Several switch–disconnectors show an inadmissible temperature rise on conducting parts, even below rated current. The operating mechanisms of the switchgear require frequent maintenance activities (condition H). The current and voltage transformers are cast-resin insulated, and they are still in as-new condition (condition H). The individual bays are in good condition (L); neither corrosion nor dielectric deterioration (partial discharges) can be detected at live parts (bushings). The dielectric clearances at the cable terminations are dimensioned properly. Interlockings and overall design are in conformity with the general requirements for personnel safety and arcing fault resistance. The primary equipment is therefore ranked as being within range M. Replacing the installation is not necessary; some switchgear in individual bays can be substituted by new devices.

Explanations for Table 2.6:

- Rule 1: The building structure of the substation shows severe defects: The dimensioning of the supply and exhaust air holes is such that in many cases, moisture condensation takes place at high-voltage parts over longer periods of time. The large ventilation holes are the origin of severe contamination on the inner components, which leads—in combination with the moisture condensation—to partial discharges at

Table 2.6 Rules for determining the overall condition of a secondary substation

No.	Building/tower	Primary equipment	Condition: secondary substation
1	H	H	H
2	H	M	H
3	H	L	M
4	M	H	M
5	M	M	M
6	M	L	M
7	L	H	M
8	L	M	L
9	L	L	L

the insulating surfaces. In view of the structural possibilities, this defect can hardly be eliminated as the requirements regarding the casing's arcing fault resistance do not allow changing the ventilation cross sections. The enclosure of the station is made of sheet steel and shows corrosion, especially on the edges. The condition of the structure is therefore ranked H. The condition of the substation's primary equipment corresponds to rule 7 in Table 2.5. The overall ranking of the substation is poor (H). The entire station needs to be replaced.

- Rule 7: The building structure fulfills all major technical requirements (condition L): The supply and exhaust air cross sections are dimensioned properly so that the dew-point conditions inside meet the general requirements and the temperature rise inside does not cause a restriction of the rated output of the transformers or of the cable connections. The structure also meets the criteria for arc testing with respect to inner faults. The general structural condition is satisfactory [25]. The primary equipment of the substation is in poor condition (H). With respect to the decision on whether to "replace the substation" or to "replace the primary equipment," the medium fuzzy area (M) is chosen.

Similarly, the other rules shown in the tables have been derived from previous expert knowledge.

2.1.3.4 Result: Secondary Substation

With the help of the procedure [2], an assessment was performed on 40 secondary substations (20/0.4 kV) and finally, the fuzzy assessment was applied (replacement/substation according to Fig. 2.22), where firstly the procedure for assessing the electrical/primary equipment–building/tower is performed [6, 7]. In this case, the result is that in total, nine secondary substations should be replaced. The pieces of primary equipment are considered in a second step, and finally, the total result of the 40 substations is as follows:

Total secondary substation	9
Primary equipment	1
Building	5
Disconnector	4

In this case, replacement of an “entire station” merely refers to exchanging the primary equipment and building/tower, since the transformer is separately treated and has therefore not been considered.

2.1.3.5 Conclusion

The procedure can also be used for more complex power distribution installations, such as substations with circuit-breakers in transformer substations or in a network. In case of a gas-insulated substation (GIS), for example, the power transformers, instrument transformers, earth switches, and cable conjunctions of a plant are serviced or replaced independently from the condition of the plant [9, 10]. The replacement of the secondary equipment is also independent of the primary equipment; an exchange of secondary systems takes place only if the primary equipment is changed. The building has no influence on the maintenance activity. As the current transformer is generally combined with the circuit-breaker housing, both pieces of equipment are combined into one component. The following components thus remain for the fuzzy decision:

- Circuit-breaker/instrument transformer,
- Disconnector, and
- Other primary equipment.

Corresponding rules are set up according to Table 2.5 for the three different components of a GIS system.

2.1.3.6 Condition Assessment of Equipment with the Help of Fuzzy Logic

While in previous chapters, a maintenance measure is derived for an entire plant of different assets with the help of fuzzy logic, this procedure is also possible for condition assessment on a device level.

Various criteria are used, which are included in the assessment, in case of the condition evaluation of equipment as a basis for the RCM according to Sect. 2.1.2.2, as given in Table 2.1. As these criteria can have different impact on the condition, it is essential to use weighting factors that take this fact into consideration. This assessment can be directly derived from the experience; from this purpose, it may be helpful to use a decision matrix according to Sect. 2.1.4.2, as shown in Fig. 2.26.

It is also possible to determine the condition assessment by using fuzzy logic according to [37, 38] as shown below. The other observations relate to the presentation of [38].

Various assessment criteria can be grouped into different categories for the determination of the condition, such as:

• Master data: (category I)	Information regarding type, rated values, location, number, etc.
• Operating data: (category II)	Age, maintenance, financial expenses, service know-how, spare parts, experiences, etc.
• Condition data: (category III)	Results of measurements, tests, visual inspections and losses, etc.

Basically, it is possible to determine the overall technical condition of equipment with the help of fuzzy logic, and for this reason, only the information of categories II and III can be used. In contrast, the master data are used primarily for decision of the strategic asset management, if, for example, a technology change is intended.

The entire working process can be summarized by two Figs. 2.23 and 2.24. All input variables x_m for condition assessment are transferred into linguistic variables y_m (fuzzification, Fig. 2.23).

After fuzzification, the y-values are subjected to a rule base, but this requires 3^m rules in case of three possible linguistic values (e.g., low, medium, and high), if m input variables are used for evaluation. This process corresponds to the illustration in Sect. 2.1.3.1, as shown in Fig. 2.18.

As equipment in general consists of various components, it is convenient to assign the output variables y_m of the fuzzification directly to the components. This is in line with the

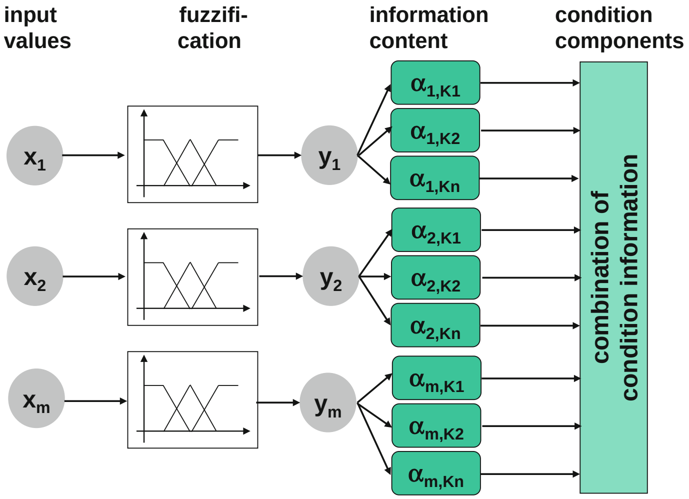


Fig. 2.23 Presentation of a condition assessment of equipment with the help of fuzzy logic, part 1 [38]

aspect that a maintenance action is performed directly on the individual components according to the technical condition.

As it is quite possible that different input variables x_m can be assigned to various components at the same time, which are referred to in this case with K_1 to K_4, the linguistic output variables y_m should also be assigned to the individual components, for example, the age of the complete equipment.

Moreover, it is possible that the information of each input variable may be different in relation to a component, as it is shown in Table 2.7, e.g., in case of four different components. In this example, the information x_1 has a great influence on the condition of the component K_4, while it is low on the component K_1 to K_3.

The implementation of that particularly important input information for the condition assessment of individual components can be performed by use of “alpha cut-sets” [39]. In this way, for example, information x_1 can be assessed with the value $\alpha_1 = 0.6$ and x_2 with $\alpha_2 = 1.0$, so that the influence of the information x_1 can be limited in this manner.

The condition information for various components can be combined after processing the information, Fig. 2.24. This figure represents the continuation of the information processing as shown in Fig. 2.23.

Different conditions of the components can be weighted to determine the overall condition of the equipment, as the impact on the functionality of the equipment may be different (z_1, z_2, …, z_m). Moreover, it is possible to define additional “knockout” rules that describe a nonlinear behavior with respect to one or more components, as given in Table 2.8.

2.1.4 FMEA Method

The FMEA method can be considered as an important part of RCM. It was applied for the first time in the aircraft industry in the 1960s with the development of the Boeing 747,

Table 2.7 Assessment of the information content of the input variables

Input variable x_m	Component			
	K_1	K_2	K_3	K_4
x_1	+	+	+	++
x_2	++	+	+	–
x_3	–	–	++	–
…	…	…	…	…
x_m	–	++	(+)	–

++ high significance
+ medium significance
(+) low significance
– no impact

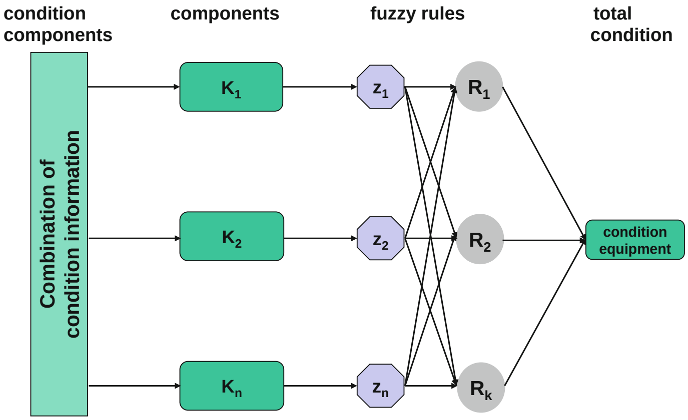


Fig. 2.24 Representation of a condition assessment of equipment with the help of fuzzy logic, part 2 [38]

Table 2.8 Rules for the determination of the entire condition

If condition	Then rules
Maximum of one component is in poor condition	The entire condition is medium
Maximum two components are in poor condition	The entire condition is medium-poor
More than three components are in poor condition	The entire condition is poor
Component K_1 is in poor condition and all others are in a medium or good condition	The entire condition is medium-poor
Component K_1 and at least one other are in a poor condition	The entire condition is poor

which was more complicated than the existing aircrafts at this time. The concepts and the basics are written in papers [43, 50]. The entire methodology is described in detail in [20], whereupon the further discussion refers.

The application of the FMEA method outlines the last work step according to the presentation of different steps within the strategy development (Sect. 2.1). While the first step deals with both the budget development and the selection of appropriate pieces of equipment regarding a service, it is the objective of the FMEA process to derive the specific maintenance activities to avoid future problems or to reduce the likelihood of outages of these devices.

The basis for the optimal diagnosis and thus the establishment of a maintenance strategy are considerations which fault or damage can occur in case of equipment and which appropriate measures should be applied to avoid them. One way is the application of the FMEA method to prepare this systematically. In the following, the application of this method is exemplarily presented on high-voltage equipment. Finally, it is possible to evaluate and to classify the results of the FMEA method in terms of failure probability of individual components, so that a sequence of operational risks of a faulty component can be derived. This result may be crucial for determining an optimal diagnosis resp. the application of maintenance activities for different components. Furthermore, the results can also be used as a basis for product improvement in the course of further development.

The principle of a FMEA study is to investigate what requirements, e.g., a circuit-breaker has to meet, and by which damages the required functions cannot be fulfilled; furthermore, which damages can be expected not only at the faulty equipment but also in the overall system and the environment (safety relevance/strict liability). Finally, an essential part of the procedure is to determine the consequence of a failure, which, for example, can lead to operational limitations, damages to persons and environment. In addition, measures can be developed, which may lead to a reduction of the failure probability, if this is necessary. The described procedure is shown in detail in [19].

While in Sect. 2.1.4.1 the basics of FMEA method is described, Sects. 2.1.4.2 and 2.1.4.3 represent the procedure using the example of a circuit-breaker. A complete sub-station is treated in Sect. 2.1.4.4 to derive various maintenance activities. Additional information is given in [20].

2.1.4.1 Methodological Basics

In the course of a successful treatment of a FMEA study, there are various questions that simultaneously illustrate the sequence of processing steps [41, 46] and can be defined as follows (the notes in the brackets refer to the headings):

- What functions and performance standards can be defined for the system component or equipment taking into account the operating conditions (functions)?
- How does a system component fail, so that the function cannot be maintained (malfunction/failure function)?
- What causes the malfunction (failure modes/failure reason)?
- What impact has the disturbance of the system component (fault effect)?
- How can the faults early be detected, if necessary in advance (detection of faults)?
- What is the failure probability (failure probability)?
- What risk does arise due to the outage and is it possible to set up a sequence of different risks (evaluation of risk)?
- Assessment of the current maintenance activities in respect of different outages (measures against faults).

The total evaluation process to perform the FMEA method can be illustrated by the workflow of Fig. 2.25.

The questions above are exemplarily illustrated by the following chapters based on the consideration for a HV circuit-breaker (SF_6 switchgear).

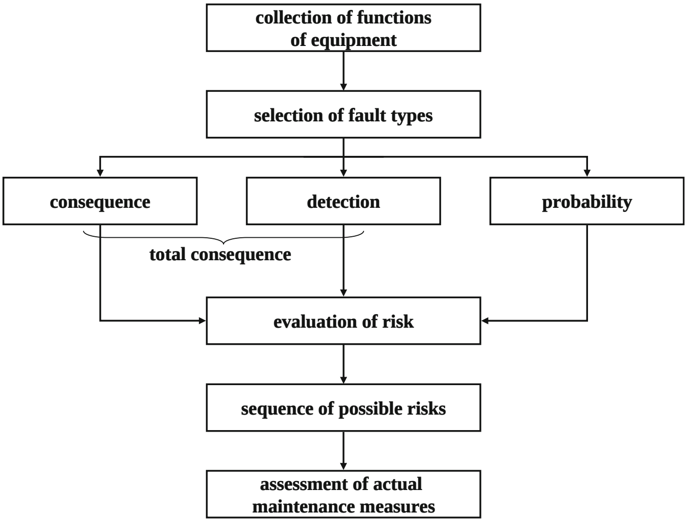


Fig. 2.25 Workflow of the FMEA assessment process

Fig. 2.26 Decision matrix for the assessment of the risk of faults (example)

criteria	consequence	fault detection	fault probability	Σ	WF/%
consequence	0	1	1	2	16.7
fault detection	3	0	3	6	50.0
fault probability	3	1	0	4	33.3
				12	100.0

Functions of a circuit-breaker

The general function of a switching device is to carry the expected power flow corresponding to the maximum-rated power based on the design.

To answer this question, the functions of a device can be divided into primary and secondary functions. While primary functions of a circuit-breaker constitute essential tasks, additional criteria are addressed by secondary functions, which are also expected.

The main functions of a circuit-breaker are defined by the application in network on the basis of national and international standards [34].

The main features which the circuit-breaker must meet under the specified conditions (max. operating voltage, max. allowable operating current and short-circuit current, max/min operating temperature, etc.) are exemplary:

- Switching off the operating current,
- Switching on the operating current,
- Interruption of the short-circuit current, and
- To secure in and off positions.

In addition, some secondary functions can be defined, which the component has to fulfill during its operating time, for example:

- Monitoring of the extinguishing media,
- Monitoring of the drive energy, and
- Indication of switch gear disturbance.

Based on the above definitions, it is obvious that primary and secondary functions can be disturbed by certain occurrences, so that the equipment cannot be operated according to expectation.

Malfunction of a circuit-breaker

A malfunction will occur if the above-defined primary and secondary functions cannot be fulfilled, which may result in a partial or complete failure. If a malfunction is severe so that an immediate outage of the equipment takes place or the device has to be switched off within 30 min, this failure is called a “major” failure, as described in Sect. 2.1.5.3. Limited malfunctions, that may be present over a longer time range, are called “minor failure” in contrast to that. These types of failures do not lead to an immediate outage. Minor failures may be removed as part of a planned maintenance activity depending on the operation. In this context, the following questions must be answered in each case:

- Which malfunctions are possible?
- How are these malfunctions triggered?

Possible malfunctions of a circuit-breaker can be defined according to the Cigre report [21]:

- No switching on operation on command,
- No switching off operation on command,
- Switching on without command,
- Switching off without command,
- No current flow,
- No interruption of the breaking current,
- No sufficient current-carrying capacity,
- Flashover to earth,
- Flashover between insulators,
- Internal/external flashover inside the chamber, and
- others.

Failure modes (failure reason)

The next step consists of defining the failure modes (failure reasons) that lead to various malfunctions that are described above. The result is to determine the faulty component of the entire equipment.

Fault effect

Fault effects are of major importance for a subsequent assessment of a fault in terms of a maintenance task, which occur as a consequence of a failure. In the present case, four main groups are defined (people, environment, downtime, and repair costs), with corresponding subgroups due to different consequences. To assess the fault effects, in total, they are considered by a score system, where multiple responses are possible. The evaluation of the score is done according to the scheme that poor effects get a maximum value. The data are summarized in Table 2.9 and present the results of a survey of users.

In addition, other criteria can be specified which dependent on the operational use. These may include, for example:

- Sales shortfall,
- Interrupted active power resp. energy not supplied,
- Penalty,
- Image damage of the company, etc., and
- Hidden faults: These faults do not have direct impact on the process, but they only take effect in case of a further failure.

The selection and evaluation of the criteria of fault effects strongly depend on the operational situation and the component under investigation.

Table 2.9 Fault effects in case of circuit-breakers, exemplary [20]

Effects		Consequence	Points
P	Persons	Injury	10
E+	Environment	SF_6 and oil	9
E	Environment	Fire	8
E−	Environment	No leakage of SF_6 and oil	7
O+	Outage time	>5 days	6
O	Outage time	2–5 days	5
O−	Outage time	2 days	4
C+	Repair costs	>10,000 €	3
C	Repair costs	1000–10,000 €	2
C−	Repair costs	<1000 €	1

Detection of faults

In assessing the fault effects, it is important whether a failure of a component or the malfunction of equipment can be recognized by a diagnostic or monitoring system in advance. In this case, a supply interruption may be avoided. For example, the probable fault effect is significantly reduced if the effect is actually significant and can lead to major damage, but detection is simply possible. Possible fault detection is also assessed to ensure that this process is sufficiently considered. In this case, a distinction is made between three different levels, which are scored accordingly.

• Not possible	The fault cannot be recognized during an inspection resp. it is not possible to detect the fault	→ 3 points
• Difficult	The fault can be recognized during an inspection resp. a diagnostic measurement is required	→ 2 points
• Simple	The fault can be recognized with the help of an inspection or by a monitoring system in advance	→ 1 point

Failure probability

The assessment of the possible failure probability can be evaluated and classified with the help of a detailed data file from individual equipment components. In the following example, the values for circuit-breakers are used, which are described in detail in [29].

Evaluation of risk

The evaluation of individual faults using the scoring system leads to a classification of risks which should be used when planning maintenance activities. Here, it is useful to apply a two-axis representation with the risk defined as the product of severity of the disturbance and the failure-associated probability (risk diagram).

Measures against faults

At the end of the entire evaluation process, the studied faults must be classified with respect to a maintenance measure in order to minimize operational risks in case of an outage. It is important to know which behavior patterns can be assigned to a fault in the selection of maintenance measures. Overall, it is possible to define different fault patterns that are specified in Sect. 2.1.5.1, as shown in Fig. 2.28. Fault patterns which show an age-related behavior should be preventively maintained or replaced after constant time intervals. On the contrary, the CBM is basically reasonable in case of faults which do not occur depending on age, but develop slowly. To solve this question, the following guideline can be used for the decision-making process:

- Is a maintenance measure economically reasonable to prevent any outage (CBM)? Is it technically possible?
- Is a planned maintenance economically reasonable to reduce the failure rate (TBM)?

- If the above solutions are not possible and the impact on people and the environment is acceptable or the fault probability is low, the transition to a corrected maintenance has to be considered.

2.1.4.2 Data Preparation

Various work steps are presented in this chapter with the help of a comprehensive database for high-voltage circuit-breakers, in which all relevant faults are documented. Exemplarily, the procedure in the event of malfunction “no switching on operation on command” is shown in Table 2.10.

According to Fig. 2.25, the assessment of the risk of malfunction is the product of three different values, namely:

- Consequence (AU),
- Fault detection (SE), and
- Fault probability (SW).

In this case, the product of the first two values (consequences and fault detection) is referred to as “total consequence.” The fault with the highest score is finally the component with the highest operational risk, so that an appropriate maintenance activity should be considered to reduce the risk.

If the various classes are assigned to a scoring system, as described above, the result depends on the random spectrum of the scale. To avoid this, the maximum effect is obtained with the help of a decision matrix according to Fig. 2.26. Two properties are evaluated by this method in terms of their influence on the overall result, in this case the operational risk. The scores assigned in the scheme are given below if the criterion in the respective row has a:

• Lower influence	1
• The same influence	2
• Higher influence	3

than the considered criterion in the column. In the example below, the consequence of a fault has a smaller influence on the risk than the possibility of fault detection (lower weighting factor). The result is obtained by the sum of the scores and based on the total number.

Table 2.10 FMEA table (abstract, exemplary)

Malfunction	Type of fault	Faulty component	Fault effects	Fault detection	Probability
1: no switching on operation on command	1.1: faulty drive	1.1.1: faulty motor	O−/C−	Simple	0.0046
		1.1.2: faulty N_2 container	O/C−	Simple	0.037
		1.1.3: faulty rod	E−/O/C	No	0.01

An evaluation according to this method shows that the considered variables should influence the product with the following maximum weighting factors:

• Consequence:	16.7 %
• Fault detection:	50.0 %
• Fault probability:	33.3 %

This means that the fault detection has greater influence on the risk compared to the other two criteria. In order to determine the risk and define the order of necessary maintenance activities, the values which are evaluated in Sect. 2.1.4.1 have to be related to the maximum possible values. In general, the evaluation according to Fig. 2.26 depends on the subjective judgment of the user and can vary in each individual case.

2.1.4.3 Example: Analysis

The risk for any circuit-breaker component can be examined by the FMEA evaluation process in this example. The evaluation of the total outage of this circuit-breaker has to be already considered so that this case is not allowed; otherwise, the assessment is trivial and no more components have to be considered. The damage of a component can cause various malfunctions. For example, a faulty motor of the drive influences the function “no switching on operation on command” as well as the failure mode “no switching off operation on command.” Table 2.11 shows the results of the operational risk calculation for the various failure modes according to Sect. 2.1.4.2 and the damage that caused them at different components.

As said above, a component can act on various functional failures and therefore, it is useful to order the components in terms of importance and to conduct a prioritization regarding the maintenance process. The different scoring system in Table 2.12 is due to the changed relationship (the components are listed exclusively). In addition, the today’s maintenance strategy for the individual components is also listed, taking into account the outage effects and probabilities.

While a one-dimensional risk approach is used in Tables 2.11 and 2.12, it has been proven good practice to establish a risk map according to Fig. 2.27 and to make a classification. The fault probability is plotted as a function of the total impact. The overall consequence (horizontal axis) results from the product of the outage consequence in case of a fault and the possibility of detection according to Sect. 2.1.4.2. To simplify the representation, the probability is measured as the percentage of all faults that have occurred, while the consequence is related to the maximum possible impact of a failure.

It makes sense for an assessment of the potential risks (according to Fig. 2.27) to define risk classes depending on various parameters that depend in detail on the operational experience and the subjective judgment of the user. The following classification is chosen, as given in Table 2.13.

Table 2.11 Sequence of operational risks and corresponding functional failure and damages

Priority	Points	Functional failures	Faulty component
1	4011	No interruption of breaking current	Grading capacitor
2	3482	No switching on operation on command	Linkage
3	1530	No switching off operation on command	Linkage
4	1455	Flashover to earth	Porcelain
5	1216	No current flow	Switching contacts
6	1196	Flashover to earth	Arcing chamber housing
7	1140	No switching on operation on command	SF_6 heating
8	1124	No sufficient current capacity	Switching contacts
9	928	Longitudinal flashover opened switching chamber (external)	Porcelain
10	830	Breaking current cannot be interrupted	Linkage
11	806	Flashover across opened switching chamber (extern)	Arcing chamber housing
12	451	No switching off operation on command	SF_6 heating
13	187	No switching on operation on command	SF_6 leakage
14	182	No switching on operation on command	Damping equipment
15	155	Switching off operation without command	Trip latch

Table 2.12 Sequence of operational risks from component damages [20]

Priority	Points	Faulty component	Possible strategy
1	3659	Linkage	Corrective
2	2999	Grading capacitor	Time-based
3	1421	Porcelain	Time-based
4	1414	Switching contacts	Time-based
5	1134	Switching chamber housing	Time-based
6	1120	SF_6 heating	Condition-based
7	222	SF_6 leakage	Condition-based
8	165	Damping equipment	Time-based
9	132	Trip latch	Corrective
10	111	Sensors	Corrective

According to the above classes, a final classification for the entire risk in “critical–high–medium–low” can be performed due to the fault detection depending on the possible fault effects according to Table 2.9 as shown in Fig. 2.27. In this case study, the evaluation of FMEA shows that almost all faults of the investigated SF_6 circuit-breakers can be classified as “low.” This leads to the conclusion that a change of the maintenance strategy

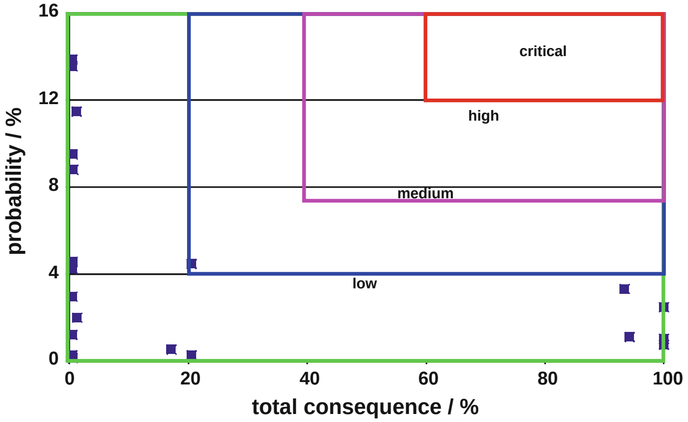


Fig. 2.27 Risk diagram

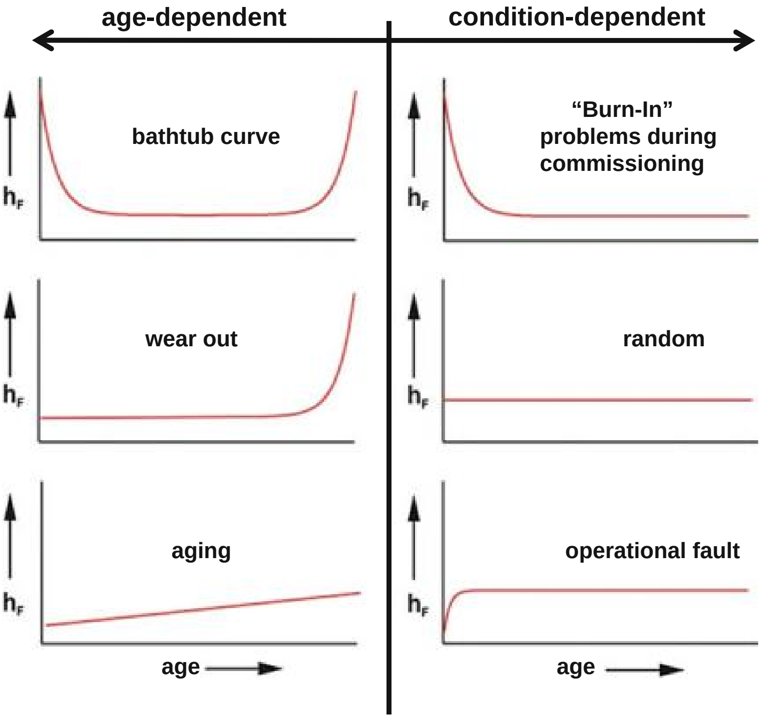


Fig. 2.28 Fault behavior patterns

Table 2.13 Classification of risk classes

Assessment	Probability (%)	Consequence (%)
Critical	12–15	60–100
High	>8	>40
Medium	>4	>20
Low	>0	>0

for such a circuit-breaker is not necessary due to the used FMEA investigation. Risks with larger effects have a low probability of failure (danger to persons, no detection of faults, faults in the switching chamber which can cause a malfunction of the switching off operation). On the contrary, the outages with a high probability (e.g., sensors or relay failure in the control area) have little effect on the entire operation and can be classified as non-critical risks. The faults which are close to the border line of the risk classes “low/medium” belong to, e.g., tripping latch spring drives according to the evaluation.

2.1.4.4 FMEA Evaluation of a Substation

In principle and in contrast to the example described above, it is also possible to determine an optimum maintenance strategy for entire substations using a FMEA study. In the following, this method is applied to a medium-voltage system and different operating components are taken into consideration:

- Switching bay (including bus bar, cable joints),
- Circuit-breaker,
- Switch–disconnector,
- MV/LV power transformer,
- Voltage and current instrument transformer,
- Protection and control, and
- Civil works.

The aim of this study was to determine their sequence as well as the possible maintenance activity depending on the effects of various faults. As described in Sect. 2.1.4.1, the following criteria are considered:

- **Fault causes**: Selection of fault causes that lead to a loss of function of the equipment (analysis of statistics information for switching devices).
- **Fault effects**: Definition of fault effects in terms of the impact on people, environment, and operation; evaluation whether a fault has no direct influence on the operation so that no immediate shutdown must take place.
- **Fault probability**: Determining the relative frequency of faults of all considered pieces of equipment within a substation according to general failure statistics and user experience.

The risk for each event can be determined by particular scores related to the assessment criteria by multiplying fault effects with their frequency, similar to the illustration in Sect. 2.1.4.3. Based on these faults, maintenance measures (target measures) can then be defined, which could avoid these fault events. Finally, it has to be checked whether these target measures are already covered by today's maintenance activity (current measure).

As a result of this investigation, both the urgency and the necessity of additional maintenance can be determined, resulting from the difference between the target measures and the current measures. Exemplarily, Tables 2.14 and 2.15 show the results of a complete analysis of a substation in terms of fault causes, the following damages (Table 2.14) and the set points, and actual measures (Table 2.15).

While Table 2.14 illustrates the order of various faults and the subsequent damages to the equipment, Table 2.15 describes the necessary maintenance activities and the activities carried out at the time to which these target measures can be assigned.

The study shows that the origin of damages in a substation is primarily caused by overvoltages resp. due to contamination and moisture. In both cases, the consequences lead to external flashovers. The measures for the prevention of these faults include, on the one hand, design checks for components to avoid overvoltages (installation of surge arresters) by the network planning department and, on the other hand, the control of humidity or contamination during inspection and maintenance activities.

Table 2.14 Assessment of components of a substation (fault causes, damages)

No.	Priority	Equipment	Cause	Damage
1	131	Bay	Lightning overvoltages	Bus bar: external flashover, electric arc
2	131	Bay	Pollution, moisture	External flashover, electric arc
3	98	Bay	Aged insulation	Internal fault
4	33	Bay	Incorrect distances	External flashover, electric arc
5	30	MV/LV power transformer	Overvoltages	Defect insulation
6	28	Bay	Lightning overvoltages	Cable junction: internal fault
7	23	Circuit-breaker	Faulty drive	Energy transmission (electric arc)
8	22	Circuit-breaker	Faulty switching chamber	Untight, dielectric stress
9	20	MV/LV power transformer	Overvoltages	Flashover to tank (base point)
10	15	Bay	Unacceptable heating of the current path	Distortion

Table 2.15 Assessment of components of a substation (target measures, actual measures); the numbering is in line with the fault causes and damages according to Table 2.14

No.	Priority	Equipment	Target measures	Actual measure
1	131	Bay	Surge arresters at appropriate points	Examination by network planning
2	131	Bay	Moisture: control of heating and windows, untight downpipe; Pollution: cleaning, especially air-insulated substations	Inspection/service (bay)
3	98	Bay	Visual inspection: color change of surface, noise, subsequent PD test	Inspection/service (bay)
4	33	Bay	Wrong dimensioning, it must be dimensioned for spacing	Requirements by project planning/approval
5	30	MV/LV power transformer	Surge arresters	Examination by network planning/project planning
6	28	Bay	Surge arresters at appropriate points	Examination by network planning
7	23	Circuit-breaker	Overhaul	Inspection/service (bay)
8	22	Circuit-breaker	Visual inspection (minimum oil); overhaul	Inspection/service (bay)
9	20	MV/LV power transformer	Surge arresters	Examination by network planning/project planning
10	15	Switching bay	Current monitoring for installations with a capacity of almost 100 % thermography test to detect "hot spots"	Inspection/service (bay)

2.1.5 Aging Behavior of Equipment

The electrical components in transmission and distribution networks ensure the power supply and the protection of people and property in the event of a fault. For this reason, high availability and excellent operating behavior are essential. Optimum maintenance strategies are necessary to achieve this goal during the entire service life. The maintenance can be grouped into different activities which can be applied to the maintenance objects according to [23, 25]:

• Inspections	Measures to identify and assess the actual condition of equipment, including the deduction of necessary consequences
• Service	Measures to delay the degradation of the existing wear reserve
• Overhaul	Measure for recovery of equipment in a defined operational condition with the exception of the improvement
• Improvement	Combination of all technical and administrative measures to increase the reliability of the equipment without changing the required function of the maintenance object

In recent years, the utilities have started to rethink the applied maintenance strategies. Starting from TBM (Sect. 2.1.1.4) with fixed time intervals and a set time for the replacement of equipment, some utilities move on to use the CBM (Sect. 2.1.1.5) or to extend the existing service intervals, depending on the type of equipment and the respective operating experience. The biggest problem, however, is to use the experience to determine the optimal time interval for maintenance activities without taking the risk of a higher failure rate. Maintenance measures can only be optimized, and specific strategies can be determined, if data on past events (faults and maintenance activities) are sufficiently available. For this reason, these events should be collected into failure statistics by the transmission and distribution system operator. Such statistics should include the time of the incident, and the type of fault and the fault cause. Furthermore, it is appropriate to additionally record the financial consequences and to continue with a risk analysis (Sect. 3.2.6) which can lead to an optimal setting of the maintenance interval period.

The following Sects. 2.1.5.1–2.1.5.5 describe the procedure how the collected failure data should be processed so that not only the well-known age behavior of the equipment, but also the future tendency can be derived. As an example, this method is applied to approximately 8600 high-voltage circuit-breakers with a rated voltage of $U_r > 100$ kV based on 6800 fault incidents, according to [8, 11, 12, 29, 30].

2.1.5.1 General Fault Behavior of Equipment

The failure frequency of asset groups is basically an important criterion for the assessment of a maintenance activity. In addition to the analysis of the recorded fault location, it is also possible to compare various pieces of equipment with respect to age, performance, design, and the mean time between failures. Based on the fundamental failure statistics, general conclusions can be derived for future service activities.

In general, following fault patterns can be distinguished for components [41]:

• Problems during (re-) commissioning	Teething problems which will be reduced during proceeding operation
• Wear-out	Problems which increase depending on the operating time and happen particularly in case of moving parts
• Operational fault	Faults which occur depending on actual operation
• Aging	Aging effects which are independent on the operational stress
• Random	Randomly occurring faults which have no age or operational reasons
• Bathtub curve	Combination of commissioning and wear-out problems

The basic characteristics of the fault behavior depending on the operating time are shown in Fig. 2.28 [8]. The knowledge of the fault history is an essential basis for the selection and determination of the applicable maintenance strategy. If the equipment shows a fault behavior corresponding to the left side (Fig. 2.28), the fault rate increases with age and a time-dependent maintenance strategy should be applied. A maintenance operation can be provided depending on time, if an accepted failure rate of the equipment is exceeded. CBM, on the other hand, is the only possible strategy to prevent faults if the failure behavior is according to the behavior on the right side. This means that firstly an indication of the fault pattern of the equipment should be observed as a function of time, before a determination of the mandatory maintenance strategy can take place.

In total, five independent basic curves can be defined (with the exception of the bathtub curve) that need to be considered in individual cases, as shown in Fig. 2.28.

2.1.5.2 Analysis of the Fault Behavior and Related Measures

The goal of fault analysis is to split the actually existing fault behavior of an asset in the five basic patterns according to Fig. 2.28. In other words, those partial curves have to be identified whose sum has the smallest deviation from the actual fault pattern in the original statistics. Figure 2.29 shows the basic procedure, which is described in detail in [30, 31]. The result is a function which is a combination of the underlying five basic functions. The coefficients indicate in what extent the various basic functions influence the fault behavior of the equipment, so that in consequence, reliable statements about the maintenance

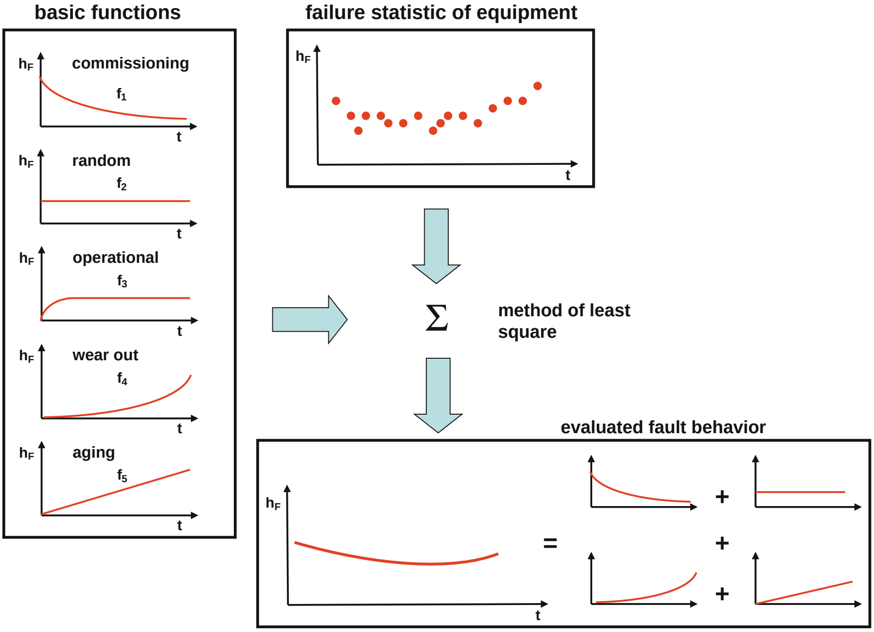


Fig. 2.29 Fundamental method to analyze the fault behavior [11, 29, 31]

strategies can be derived. Thus, it can be concluded that exemplarily, an actual fault course is more related to wear-out problem than to a normal aging process. Then, it is possible to make a decision about a time-based or CBM strategy depending on the fault patterns.

The following conclusions can be derived due to the fault analysis depending on the basic functions as shown in Fig. 2.28:

• Problems during (re-) commissioning	Provide information on the quality of the installation or the service after maintenance measure, and better training of the staff is appropriate or a revision of the design
• Wear-out	By altering the design, failure probability can be reduced or the component can be replaced or serviced in time, if a minimum requirement is not achieved
• Operational fault	This type of fault should rarely occur in the area of power supply, so that measures should not be needed. Possible measures include changes of the design/control or adjustment of the business process
• Aging	Can be influenced by structural measures on individual components or by the usage of modified material, resp. premature maintenance measures ahead of schedule to prevent a malfunction
• Random	A maintenance activity for the equipment is not recommended, but the local conditions may be controlled as a result of third-party influence (atmospheric surges, small animals, etc.)

The basic procedure is shown below based on the evaluation of fault statistics of high-voltage circuit-breakers, and also, the derived maintenance measures are described.

2.1.5.3 Data and Equipment Model of Circuit-Breakers

A group of high-voltage circuit-breakers is used for the following analysis, which is composed of different arc extinguishing media and drives. Specifically, the following criteria are used:

Extinguishing medium	Air blast	1357	15.9 %
	Minimum oil	3014	35.2 %
	SF_6	4184	48.9 %
Drive	Pneumatic	1701	19.9 %
	Hydraulic	3985	46.6 %
	Mechanical	2869	33.5 %

In total, 8555 circuit-breakers are considered with different extinguishing media and drives, and the age behavior of the collective is shown in Fig. 2.30. The first installations were made in the time range from 1960 to 1970, while most assets went into operation in

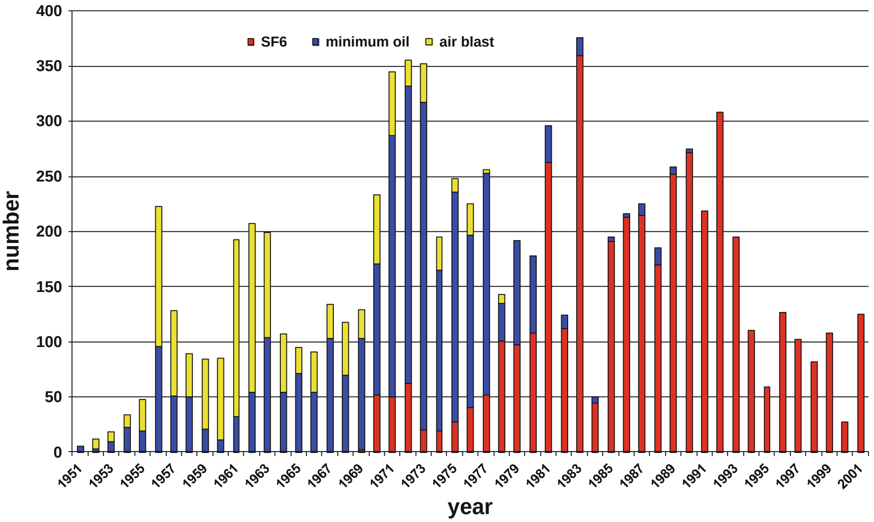


Fig. 2.30 Age distribution of HV circuit-breakers [8]

the subsequent decade. Since that time, a reduction of the annual investment can be observed.

The average age of the studied assets can be determined from the information provided by Fig. 2.30:

• Air blast:	38.9 years
• Minimum oil:	31.2 years
• SF_6:	14.9 years

For the evaluation of faults, it is necessary to develop the equipment model for a circuit-breaker and to assign all fault locations clearly to a component, as required maintenance action is also applied to these components.

The model used in this case is shown in Fig. 2.31. The example has in the first level six classes, which are divided into subclasses. For example, the drive has five further subdivisions to describe additional components. In addition, a class “unknown” and “other” is listed in each section, to include faults that cannot be allocated due to the fault description.

In total, 6776 events were recorded from the collective circuit-breakers which cover a period of 50 years. Table 2.16 shows the faults due to the classification according to Fig. 2.31. These figures include both “major” as well as “minor” faults, since in each case, both types lead to a maintenance activity and thus a reaction of the maintenance staff. The

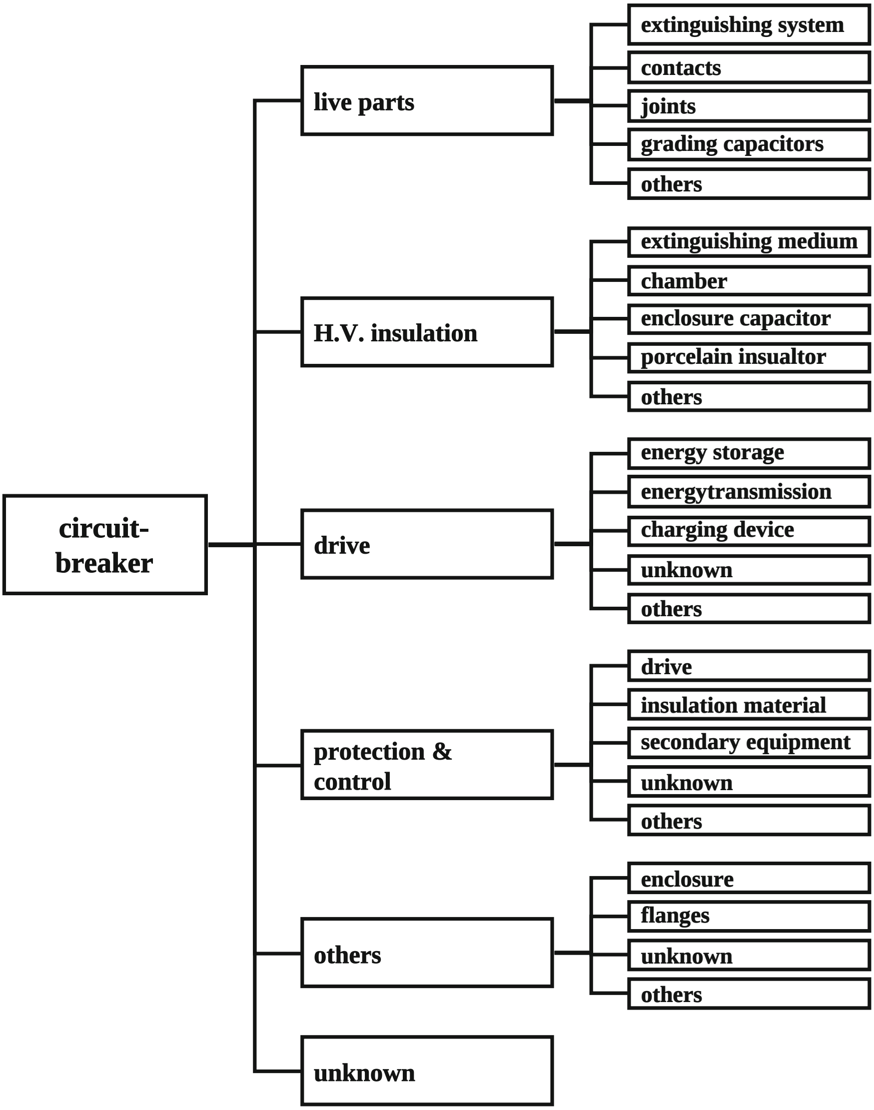


Fig. 2.31 Equipment model of a circuit-breaker (example) [11]

consequence is that both types of faults must be considered in search for an optimal maintenance strategy. This observation is in contrast to reliability calculations to determine the energy not supplied or the frequency of interruptions at system nodes. In these cases, only “major” faults are taken into account.

Table 2.16 Failure distribution depending on the type of circuit-breaker (values in percent)

Component	Type circuit-breaker		
	Air blast	Minimum oil	SF_6
Live parts	23.8	18.3	4.7
HV insulation	9.8	7.3	2.6
Drive	30.3	42.2	38.0
Protection and control	20.3	18.5	35.4
Other	2.0	11.4	11.8
Unknown	13.8	2.3	7.5

The following definitions are used to define the two fault classes according to [21]:

• “Major” fault	Fault or damage at any equipment whereby several essential functions are not fulfilled. The result is an immediate change of the network condition, which results in an action within 30 min A maintenance action is initiated immediately
• “Minor” fault	Fault or damage at any equipment or component failure, which does not lead to a “major” fault The damage can be repaired by a scheduled maintenance action, taking into account the operational needs

Table 2.16 shows that most of the faults are caused by the drive, regardless of the type of circuit-breaker. The high percentage of fault of SF_6 circuit-breakers in the area “protection and control” is mainly due to the failure of the pressure sensors as well as density sensors and failure of alarm signals.

2.1.5.4 Fault Behavior of Circuit-Breakers

For further consideration of maintenance strategies, only SF_6 and minimum oil circuit-breakers are considered, because, firstly, the number of air blast circuit-breakers is much lower and, secondly, they should be replaced in the next few years due to their age. Figure 2.32 shows the failure rate of the minimum oil (Fig. 2.32a) and SF_6 circuit-breakers (Fig. 2.32b) as a function of the operation time. A clear trend in the failure behavior of minimum oil type is obvious. It can be observed that in the time range between 10 and 30 years after the installation, the failure rate exceeds the total mean value of 2.1 failures/100 c.b. and year. The fact that the failure rate decreases again toward the end of the observation period may be due to the fact that only devices with a very good performance are still available, as all the rest have been replaced by new equipment. This phenomenon is basically determined in case of a technique that has been used for several years, as all construction-related bugs have been removed and these devices are still in operation, which are characterized by a particularly good behavior.

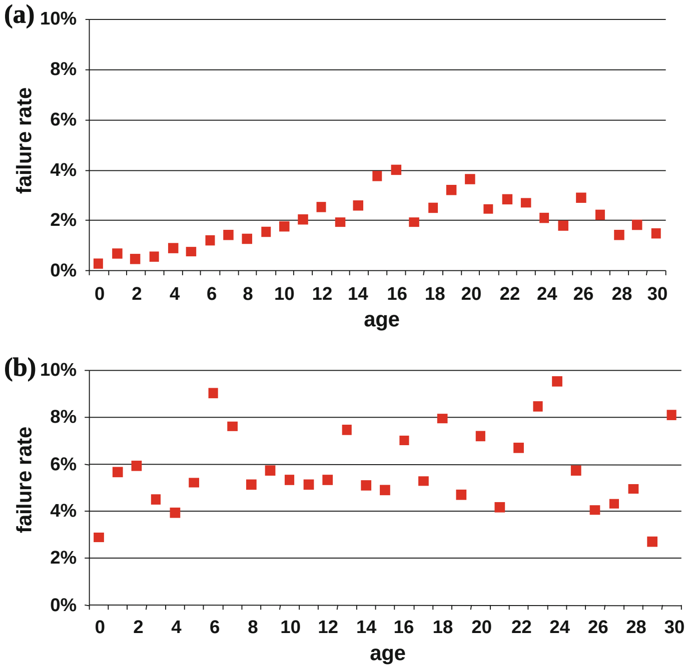


Fig. 2.32 Failure rate of considered circuit-breakers, minimum oil (a), SF_6 (b) [8]

On the contrary, the failure rate of SF_6 circuit-breakers is randomly distributed over the observation period and no distribution or trend can be clearly seen. In this case, the average rate exceeds a value of 6.0 failures per 100 c.b. and year and this is higher than the value of minimum oil circuit-breakers. Finally, air blast circuit-breakers have a failure rate of 2.6 failures per 100 c.b. and year, but this value cannot be directly related to others, as the statistical basis is much lower. In addition, similar to the case of minimum oil circuit-breakers, failure-prone devices have been taken out of service in this case also and are therefore no longer included in the statistics.

Because maintenance measures have always been carried out at circuit-breakers during the entire operating time, it is useful to plot the failure rate as a function of the event-free time [29]. It can be assumed that the fault behavior of the device is affected by the maintenance activities, which have a different intensity. In this context, the word “events” summarizes the following actions: faults, measurements, inspections, maintenance, or commissioning activities. This means that neither fault repairs nor other maintenance activities were carried out at the equipment during the event-free time. The representation is thus suitable to derive the statement how long a component can be operated without a maintenance action, so that optimum service intervals can be defined [31].

In a first step, Fig. 2.33 shows the failure rate of a complete SF_6 circuit-breaker as a function of the event-free time to illustrate this approach. The principal representation of

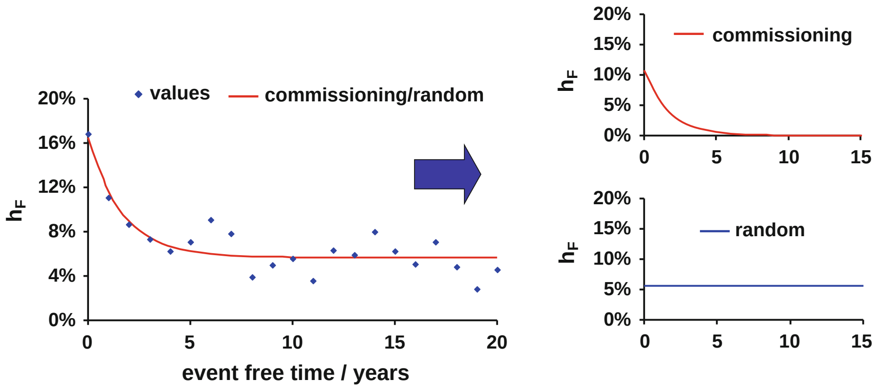


Fig. 2.33 Fault behavior of SF_6 circuit-breakers [8]

further figures can be derived in which the separation of the general trend curve of the individual functions is performed (Figs. 2.29):

- On the left, the failure rate is plotted as a function of the event-free time as annual value, and this means that after every maintenance service (including commissioning), the time-dependent counting starts again from "zero."
- Based on these values, the basic equations which fit the collective best are determined according to Sect. 2.1.5.2. It is then determined which basic equations have the greatest impact on the fault behavior (right side of the figure).
- Finally, these curves are superimposed and recorded in the output image as a regression line (left side).

From the representation in Fig. 2.33, it can be seen that the statistical behavior is mainly composed of a commissioning and random component. This means that the probability having a fault in the same year after an event has occurred, which means a maintenance measure took place is high. In contrast to the representation of the entire circuit-breaker (Fig. 2.33), it is useful to show the failure behavior of the individual components, as maintenance is finally performed on component level. In this context, components are the items in the second level of the equipment model (Fig. 2.31).

SF_6 and minimum oil circuit-breakers are exclusively considered, because the number of existing air blast circuit-breakers is too small to obtain reliable information. In addition, the "live parts" and "isolation" are grouped together in Table 2.16 to the class "primary component." Figures 2.34, 2.35, 2.36, 2.37, and 2.38 show the failure rates of different components depending on the event-free time.

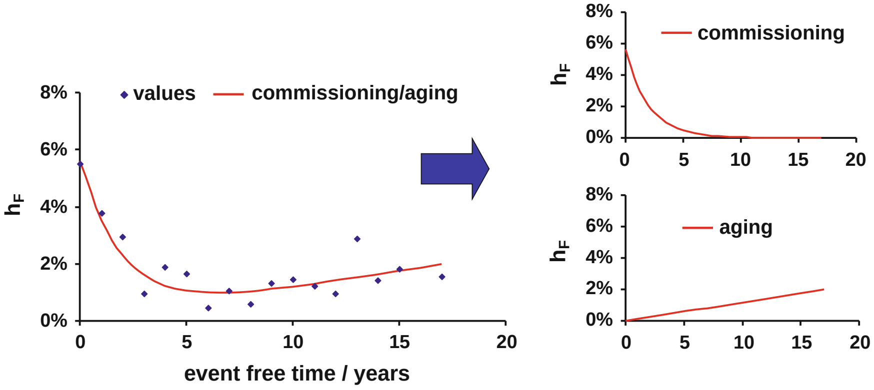


Fig. 2.34 Primary components of SF_6 circuit-breakers [8]

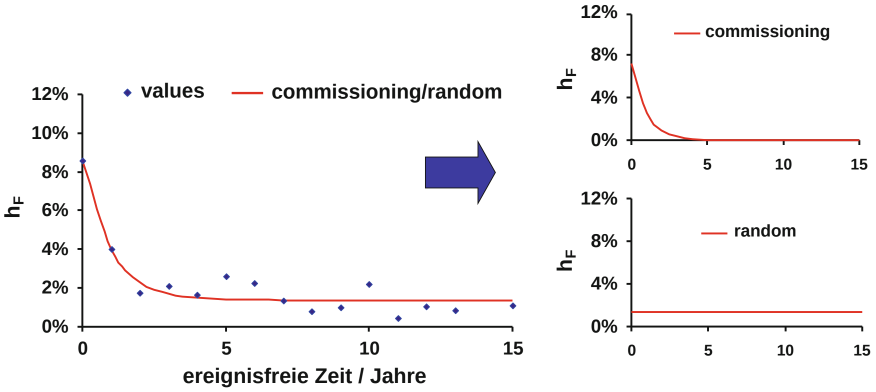


Fig. 2.35 Primary components of minimum oil circuit-breakers [8]

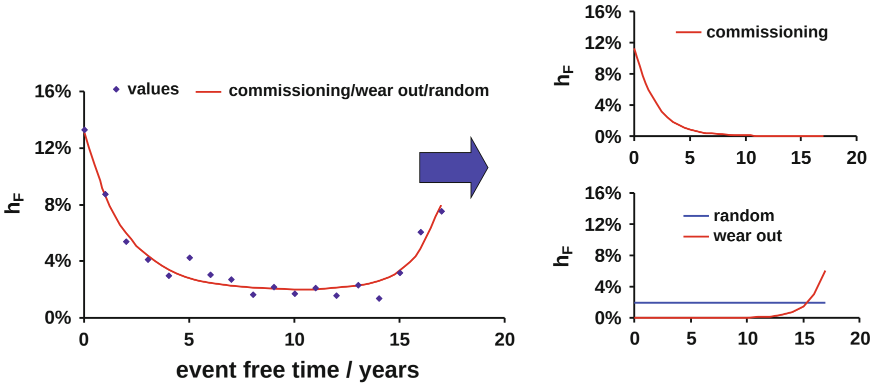


Fig. 2.36 Hydraulic drives of SF_6 circuit-breakers [8]

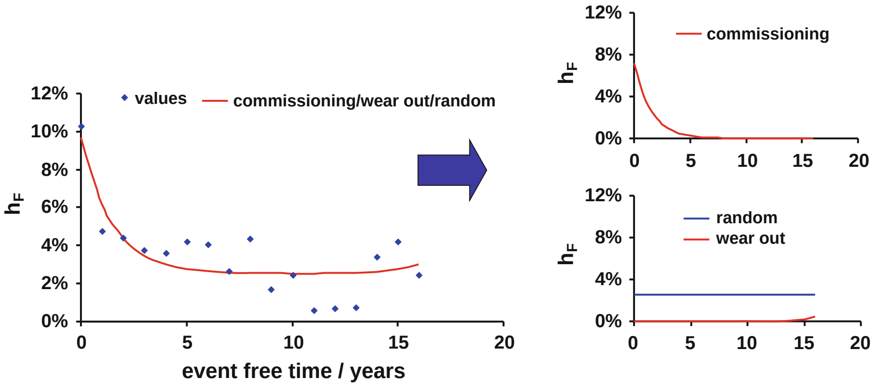


Fig. 2.37 Hydraulic drives of minimum oil circuit-breakers [8]

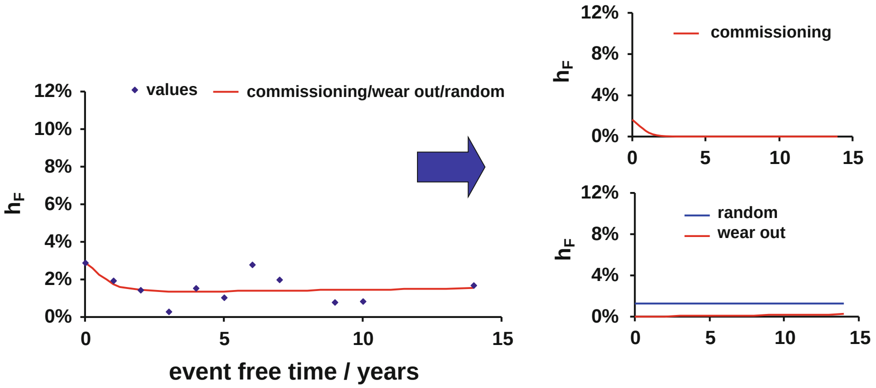


Fig. 2.38 Mechanical drives of minimum oil circuit-breakers [8]

The following components have been evaluated in figures:

• Primary components of 4184 SF_6 circuit-breakers with 2018 faults	Figure 2.34
• Primary components of 3001 minimum oil circuit-breakers with 2144 faults	Figure 2.35
• 3473 hydraulic drives of SF_6 circuit-breakers with 1694 faults	Figure 2.36
• 1059 hydraulic drives of minimum oil circuit-breakers with 638 faults	Figure 2.37
• 2270 mechanical drives of circuit-breakers with 167 faults	Figure 2.38

The results in Figs. 2.34, 2.35, 2.36, 2.37, and 2.38 show that in general, commissioning is the main cause of component failures. This means that the probability of having a second fault directly after a maintenance activity at the component is high. This behavior is especially pronounced at hydraulic drives (Figs. 2.36 and 2.37), compared with the mechanical type (Fig. 2.38). A similar fault behavior can be derived from the primary components of SF_6 circuit-breaker, but in this case, also an aging behavior is clearly observed (Fig. 2.36).

In addition, hydraulic drives of SF_6 circuit-breakers show an increasing wear-out problem (Fig. 2.36) after about 11 years, but no aging can be detected due the progression curve. On the contrary, only few faults are indicated as a result of commissioning problems in case of mechanical drives of minimum oil circuit-breakers. In all studied cases, random faults are always seen that occur during the operating period.

A detailed and more extensive evaluation of the fault behavior is seen when, for example, the assets are grouped into two age groups (<20 years and >20 years), as described in detail in reports [12, 29].

2.1.5.5 Assessment of the Results

It is possible by evaluating the fault behavior of equipment to derive appropriate maintenance measures and the recommended intervals. Moreover, it should always be possible to express a technical reason for the fault behavior to make the right decisions, as shown below. Technical constraints have basically to be considered, if, as in this case, minimum oil and SF_6 circuit-breakers are compared.

- Minimum oil circuit-breakers reached their maximum performance per interrupting unit in the mid-seventies with approximately 145 kV/31.5 kA. Major manufacturer stopped the development activities, and minimum oil technology was replaced by SF_6 technology.
- SF_6 units reach today 400 kV/63kA or even more. From this point (about 1975), SF_6 technology is the dominating technology.
- In addition to that, requirements from the grid and consequently from standards have increased: short-circuit current, capacitive current switching, electrical and mechanical endurance, type testing, etc. These additional requests may lead to higher stresses for components on SF_6 circuit-breakers compared to those of minimum oil devices.

The mechanic and hydraulic drives can be characterized by following aspects:

- The hydraulic drives are very complex in structure, so that the production requirements are very high and difficult to control during manufacturing and commissioning. On the other hand, there are less moving parts in case of a hydraulic drives compared to mechanical ones and wear-out problems are reduced due to the natural greasing of hydraulic oil.
- On the contrary, mechanic drives are easier to check during production and commissioning. However, the high number of moving parts leads to wear-out problems during the operational time.
- As a consequence, hydraulic drives have more commissioning problems and show less aging behavior.

- In addition, it has to be mentioned that in many applications, hydraulic drives are used to operate high-current SF_6 circuit-breakers, e.g., puffer breakers for 50–100 kA, whereas mechanic spring drives are mainly used to operate breakers which need less drive energy. This has the consequence that a direct comparison of the two drive technologies is not always meaningful due to different technical requirements.

It can be concluded as a result of the example above that in many cases, the extension of maintenance intervals can be made depending on the used circuit-breaker-type resp. drives. The following maintenance measures can be derived:

- Due to numerous commissioning problems, which are particularly of importance for high-voltage components (primary component) and for hydraulic drives, maintenance activities should be carried out with a greater care.
- In addition, the technical condition of components should be better monitored so that consequently, the number of non-necessary maintenance actions can be reduced. This may have the result that failures during recommissioning can be reduced. With the use of additional diagnostic and monitoring methods, the additional expenses for equipment and evaluation have to be considered in each case.
- The analysis shows that in case of hydraulic drives, the inspection intervals may be extended up to a maximum time of about 12–15 years. In contrast, the cycle should be about 10 years for mechanical drives. However, due to the low number of devices considered, this is only a rough estimation.

The figure shows that it is essential to evaluate fault events in case of definition of maintenance strategy, e.g., measure and cycle. In general, failure rates of equipment are recorded in dependence of the operating time. Since there have been usually maintenance activities during this time, the fault behavior is influenced by the activities, so that sometimes, no meaningful conclusions are possible. It is much better to record the failure rate as a function of the event-free time in order to select the optimal maintenance strategy.

2.1.5.6 Consideration of the Aging During the Condition Assessment

In general, it is possible according to Sect. 2.1.2.2, as given in Table 2.2, to define a condition assessment by various criteria and set up the condition—importance diagram for an asset group. In order to assess how the technical condition could change over a short period of, e.g., 5 years in the future, it is also possible to modify the time-dependent condition criteria (age, test results, etc.) accordingly. In contrast to this, the assessment of the time-independent criteria remains constant, such as cycles per year.

Another method, how the expected aging behavior of the equipment group can be derived from previously evaluated data, is presented in Sect. 3.4.4, by applying the distinction between real and artificial age.

2.1.6 Lifetime of Electrical Equipment

Because of aging behavior and wear-out, equipment has an average life that is depending on various conditions. The consequence is that there are average and maximum values of the operational life for different pieces of equipment. In recent years, various statistics have been published that provide a good overview. The values which are shown in the following example were published by a Cigre working group (37-27) for assets in the area of high-voltage engineering, as given in Table 2.17 [51]. If it is assumed that the life of the equipment is subjected to a Gaussian distribution, mean values and the associated standard deviations can be specified. Additionally, a time range is provided in which the average life can vary.

The values which are listed in Table 2.17 represent the survey results gathered by the members of the working group, but they can certainly be regarded as representative. The table shows, however, that the possible operational life may differ from the mean value, depending on the individual conditions. For example, the life of a steel lattice tower varies between 35 and 100 years, while this value is in case of a SF_6 circuit-breaker between 30

Table 2.17 Statistical values of the life of electrical equipment [51]

Equipment	System voltage/kV	Mean value/ years	Range/ years	Standard deviations/ years
Circuit-breaker				
Air blast	110–275	41	30–50	6
	≥345	40	30–50	6
Minimum oil	110–199	42	30–50	6
	200–275	41	30–50	6
	≥345	38	30–45	5
Gas	110–199	43	30–50	6
	200–275	42	30–50	6
	≥345	42	30–50	6
Earth switch, disconnector	≥110	42	30–50	8
Current transformer (oil)	≥110	39	30–50	7
Voltage transformer	≥110	39	30–50	7
Power transformer	≥110	42	32–55	8
SF_6-substation (indoor)	≥110	42	30–50	8
Electromechanic protection	–	32	20–45	9
Overhead line rope (ACSR, aluminum–steel)				
Normal environment	≥110	54	40–80	14
Heavy pollution	≥110	46	30–70	15
Overhead line towers (steel lattice)	≥110	63	35–100	21
Wood poles	≥110	44	40–50	4
Cables (oil filled)	≥110	51	30–85	20

and 50 years. For a calculation of a long-term investment strategy according to Sect. 3.4.5, "Simulation: Statistical failure rate," the values listed in Table 2.17 can be taken as an approximation.

The reasons for the end of the technical life of the different pieces of equipment may be different and are given for the items listed in the Table 2.17 as follows:

- Circuit-breaker: Changed technical requirements (rated values), increased failure probability and in consequence increased maintenance expenses, reduced know-how of the service staff, and deficient spare parts;
- Earth switch and disconnector: Changed technical requirements (rated values), corrosion and mechanical wear, and increased maintenance costs;
- Current transformer (oil): seal problems;
- Voltage transformers: moisture problems;
- Power transformers: Reduction of oil insulation, changed technical requirements (rated values), increased operational temperature, and overloading;
- SF_6 substation (indoor): Changed technical requirements (rated values), increased fault behavior (reduction of insulation, seal problems), mechanical wear, increased maintenance costs, and deficient spare parts;
- Electromechanical protection: Corrosion of contacts, changed requirements resp. functionality, reduced know-how of service staff, and deficient spare parts;
- Overhead line conductor: corrosion and conductor grease, insulator faults, increased conductor temperature due to loading, and quality of material;
- Tower (steel lattice): Influence of environment, increased corrosion (also at fundament), stress of steel/concrete junction, concrete spalling, and material fatigue;
- Wood pole: Increased maintenance activities and insect attack; and
- Cables (oil filled): Increased environmental requirements, sheath corrosion, thermal stress, and oil leaks.

In addition to the statistical information in the area of high-voltage installations, values from the range of low- and medium-voltage equipment are listed in Table 2.18 according to [52]. In addition, Table 2.19 shows the expected life of pipes in gas distribution networks according to [33] or water pipe networks according to [34], as given in Table 2.20. In general, in the cited literature, only data for the life are provided, while for the determination of a renewal strategy according to Sects. 2.1.2.4 and 3.4.5, statistical density functions are assumed, e.g., a Gaussian distribution. The density function is determined by the following procedure taking the specified useful life into consideration:

1. The mean value μ is calculated by the mean values of the useful lives.
2. It is assumed for the calculation of the standard deviation σ that 90 % of the total asset group will be replaced within the useful life.

The derived statistical data are also listed in Tables 2.18 and 2.19, using the above conditions.

Table 2.18 Statistical data of life of electrical equipment ([52], resp. slightly changed)

Equipment	Mean value/years	Range/years	Standard deviation/ years
Secondary substation			
Compact	42.5	40–45	1.5
In building	45	40–50	3
Pole mounted substation	45	40–50	3
MV bay			
Primary equipment	45	40–50	3
Secondary equipment	27.5	25–30	1.5
MV cable network	70	65–75	4
MV overhead line network	45	40–50	3
LV cable network	70	65–75	4
LV overhead line network	45	40–50	3

Table 2.19 Statistical data of life of gas distribution networks and material/pipe covering [32]

Equipment	Mean value/years	Range/years	Standard deviation/ years
Cast iron DN ≤ 150	70	50–90	12
Cast iron DN > 150	75	50–100	15
Steel/jute/asphalt	70	50–90	12
Steel/coal tar/wool felt cardboard	70	50–90	12
Steel/bitumen/textile	75	50–100	15
Steel/PE	80	50–110	15.5
St/PE/FZM	100	80–120	10
PE	75	50–100	15

Table 2.20 Statistical data of life of water networks [33]

Equipment	Mean value/years	Range/years	Standard deviation/ years
Cast iron	70	40–100	18
GGG/PE/FZM	120	100–140	12
Steel	80	60–100	12
PE	60	40–80	12

2.1.7 Strategy for System Development

In addition to the management of the existing network, it is one of the main tasks of the asset manager to estimate the future development of the network with all eventualities. Starting from the existing conditions, he has to define a strategy regarding the system development in the future. For this purpose, on the one hand, predictions in various areas of the system demands are required; on the other hand, technical assumptions are directly to specify which are able to harmonize the historical structures in the sense of a target planning network development.

2.1.7.1 General

Network infrastructure is a complex system with extremely durable assets, and this is of particular importance in the derivation of a long-term strategy. Therefore, a short-term or dynamic change without regulatory control in general will not lead to a long-term optimization. The system structures grow in a historical development as a result of external influences and demands. The role of network development strategy consists essentially of making assumptions and forecasts to determine the long-term conditions for the infrastructure. On this basis, any construction project and any development will be aligned with this development to avoid stranded investments and at the same time provide a secure infrastructure according to the requirements of customers and regulatory authorities. This task is more difficult if the forecast areas are very volatile. For example, it was extremely difficult in the so-called economic miracle of the twentieth century to predict the load development and the industrial and commercial settlement of companies in a defined area over a year and accordingly to provide an infrastructure system promptly. Today, a similar situation is caused in Germany by the energy transformation phase, in which the development of decentralized supply and the resulting demands on infrastructure are not nearly predictable.

2.1.7.2 Forecast

Forecasts are needed in many areas in order to define future needs of the infrastructure. These areas are partially combined and usually depend on external factors, such as public perception, technology developments, and policy decisions up to the influences between several infrastructures, such as highway construction in conjunction with industry growth and resulting energy needs. The application of the forecast is characterized by more short-term significance in the range of 2–5 years in some cases up to 10 years. The results of the forecast are a criterion for the system development strategy among other factors described in the following chapters. Relevant topics to forecast for the power networks are, for example:

- General load development of household customer,
- General economic trend,
- Development of decentralized generation/feeding,
- Consequence of political decisions (e.g., first-home buyer allowance, law for energy saving),
- Technology development (e.g., electric mobility, heat pump) and energy storage, and
- Development of parallel infrastructures.

The effects of these system boundaries have to be generally considered to obtain basic assumptions regarding all infrastructures (e.g., for a federal state). But they have to be territorially improved, as the development can significantly vary in different regions. Thus, for example, the network development in a 110 kV grid region with pronounced long sunshine or wind periods may differ significantly from another region in which there is a straight extension of the motorway and thus the development of industrial areas.

The number of system boundaries can increase depending on the nature of the infrastructure system or can split into various parts. For example, the development of competition by mobile telephony has to be considered in case of telecommunication infrastructure systems or in case of gas systems by alternative heat generation. But for the asset manager, the basic principles of the forecast will be the same for each system.

2.1.7.3 Planning Assumptions

The definition of planning premises is required for a reasonable implementation of network development. On this basis, the network planner is able to determine the appropriate size of the development projects of an infrastructure system. One of the most common planning assumptions in the electrical grid, for example, is the "$(n - 1)$ criterion," which means that in case of an outage of important equipment in the system, the transmission or distribution task should be taken over by other assets. The consequence is that a single failure will not lead to an interruption of supply for the customer. For example, it is said in [53]: "From the $(n - 1)$ criterion all grid-related issues are derived, in particular the system services to be provided (e.g., voltage stability including provision of reactive power), equipment capacity, the concept of protection and stability issues, if needed."

Such planning assumptions are quite different depending on the infrastructure system, but always include the basic topics:

- Quality aspects, safety,
- Load capacity/rating,
- Definition of structural parameters,
- Compliance with standards and accepted rules and laws, and
- Economy and efficiency.

These topics are partially competing with each other and may lead to contradictory premises. An increase in quality without constraints or additional benefits will always be in conflict with the principle of economy. Therefore, a set of the most important rules has to be defined in which the planning assumptions are fixed, and also, the mechanism is described for special cases. Following topics will be examined in more detail.

Quality aspects, safety

Quality aspects are defined by Key Performance Indicators (KPIs) (see Sects. 3.3 and 3.3.3). It is described how well the system is able to meet its tasks during normal operation time. However, the impacts of outages are to be considered, and the impact on the planning assumptions is assessed by these KPIs.

It is necessary to distinguish between absolute limits, which generally must not be exceeded at any time, and the limits must not be violated by integrating over a predetermined time interval. Absolute maximum ratings are rarely under planning assumptions and are of significance only for the technical planning of assets in the context of safety-related issues (avoidance of risk to people and property). As absolute limits must be kept in all cases during normal operation, a safe margin of the considered planning premises from system rating is required. The amount of short-circuit current is one example of an absolute limit in power systems. The assets have specified and tested short-circuit strength. If, for example, the short-circuit current in a meshed network increases due to a new connection under planning, it must be ensured that the short-circuit strength of existing assets is not exceeded during normal operation.

However, most boundaries are of integral character with a corresponding fuzziness and leave an appropriate design range and interpretation for the planner. For example, road systems are not designed for the two main travel days on beginning and end of vacation, and the telecommunication systems are not constructed for the hour during turn of the year, in which each person would like to wish everyone a Happy New Year. In this case, temporal overloads are accepted, i.e., congestion or temporary non-connection. Any infrastructure system allows certain “breathing” in the aspects of quality. Operators of infrastructure systems need to define a level of quality to be achieved by the network management, and this level will be met by the long-term planning assumptions in the developed regions. A short-term worsening of the quality due to economic reasons, which is again increased in future in case of better economic situation, is not reflected in the planning assumptions due to their long-term effect. Yet of course, the quality level is one of the biggest factors of the economic efficiency in network development. Depending on what type of risk of temporary non-compliance with the quality target is accepted, other types of networks or reduced systems can be designed, which provide much less costs than potential “high availability systems.”

A well-known benchmark of quality aspects in supply systems is the so-called Zollenkopf Curve for different voltage levels (Cigre 1968 [56], Fig. 2.39). Areas are defined in which power failures should be avoided due to their severe impact. The curve “Cigre 1968” defines the appropriate interruption time depending on the interrupted active power.

The “Cigre 1968” curve for the accepted interruption time is defined by two key points, 24 h at 100 MW and 1 min at 10 kW, and these values are linearly connected (double logarithmic scale). The performance areas can be interpreted according to Fig. 2.39 as follows:

• 1000–100 MW:	Outage of 110 kV system group
• 100–10 MW:	Outage of 110 kV substation
• 10–1 MW:	Outage of MV cable
• 1–0.1 MW:	Outage of secondary substation
• 0.1–0.01 MW:	Outage of LV cable

The above limiting curve (Cigre 1968) has the disadvantage that the frequency of interruption is not taken into consideration. For this reason, additional details were given

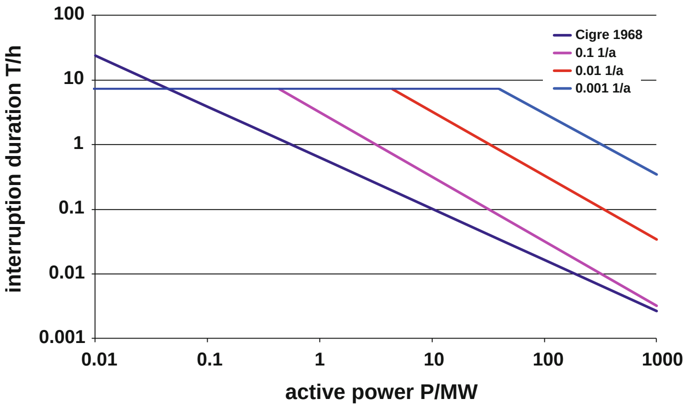


Fig. 2.39 Accepted interruption time depending on the interrupted active power P per MW [17, 56]

taking into account the interruption frequency per year, which are also included in Fig. 2.39 [18]. This means that the consumer is willing to accept longer interruption duration at a given active power, if the interruption frequency is lower.

Load capacity/rating

The load capacity/design of infrastructure systems implies a decision, how many pieces of equipment will be used in the system to meet the defined task. Again, it has to be described for what purpose the system must be designed during normal operation. In case of electrical power and water networks, it has to be assumed that all customers can be supplied with sufficient power or water at all times. Accordingly, requirements for power and water consumption of the customers must be taken into consideration based on the past experience or measurements and the need to be adjusted continuously. Particularly in power networks, the design due to the changing requirements by means of distributed generation and "Smart Grid" (Sect. 1.2) has to be monitored closely, but much more experience is needed.

So far, for power systems, load assumptions were estimated in the different areas as follows:

- Calculation of the yearly peak load of medium-voltage outgoing feeders (P_{maxABG}) of substations

  The maximum loads P_{maxABG} of outgoing feeders can be calculated by:

1. Evaluation of archived data of the network control system.

   The day of the measured maximum load is defined as the reference date during the measurement period. If the measurement period is one year, the measured maximum load is equal to the annual peak load.

2. Evaluation of the power flow measurements.

   The maximum load determined by the power flow measurement is not the annual peak load, but refers to the measurement period (e.g., 1 week). Here, the annual peak load $\mathsf{P}_{\mathrm{maxABG}}$ of an outgoing feeder is determined by the measured peak load $\mathsf{P}_{\mathrm{LFMABG}}$ during the power flow measurement (LFM) according to the following equation:

$$\mathsf{P}_{\mathrm{maxABG}} = \mathsf{P}_{\mathrm{LFMABG}} \cdot \frac{\mathsf{P}_{\mathrm{maxTR}}}{\mathsf{P}_{\mathrm{LFMTR}}} \tag{2:5}$$

with

$\mathsf{P}_{\mathrm{maxTR}}$	annual peak load of the feeding HV/MV power transformer
$\mathsf{P}_{\mathrm{LFMTR}}$	peak load of the feeding HV/MV power transformer within the measurement period of the power flow measurement

The annual peak load of HV/MV power transformer is due to the non-simultaneity of the outgoing maximum loads less than the sum of annual peak loads of the outgoing feeders, so that the equation applies:

$$\mathsf{P}_{\mathrm{maxTR}} \backslash \sum \mathsf{P}_{\mathrm{maxABG}} \tag{2:6}$$

For HV/MV power transformers, the non-simultaneous maximum loads are related to the maximum load of the power transformer by the scaling factor $\mathsf{k}_{\mathrm{TRmax}}$.

$$\mathsf{k}_{\mathrm{TRmax}} = \frac{\mathsf{P}_{\mathrm{maxTR}}}{\sum \mathsf{P}_{\mathrm{maxABG}}} \tag{2:7}$$

Today, it must be ensured that in regions with high concentration of power generation from renewable energies, the current direction in case of reverse power flow has to be considered. The consequence is that the power transformer must be designed for the power flow in both directions. It is increasingly common that the reverse power flow from decentralized energy generation is the dimensioning factor for rating the 110 kV systems. Particularly, the rating for the load case “low consumption–high generation” (e.g., Easter Monday, White Monday) has to be taken into consideration. The installed generating capacity of the region is used, extended to the still expected new generating facilities which are weighted with a specific territorial diversity factor of generation plants.

- Load assumptions for household customers
  The yearly peak load of a household customer/housing unit can be calculated by Eq. 2.6:

$$\frac{S_{\max}}{\text{customer}} = \frac{S_{\text{base\_load}} + 1\,\text{kVA=HU}}{n} = \left(1 + \frac{S_{\text{base\_load}}}{n}\right)\text{kVA} \tag{2:8}$$

n number of customers (housing units, HU), which are connected to the considered equipment (LV power transformer, low-voltage feeder)

The following values are taken into consideration for the base load of LV power transformers and low-voltage feeder:

- 40 kVA in regions with natural gas supply and
- 60 kVA in regions without natural gas supply.

Note The analysis is applied separately for any low-voltage feeder of a secondary substation and for the feeding LV power transformer. This means that the maximum load of a substation is always less than the sum of maximum peak loads of all low-voltage outgoing feeders. This approach leads to a scaling effect which is exemplarily listed in Table 2.21.

In the future, this table can only be understood in different regions as a basis. Depending on the self-generation of many households, the overall view is to be provided with appropriate correction factors on the consumption side. Otherwise, the energy which is temporarily “too much” generated must be dissipated in the low-voltage network, so that the return power flow direction has to be used for the rating. An increase in planning complexity can arise if there should be a wider distribution of battery storages, which in turn cause a change in the requirements for the infrastructure system.

Table 2.21 Power $S_{\max}$ per customer (kVA) depending on the housing units (HU)

Number HU	With natural gas supply	Without natural gas supply
5	9.0	13.0
10	5.0	7.0
15	3.7	5.0
20	3.0	4.0
30	2.3	3.0
50	1.8	2.2
100	1.4	1.6
150	1.3	1.4
300	1.1	1.2

- Load assumptions for industrial customers

  The registration power is, if it is known, a basis for planning with an assumed simultaneity factor $g = 1$. The currently existing trend to build one's own power generation (combined heat and power, CHP) in the commercial and industrial sector has to be taken into consideration, but changed the registration power, so that the existing planning system will not be changed in this region.

  If the requested power is not available, the following experienced data can be used, as given in Table 2.22.

- Load assumptions for existing LV power networks

  The following approaches can be used to simplify the calculation of existing LV power networks (extension, network strengthening, and voltage drop):

  - LV outgoing feeder: $\text{Load}_{\text{LV\_feeder}}$ = load assumptions (HU) + Σ confirmed load (storage heating, industry limited power, heat pump, and air conditioning)
  - ON power transformer: $\text{Load}_{\text{ON\_transformer}}$ = load assumptions + $x \cdot \Sigma$ confirmed loads (storage heating, industry limited power, heat pump, and air conditioning) with x as appropriate scale factor depending on the size and kind of the LV network.
  - Reverse power flow: $\text{Feeding}_{\text{NS-network}} = y \cdot \Sigma$ (installed generating capacity) + $z \cdot \Sigma$ (potential of additional power generation) with y as area-specific simultaneity factor and z as a discount factor, which describes how much of the additional power generation can be installed during a defined period.

- Load growth rate

  The state-of-the-art assumption for the global average load growth rate is currently 1 % per year.

  Larger registered connected load and well-known regional characteristics are taken into account. Load growths from the redevelopment of residential or commercial regions are also considered in network planning.

Table 2.22 Field data for single customers related to the useful resp. built-over area

Utilization	Surface load in VA/m^2
Administrative building	70–100
Department store	150
Hotel building	60
Repair shop, turnery, spinnery, weaving mill	50–100
Tool shop, mechanical repair shop, welding plant	70–300
Press plant, hardening plant, smeltery, rolling mill	200–500

New distributed generation units, which are politically desired in many locations, are a further component which has to be inserted in the global load growth rate for future development. However, this component is of importance only after the penetration of distributed generation with different independent production technologies (e.g., solar, wind, gas turbine, and fuel cell) reaches a certain value which ensures also a low simultaneity factor of production outages. For example, in Germany, even after the increase of distributed generation, network planning has the problem that all operating cases have to be considered, including the case that the generation units are not active. In 2012, the momentary load consumption was covered by renewable energy generation plants from more than 40 % (low load, clear sunny, and windy weather) to less than 1 % (high load, largely windless overcast sky). Consequently, the last case is the design case. The total load analysis has only to be considered in a network-area-specific manner, if a permanent power generation is available (e.g., stronger propagation of CHP, fuel cells to increase the independent self-generating) or the storage technology will find a wide distribution, so that an equalization of the load on the network will be expected.

- Load capacity of equipment

  If the reverse power flow is not important for the design of the components, the utility load is assumed for the rating regarding the load capacity of equipment of medium- and low-voltage networks, which is shown for example in Fig. 2.40. However, in case of reverse power flow, feeding load curves have to be prepared depending on the power generation mix, which are determined in a special case by a defined simultaneity factor. These feeding load curves are basically modeled as negative utility load curves.The load factor (relationship average/maximum load) will be scaled by an appropriate

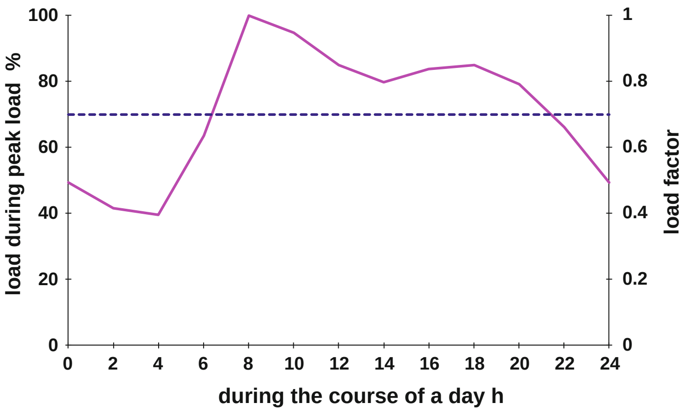


Fig. 2.40 Daily load curve and utility load; solid line relationship in % of the load at peak load; dotted line relationship of the medium load to the peak load

factor (e.g., 0.7) to include the simultaneity and the short-term load fluctuation into the capacity of equipment.

Definition of structural parameters

The determination of structural parameters is important information, how infrastructure areas will develop up to a certain extent or redevelop in case of renovations. In general, the use of new technologies with higher reliability, lower operating costs, and increased capacity allows the reduction of structural complexity and thus, the total amount of infrastructure assets. This is related to both number of network connections and components at system nodes such as substations, gas regulator stations, and water works.

As an example of structure determinations in power distribution networks, a possible definition of the low-voltage network structure is shown in Fig. 2.41. Depending on the service quality requirements, the possible alternatives can be evaluated and defined in the planning principles.

Compliance with standards, accepted rules, and laws

In case of compliance with standards, rules, and laws, the protection of the strategies and procedures are basically in the foreground that are specified by the asset management, compared to strict liability (danger to people and property) and the avoidance of organizational faults. Planning assumptions are always based on the principle that these rules

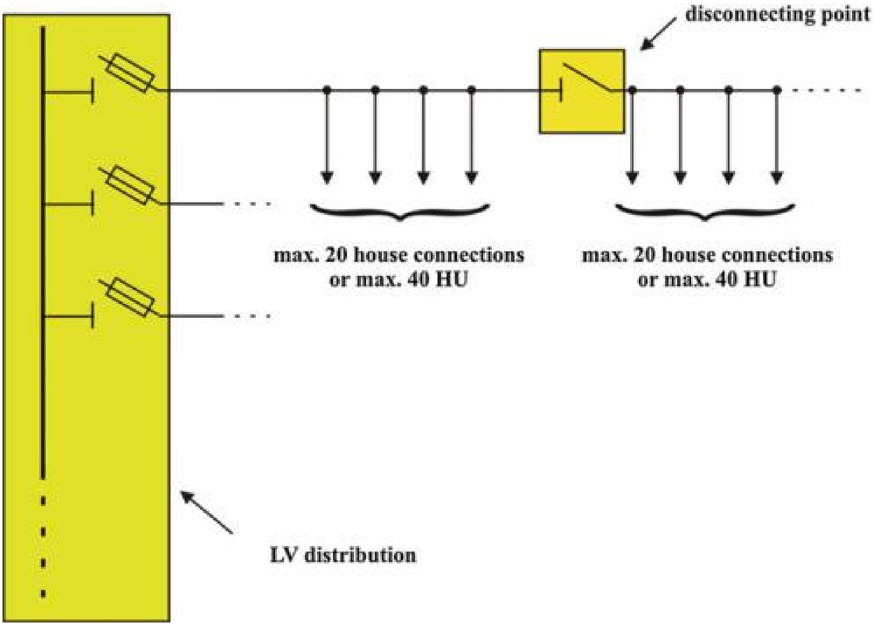


Fig. 2.41 Separation of a low-voltage network with columns; HU housing units

and standards, established by independent experts, must be a basis for decisions and the rating of the infrastructure. The compliance with laws is self-explanatory, but must also be formally mentioned in the planning premises and documented.

Economy

The asset management is the combination of technology functioning, rating, and dimensions on the one hand and efficiency on the other. In the life cycle of infrastructure systems, the planning phase is the period during which the leverage of the decisions to be taken is the greatest, as shown in the Fig. 2.42 [13]. Therefore, a clear assignment of variants has to be met in the planning premises and the procedure for the assessment of the differences has to be described, which occur during the economical comparison of alternatives. This may be the utilization of the net present value calculation and life cycle costs assessment (Sect. 3.1.3.2), including the consideration of higher investment costs versus higher operating expenditures.

If a decision is taken by the asset management, the other effects are more or less fixed, that is, the "leverage" of decisions is relatively small in later phases of the life cycle.

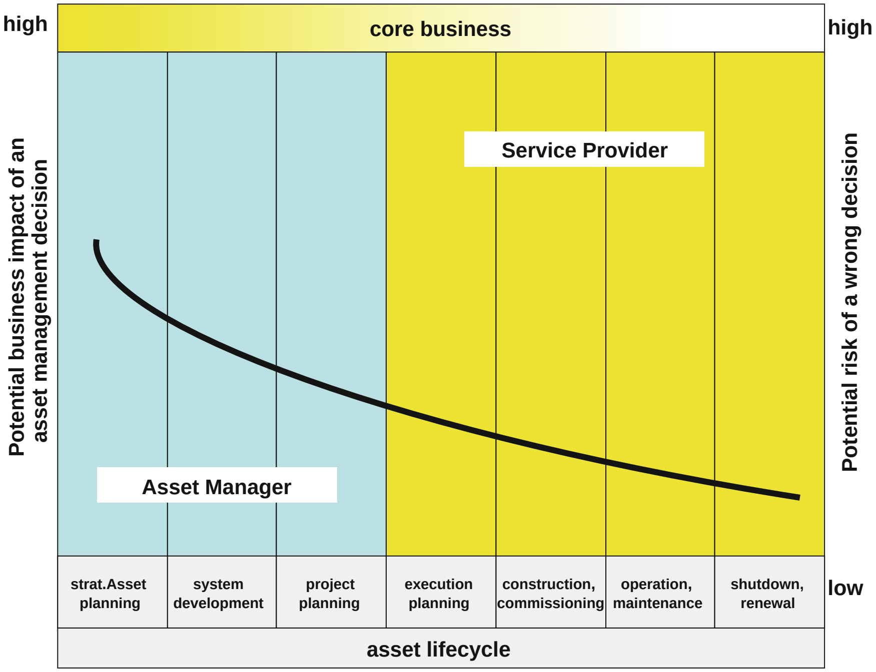


Fig. 2.42 Economic leverage effect in case of asset life cycle, schematically [13]

2.1.7.4 Considerations of the Target System Planning

The relation of network development and renewal strategy (Sect. 2.1.8) is reflected in particular during the strategic planning development. The development of historically grown infrastructure systems is one of the major challenges for the asset management. The target is to identify which pieces of equipment, installed in the past, have to be optimally dimensioned due to a geographically "targeted" network according to the current planning assumptions.

Also, a certain hierarchy exists in the target network planning of the target infrastructure system: upstream system levels, the so-called highways, and the downstream system levels, corresponding more closely to the "federal and local roads." This analogy can be applied to electricity, gas, and water supply networks. The upstream system levels of the strategic network are marked by large individual project costs, large implementation efforts even in the area of necessary legal permissions, and high public perception. This leads to an intensive variant testing with usually ongoing discussions over years about the proper implementation of a viable long-term implemented structure. No universal representation of an approach can be derived in this segment, as the strategic network planning is always an intensive individual consideration. The frequency of the review of such strategic network planning in upstream system levels is 10 or more years. This is also evident in the analysis of the German Network Development Plan (NDP), published since 2012 in coordination with the Federal Network Agency. This report describes and observes the development of the transmission network over the next 10 years. This is also true at European level with the so-called Ten Year Network Development Plan (TYNDP), which is published by ENTSO-E in Brussels.

In downstream system levels, however, the mass of the equipment is already installed, and thus, the largest volumes of investment are available in case of the strategic network planning. A systematic approach can be developed by appropriate specifications for the majority of structures so that optimized network structures are possible which may be adjusted due to external short-term influences according to the master plan. Of course, the influence of third parties (municipalities, business, developer, etc.) will be taken into account in the short term, particularly in these structures, and this is the reason that a medium-term stable strategic network planning is not available. Therefore, a revision is depending on the economic cycle in these system structures, and the frequency for checking the strategic planning is about 5 years (if no direct short-term necessity exists for an action).

A target network planning never stops in case of sufficiently large systems, but an adaptation to the latest findings is sequentially made by the implementation of updated planning assumptions over the entire infrastructure, e.g., technology, quality, and customer requirements. An optimal "target" network is therefore mostly theoretical, but cannot actually be achieved.

2.1.7.5 System Planning of Smart Grids

The term Smart Grid is now overused in the energy landscape for all kinds of future-oriented technologies. However, this term needs to be resolved in different subjects. In power systems, Smart Grid means significantly higher degree of automation of the individual network segments is to be understood with an exponentially increasing amount of data. A basis for Smart Grid is the distributed data acquisition, processing in areas of automation and control algorithms as well as their transport under consideration of security aspects, e.g., into a dispatching center. For this purpose, a reliable and secure communication system is required. In addition to Smart Grid, the term Smart Market is often stated, in which intelligent merchandising concepts are developed and offered flexible products for the energy market and for system services. One aspect of Smart Market is Smart Home which represents an optimal energy portfolio for the individual customer, household or industry by use of transparent information of energy consumption, flexibility, and automation technology.

Historically, in the sub-area network planning process, the infrastructure guaranteed the distribution of energy from large power plant down to the low voltage customer. Herewith, the planning assumptions are taken as the basis which are already described in Sect. 2.1.7.3, e.g., with defined loads according to Tables 2.21 and 2.22. In this case, the "target" network is planned as a passive system, which can meet this task at any time. However, due to the changes in the generation market, with significant energy generation also in the lowest voltage level, this passive system converts into a system with more and more active components such as photovoltaic systems or cogeneration power systems (combined heat and power), which are currently still uncontrollably connected to the energy grid. Until 2010, this circumstance was no great challenge for the planner of the infrastructure system, as the amount of locally generated energy did not cause a reverse power flow of the low-voltage networks. The balance of locally produced energy related to the decentralized consumed energy was positive. Temporary network conditions are caused by the progressive development that low-voltage systems represent "area power plants." Combined with wind turbines and larger production units connected to the medium-voltage network, which also becomes a network with reverse power flow, the high-voltage networks develop into an energy generation network. This results into various issues in case of the network planning, e.g., starting from voltage stability and harmonic problems, protection, and short-circuit current considerations up to a lack of transmission capacity. The capacity issue can be explained most clearly. Since the network was designed in its duty to provide a defined transmission capacity (with respect to the consumption load), it is also able to handle the power flow in a different direction to the upstream networks. But it reaches its limit, if the energy generated locally exceeds at any time the sum of consumed energy and the planned transmission capacity. Thus, the regeneration or generation case is responsible for the network design and can cause massive network expansion. Figure 2.43 illustrates this situation schematically. The following load cases are shown:

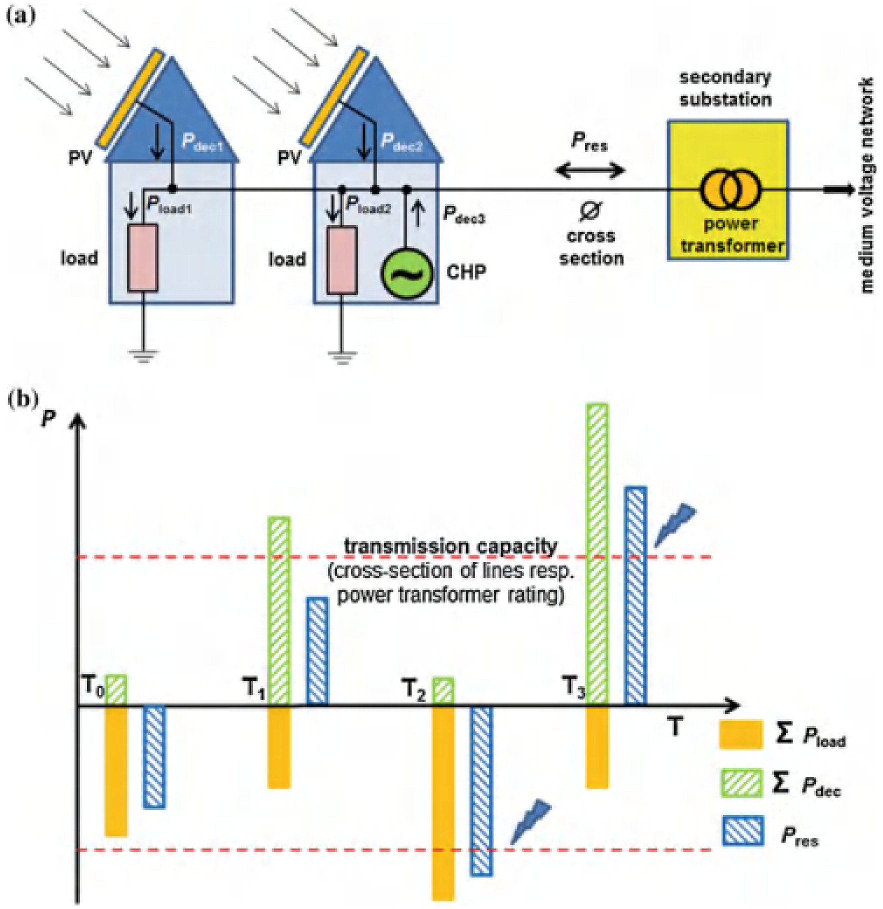


Fig. 2.43 Single line diagram (a) and load cases (b) of a low-voltage system; $P_{load(n)}$ consumption of nth load; $P_{dec(n)}$ decentralized power generation (nth power plant); P_{res} residual power; PV photovoltaic; CHP combined heat and power

• T_0	It corresponds to the design case during load operation, and the residual power is less than the transmission capacity and flows to the low-voltage grid (downstream)
• T_1	It corresponds to the design case during generating operation, and the residual power is less than the transmission capacity and flows from the low-voltage grid in the direction of medium-voltage network (upstream)
• T_2	It corresponds to the overload case during load operation, and the residual power is larger than the transmission capacity; line or transformer are overloaded in the load direction
• T_3	It corresponds to the overload case during generating operation, and the residual power is larger than the transmission capacity; line or transformer are overloaded (upstream)

The four identified load cases represent the fundamental challenges of the network planning. In terms of network planning in the passive system, largely static methods of calculation are sufficient. The load cases T_0 and T_2 are relevant under these considerations. These are wide predictable planning cases as existing loads are known, the load growth can be estimated, and larger load steps are recognizable by new customer registration in advance. Thus, the planning and design security for the infrastructure system can be sufficiently achieved during low- and heavy-load cases by simple load flow and short-circuit current calculations. The question arises, if the load case T_3 is considered, which is the determining value limiting the distributed generation capacity. It turns out that the installation boundary in case of photovoltaic is defined by suitable installation area and in case of wind power by windy sites. Estimations in several German Federal States regarding the potentials have shown that in southern Germany, sufficient suitable roof surfaces are available in today's buildings to multiply tenfold today's installed PV capacity [22, 55]. Figure 2.44 represents the original planning design against the challenges arising therefrom in the distribution network.

If the required capacity expansion is considered only against this background, it is clear that the low-voltage grid would have to be expanded in the networks concerned with the eightfold to tenfold capacity, the medium-voltage network even with three to five times the capacity. Considerable capacity expansions are also required in the 110 kV grids, because the energy must be distributed during the peak generation via this network from the generation area. The German Energy Agency (regulator) extrapolated the required

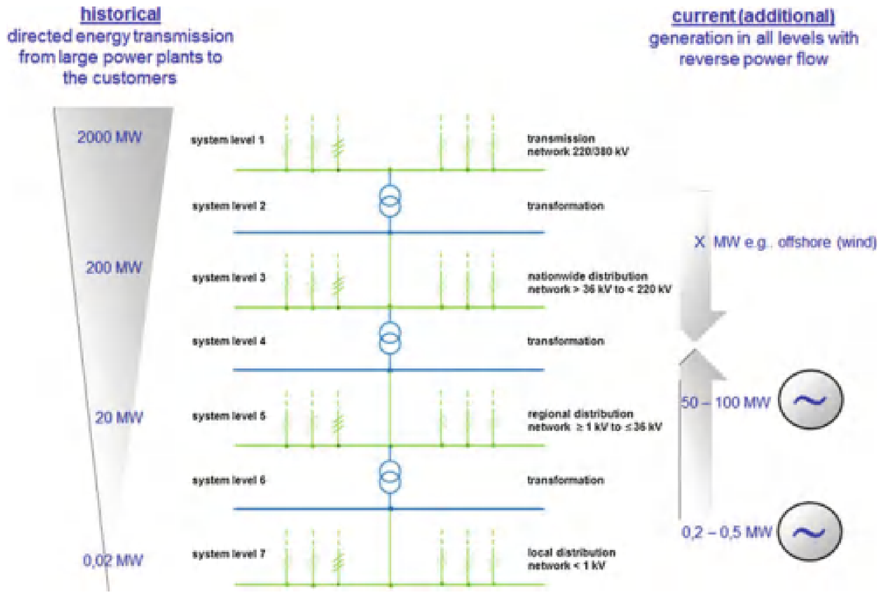


Fig. 2.44 Comparison of historical and current tasks of electrical infrastructure system in Germany

network expansion in Germany according to a distribution network study in 2012. If no Smart Grid mechanisms are used, the network planning remains in its structure and the network will be designed for the maximum static load case with corresponding high investment costs. Since this maximum load case occurs only in a very few hours per year, this approach is very expensive and uneconomical.

In order to find a better alternative for the planning and the network expansion, changes in the legal and regulatory framework are discussed, which put an emphasis on flexible options for load and generation, thereby increasing the possibility and the need for a Smart Grid development for network operators. Two main groups can be distinguished under these options:

- Load management—controllable loads:
  This group includes all possibilities to control the network load in the considered network area, both in the positive and in the negative direction. These include controlled load shifts in case of industrial customers, energy-controlled temperature management in refrigerated warehouses, storage heater control in household customers (power-to-heat) but also, for example, charging of storage batteries or storage power plants.
- Feed-in management—controllable distributed generators:
  This group includes all control operations with effects on the energy generation processes in the considered network area. Gradual reduction of generation is necessary in case of volatile generation such as photovoltaic and wind power. In contrast to these, the generation of other units can volitionally be increased or stabilized. Examples include cogeneration plants, biogas power plants with gas storage as well as feeding from storage batteries, and storage power plants.

These options are only used on medium- and low-voltage level when a stable communication infrastructure provides information regarding the network capacity utilization, in order to recognize and to document the need for intervention. Also, control signals must be provided for the flexible options which have to be used according to the network requirements. The required energy-related processes are to be treated in detail at this point, such as balancing group management or billing processes, as the technical effects are in the foreground. Figure 2.45 illustrates schematically a considered grid area, the influencing factors and the flexible options, and the considered boundary planning conditions.

In the described system change which will be expected with the utilization of active and uncontrolled components on the one hand and the use of flexible options on the other hand, a classical static calculation method is no longer sufficient. There must be a transition to a dynamic planning that includes the active components and control options and makes a network planning and optimization possible. Ideally, all parameters and their behavior are known in response to the changing boundary conditions. In other words, the network planner has available all power data of connected consumers and producers and he knows the considered wind and sunlight in the network area during the year.

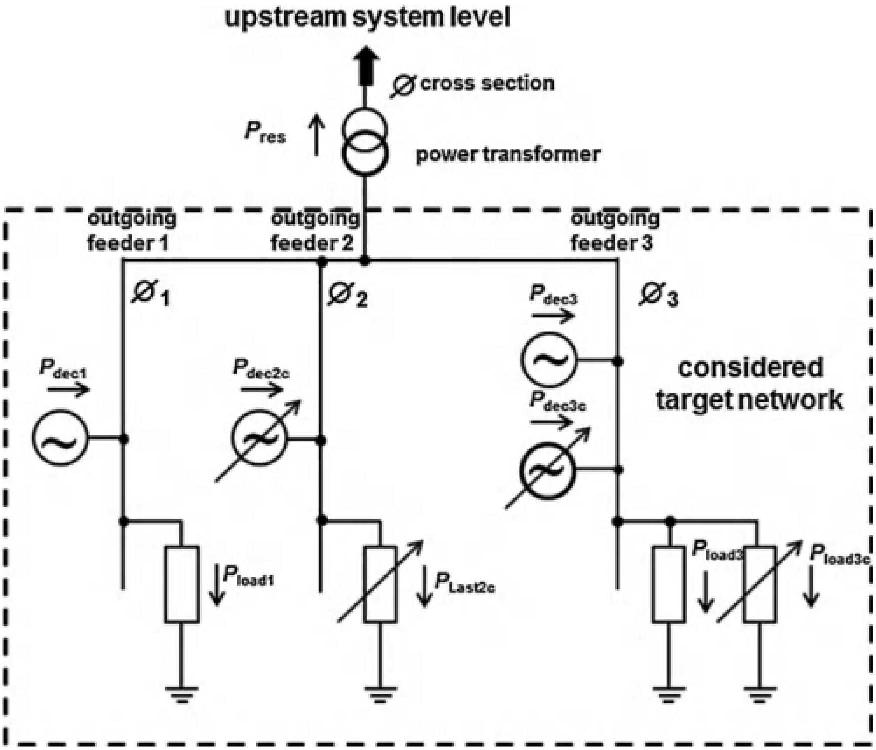


Fig. 2.45 Influencing factors and flexible options of a planning area; $P_{loadn(c)}$ consumption of nth load (uncontrolled/controlled); $P_{decn(c)}$ decentralized power generation (nth power plant) (uncontrolled/controlled); P_{res} residual power

These values will be connected in a future technical development step of Smart Grid with the use of Smart Meters by the installed sensors which are available in the network. In addition, there will be an improved forecast of weather conditions to assess the Renewable Energy Act (REA) generating units. Furthermore, the probability will be an issue of future network planning, since there will be no exact predictions for the behavior of uncontrolled loads and generation units. The use of the probability in the network planning is studied in university research for several years, for example, in [49] and will attract increasingly interest in the operational use by network operators due to the changing environment [48].

The required values for the degree of simultaneity of various influenced factors must always be reverified by operational experience and data collection on a large scale (keyword BIG DATA) to utilize in network planning. The dynamic planning calculations, conducted by these input variables, provides a simulation of the future network operation, taking into account the probabilistic, uncontrolled components, under consideration of the expected flexible options (controllable loads and generation units). Systems are not yet available which are able to perform a complete simulation over 8760 h of a representative calendar year. These have to be developed with the real implementation of Smart Grid technology. In a first approximation, so-called time-series-based planning calculations are carried out in practice to be able to implement the fundamental strategic network planning according to the new models. Four basic calculations are sufficient to determine the future network parameters in classical planning using load flow and outage calculations ($n - 1$) during the heavy-load case, as well as short-circuit current calculations with maximum and minimum generator feeding. Exactly, these four basic calculations are now performed with defined expected values in the time-series-based planning for a lot of different load cases at different times. Which number of load cases is sufficient in the first step depends also on the complexity of the network and the expected development of the active components. This has to be assessed and determined by the responsible system operator. However, expected extreme cases of load and power generation must be represented by time series, so that the calculation of the future operation has its validity. The outgoing feeders according to Fig. 2.45 have to be understood as the basis of different system types to develop the time series under consideration of the flexible options. The target is always to avoid overloading of the cross section and thus the transmission capacity of the individual feeders. The limiting capacity regarding the outgoing feeders of the power transformer or the line of the upstream network must not be exceeded during any load case. The exceeding of the limiting capacity of components is in a certain extent technically possible, but lead to an increased deterioration and consumption of life endurance. Therefore, these considerations are not the basis of the planning concept and should in general be avoided in case of a sustainable asset management process.

- Outgoing feeder 1 (Fig. 2.45) represents the uncontrolled network without Smart Grid options. The basis for system planning is the expected load and generation development whose simultaneity is to be defined by representative weather data for generation and historical load data. An example of an extreme load case is a public holiday with reduced load, high wind levels, and strong sunlight. As no controllable flexible options are available, the network must be designed for the maximum power supply that can be expected.
- Outgoing feeder 2 (Fig. 2.45) is an example of a so-called micro-grid. Both, the load and the power supply are fully controllable. The load of the cable cross section can be used in such a network in any order. Consequently, the network design can be reduced independently on the conditions, because the network does not take over load transmission characteristics in the proper sense, but has only to bring load consumption and power generation into balance. Both load and generation can be controlled technically to the value “zero.”
- Outgoing feeder 3 (Fig. 2.45) represents the combination of the two other outgoing feeders. Here, different load situations are to be considered in order to achieve a reasonable network design. The actual minimum design is determined by the uncontrolled loads, which must satisfy all load cases. This design can be reduced to the extent that such a controllable activatable power generation is present, which may also cover

the affected uncontrolled load consumption. In this case, the probabilistic assessment should be taken into account, especially differences in the availability of network and generation units. The uncontrolled generation is to be considered in a similar combination with controllable loads. These quantities determine the rating of the feeding back situation together with the controllable deactivated generation. All eventualities have to be performed by time series for the special network considered.

In the future, the asset manager has the possibility to adapt changed active network components in the lower voltage levels by the early alignment of the network planning regarding flexible and controllable options. A maximum design of networks can thereby be avoided for all generating units which would be in service only a few hours per year. Otherwise, this would lead to "stranded investments" under consideration of the further development of controls and network automation. Other active components, such as electric mobility and power to gas can be taken into account in future planning in this system by easy modeling of defined probabilities.

2.1.8 Renewal Strategy

Several steps have to be considered when implementing a renewal strategy, on the technical, economic, and strategic level. Thus, different areas of the company are involved in the decision making.

2.1.8.1 General

Infrastructure systems are usually subjected to investment cycles which can be determined by various factors; for example, the historical development of territories as well as the recent development of new technologies has to be mentioned. Due to these investment cycles, there will be times when a greater proportion of the available asset fleet comes at the end of the technical life. This issue plays a substantial role on the reliability of the network and is related to the replacement of the equipment and the time, with a simultaneous increase in costs of operation and maintenance. Therefore, this is a critical situation for the utility, so it is useful to develop methods and strategies how the replacement of the exchanged equipment can be ensured with a required reliable system level at the same time. Here, the reliability of the network is affected in two ways as shown in Fig. 2.46. Firstly, a delayed replacement of assets leads to increased outages as a result of a greater failure rate which in turn leads to longer repair times (outer ring). In contrast, a more rapid replacement of the components leads to a reduction of the acceptable reliability levels, as the network is in a "weak" condition due to the replacement [51].

Therefore, it is the task of the asset manager to optimize the investment of new assets over a predetermined time period in order to avoid load peaks in terms of human and financial resources in the medium- and long-term period.

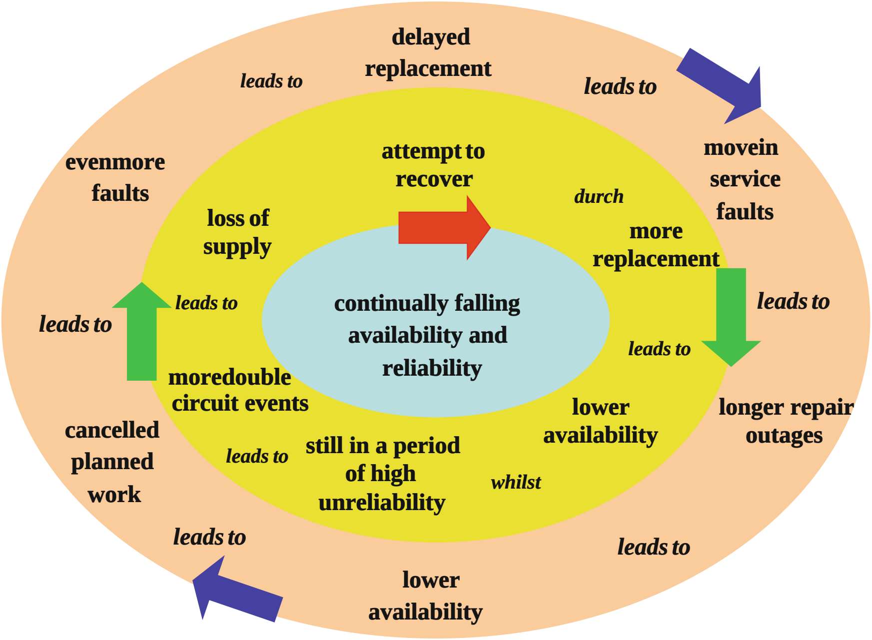


Fig. 2.46 Changing of the system reliability depending on the replacement of assets [51]

In contrast to the representation according to Sect. 3.4, "asset simulation" only the replacement of the equipment is considered in the following, while the calculation of the total financial expenditures (CAPEX and OPEX) of equipment is considered in Sect. 3.4.

2.1.8.2 Criteria of Renewal

The decisive reasons for the exchange of electrical equipment have been determined in a survey with various utilities [36]. Following statements are exemplarily found in order of the importance:

- Lack of support by the manufacturer,
- Know-how of the service staff,
- Lack of functioning, wear,
- Environmental influences,
- Safety,
- Spare parts,
- Exceeding the rated values,
- Maintenance costs, and
- Reliability.

Of course, the reasons listed above always depend on the type of the equipment and the operational experience, but it turns out that in this case, the time for the renewal of equipment does not primarily depend on age. Instead, the decision is mainly influenced by criteria that have an economic background. The various criteria can be assigned to different classes, and these include:

- Technical:
  - No or poor functionality,
  - Increased failure rate,
  - Obsolete technology,
  - Aging and wear,
  - Lack of spare parts,
  - Reliability, and
  - Less rating, exceeding the rated values
  - …
- Economic:
  - High operation costs (maintenance, spare parts policy, non-availability, costs of power losses),
  - Expenditure for depreciation,
  - Costs for monitoring and diagnostics,
  - Low investment costs of new equipment,
  - High financial expenditure for spare parts,
  - Environmental costs, and
  - Low service know-how.
  - …
- Strategical:
  - Injury to persons and damage to property,
  - Outdated technology,
  - Loss of company's image,
  - Changed network strategy,
  - Regulatory and legal requirements,
  - Dependency on equipment manufacturer,
  - Availability of financial resources, and
  - Long-term strategy of the company.
  - …

From the listing above, it is obvious that identical criteria may appear in various areas. For example, the outdated technology of the equipment causes high maintenance costs and lack of service know-how with the result that the company will no longer support the technology due to high environmental damages, which can lead to a loss of image.

2.1.8.3 Decision Levels

Different levels, which differ in various input and target values, can be defined with respect to the decision process according to [47]. The levels can be described as follows:

- Strategical,
- Technical organizational, and
- Operational.

This classification corresponds to various steps that are generally defined for the development of an overall asset strategy according to Sect. 2.1.

The content of these various levels can be defined as follows:

• Strategical	In this step, the global definition of the budget takes place for the replacement of equipment under the boundary conditions that all groups involved in the process carry the strategic, long-term development. Basically, it is sufficient to assume the statistical functions in case of determining the necessary expenses for the replacement of the assets. These values are sufficiently described by their mean values and standard deviations and results in an index value for the whole asset value of the considered infrastructure system. Based on this, a total budget value is determined by the corresponding age structure and a value for the replacement of the entire system. This can strategically be changed with boundary conditions such as quality aspects before finalization Use of long-term asset simulation (Sects. 2.1.8.4 and 3.4) Area of activity: Asset owner
• Technical organizational	At this level, the implementation of the renewal strategy takes place under consideration of the requirements of the strategic level (budget allowance in terms of the global renewal and network development). Here, the individual strategies are developed and particular groups of the infrastructure down to single equipment levels are analyzed with the help of information from the operational level (technical data of the equipment, age, aging, behavior, reliability, etc.). As a result, the concrete renewal strategy is determined by establishing time and place for the exchange of equipment The solution of this question is performed by simulation and economic calculations (Sect. 3.1.3) Area of activity: Asset manager
• Operational	On the basis of individual strategies, the selection of individual measures must be made from a suitable renewal conglomerate, if applicable. In this case, the technical condition of the equipment is the main input variable in consideration of the service know-how of the local staff. But also the membership of the equipment to a larger assessed fleet is an input value for the final decision on the need, timing, and scope of renewal measure. Consequently, necessary decisions are made in this step regarding the replacement measures for the individual operating equipment, such as exchange, replacement of components, event orientation, continued operation, and medium-term renewal of a larger unit Application of risk analysis for a single equipment (Sect. 3.2.6) Area of activity: Asset manager together with asset service

The following section focuses on the technical organizational level.

2.1.8.4 Modeling of the Technical Organizational Level

Different models can be used for the simulation of assets resp. groups of equipment on the strategic level. In this case, the objective is to set long-term investment decisions. Basically, the following types of simulation are available to solve this problem:

- Age dependency,
- Statistic model (Gaussian distribution), and
- Simulation with the help of the survival function.

The models listed above are shortly described in the following and shows the different characteristics on the basis of an example [47].

In this case, the determination of the medium- and long-term budgets is derived depending on the statistical behavior of the entire asset group (top-down), in contrast to previous evaluation of the investment budget regarding the replacement of equipment starting with the condition of the individual components (bottom-up). It should be noted that the various asset groups are considered independent of each other.

Age-dependent boundary value

When using this model, it is assumed that the equipment replacement generally takes place between service years t_{min} and t_{max} based on the operational experience. In order to determine the number of assets to replace in the next five years, the units which enter and leave this time span during the observation have to be counted. For example, Fig. 2.47 shows the age distribution of an asset group of in total 100 units, according to the example in Sect. 3.4.4.1.

Assuming a time range for the replacement of equipment from 36 to 46 years, the number of devices to be renewed in the next five years on average is:

- n_{min} := 6 (minimum number within 5 years)
- n_{max} := 29 (maximum number within 5 years)

Here, the minimum number n_{min} of the replaced equipment is determined by the components that exceed the maximum age of 46 years during the next five years. In contrast to this, the maximum number represents the equipment which already is in the selected period of time or will come into it in the next five years. In general, this method is a rough estimation and it is appropriate under circumstances to take the average of the two extreme values for an assessment the investment budgets.

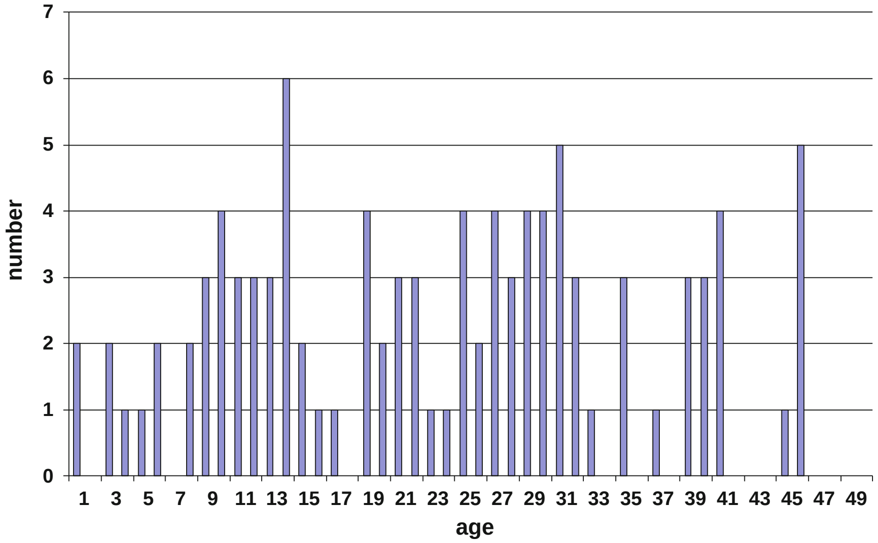


Fig. 2.47 Age distribution of the asset fleet

Statistical model (Gaussian distribution)

Before using a statistical model for determining the number of assets which are to be replaced, the density function of the exchange rate λ of an asset fleet must be available. Naturally, the basis is that a sufficient population is available, so that a Gaussian distribution can be assumed. For example, in Table 2.17, mean value of $\mu = 42$ and a standard deviation $\sigma = 6$ years are assumed for the renewal rate of the considered equipment (circuit-breakers). In addition, it is assumed that all assets which are older than >46 years are to be replaced. The number of assets to be replaced every year in the time range of 5 years can then be determined.

In general, statistical distributions can be described, by using any of three different functional equations:

- Density function $f(t)$ according to Sect. 3.6.2.6
- Distribution function $F(t)$ according to Sect. 3.6.2.7
- Hazard, resp. exchange rate $\lambda(t)$ according to Sect. 3.6.2.8

Based on the density function $f(t)$, the two other functions can be derived. If the age distribution of the components is present, it is therefore possible to calculate the elements which should be replaced within a predetermined time range with the help of data related to the mean and standard deviation (Sect. 3.4.5).

Figure 2.48 shows the exchange rate, which is determined on the basis of the above-mentioned requirements of the normal distribution. It presents numerical values for the

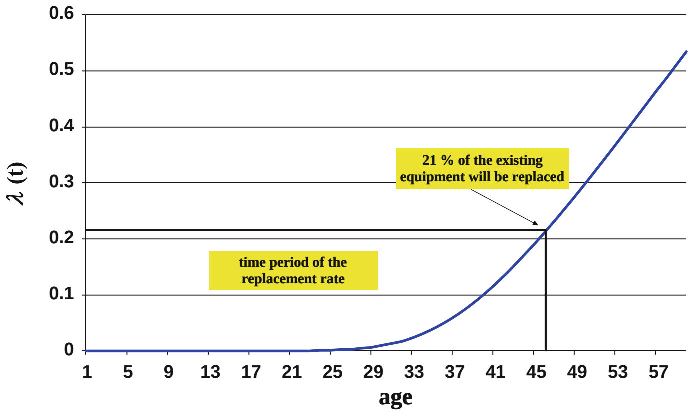


Fig. 2.48 Exchange rate of the asset fleet as a function of age

time periods >46 years. The replacement rate is thus the number of devices that are exchanged, based on the still-existing devices. The multiplication by the age distribution according to Fig. 2.48 therefore reflected the annual number of assets which will be replaced. In addition, the assets are taken into consideration which excess the prescribed maximum age of 46 years. Because of the continuous function of the normal distribution, the assets are also replaced which are less than 36 years old based on the exchange rate $\lambda(t)$.

The result of the simulation is that in the next five years in total, 15 pieces of equipment must be replaced based on 100 original components. This result is thus in the middle of the rough estimation, which is calculated using the age-dependent boundary value. The number of replaced annual assets is shown in Table 2.23 (values are not rounded).

In addition to the application of the normal distribution, lately the usage of the Weibull distribution (Sect. 3.6.2.3) has been proved useful as various periods of life of equipment can be mapped by appropriate selection of factors in order to describe the complete "bathtub curve."

Table 2.23 Number of annually replaced assets (statistical model)

Year	Number
1	6.6
2	2.4
3	1.7
4	1.9
5	2.0
Sum	14.6

Exemplary statistical data of the life span of the selected assets are listed in Table 2.23 in the field of electrical power supply, which may be used for this application.

Based on the exact age of the asset distribution, the collective behavior of the entire asset fleet is analyzed by the application of the statistical model. Thus, an assignment of the exchanged assets to the current distribution is not possible.

Reliability model

If the distribution function F(t) or the replacement rate $\lambda(t)$ is known from practice, this information can be used directly for the calculation of exchange rate. The difference from simulations according to the statistical model above is that no Gaussian distribution is available. This means, however, that the history of the replacement age of the replaced equipment is known and a sufficient large population exists.

Basically, it is also possible to derive a distribution function F(t) from the condition and age distribution according to Sect. 3.4.4.1, Fig. 3.38. In this case, it is assumed that the assets with the best condition with respect to the age will reach the maximum given age. As described in Sect. 3.4.4.1, an artificial age of the equipment can be assumed from this requirement, so that a distribution function F(t) can be derived individually for this equipment collective.

2.1.8.5 Assessment of the Models

The method provides the best results, which uses the last-described reliability model, but in this case, it is assumed that the replacement rate $\lambda(t)$ is available in a suitable form considering the aging behavior of the collective. If this is not given, it is useful to use values for the mean value μ and standard deviation σ of the default behavior which are derived from the own experience or appropriate literature, as given in Table 2.17.

The estimation on the basis of age-related limits represents in every case an upper and lower limits on the number of assets, which have to be exchanged, so this procedure can be used as a rough approximation.

2.1.9 Short- and Long-Term Considerations

A fundamental result of renewal strategy is the average annual funding requirement: the renewal budget. The choice of the observation period is of great importance. Usually, in the event of infrastructure systems with lifetimes between 30 and 70 years, it cannot be spoken of a strategy as such, if an analysis is determined regarding the need for renewal in the coming 1–5 years. On the other hand, a larger observation period of more than 25 years has to be questioned, as the criteria underlying an investment cycle cannot be predicted and the considered strategy will not be implemented with high probability. In addition, the inclusion of assets, which are to be exchanged later than 25 years after the time of analysis, falsifies the awareness for the measures in the previous renewal periods.

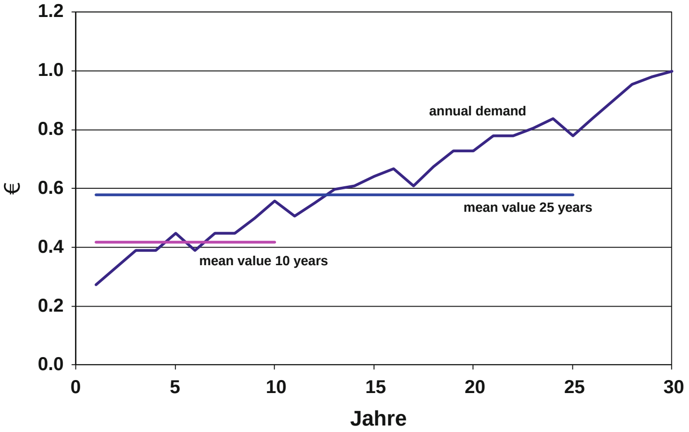


Fig. 2.49 Determination of renewal volumes depending on the period under consideration

A time range between 10 and 25 years appears to represent a reasonable value, depending on the infrastructure system size, in which the underlying investment cycles of the system are of great importance in choosing the given period. By identifying the financial needs of the yearly renewal, which is above the average of the given period, the range exists in the first years of the period to do something more than necessary, but to achieve an equalization of expenses over the entire period. An observation period, which is too large, leads to significantly elevated initial expenses, in the opposite a reduced time range leaves no space for regulation, as shown in Fig. 2.49.

Basically, a renewal strategy should be triggered either due to technological or due to political changes or be checked after shorter time intervals (5–7 years) and adjusted, if necessary. This means that an examination is performed for a new analysis period and to define a new annual budget for equipment renewals.

2.1.10 Project Development and Assignment

The asset management is not only responsible for strategies, but also includes the identification of business needs, construction projects, and the assignment of service areas or service management companies to handle the processing of these activities and projects. In this context, asset management is based on the information arising from inspection and service, which are stored in the information systems and databases. These systems and databases are described in more detail in Chap. 5.

The project development and commissioning is subjected to a defined process flow which is divided into the following sub-steps:

- Project identification:
  To identify necessary performance contents and individual projects from various project events (renewal, extension, faults, causing others) and to place in the overall context of the infrastructure.
- Analysis of variants:
  To define possible solutions of the problem and to evaluate corresponding variants.
- Preparation of specification:
  To identify the variants with the best solution spaces and to describe a concept with a sufficient accuracy for the project planning and calculation.
- Compilation of specification:
  Rough planning and costing of alternative solutions for decision regarding the intensity of labor concerning the corresponding design parameters (technology, costs, time).
- Economic considerations, if applicable optimization:
  To check the solution strategy for conformity and compliance with the specifications estimated resp. with the budget during the planning phase may be another variant discussion.
- Assignment and allocation of financial resources:
  Providing the funds, which are fixed by the specification for different solutions, and written assignment of the implementation.

There is a transition of responsibilities in the overall organization of asset management and service provider, particularly in the preparation of the functional specification. This will be taken over by the executed service department if necessary from service providing market companies (service provider, Sect. 1.5), as the operational implementation is described with the appropriate conditions, such as technology, performance, time required, and costs. Consequently, during the next step, the asset management is able to conduct an assessment of variants including economic calculation. On this basis, a decision is carried out for the commission together with the allocation of funding (project budget).

In this context, the principle is applied “no performance without commissioning and funding” and thus, the responsibility of the asset manager is clearly expressed. If he does not order and not explain the cost takeover, the service department or the service company will not be active and will not provide the service.

However, a project contract is not always actually meant, and there are multiple forms of commissioning from a framework agreement (e.g., in the periodic maintenance area) via a ground-level agreements (e.g., ensuring the documentation) through to specific individual activities and planned projects (construction of a concrete line or system connection). But all contracts follow the above steps and have to be based on written agreements, which should be able to stand up in court, due to the security organization. The scope, quality, and costs of a service have to be described, and a clean transition from the asset management to the service provider has to be defined.

2.2 Developing and Securing of Standards

The basis for a legal asset management without actual faults of the organization is based on accepted standards. These are developed on the one hand by external expert committees, which are organized in technical associations. On the other hand, they have also to be adapted to the specific requirements of each of the considered infrastructure system and thus have to be formed into an internal set of rules. The expertise of the guidelines is provided by the asset management which has the authority to interpret the external regulations, but also the responsibility to perform the internal legislation comprehensively, to maintain and to provide the publication.

2.2.1 Intern Regulations

Comprehensive internal regulations in various areas are required for the organization, operation, construction, and the establishment of infrastructure systems. This framework must be accessible for the relevant departments, and the reflection has to be guaranteed in line with the official norms and standards described in the next paragraph. In contrast to this, the internal rules may be formulated not necessarily neutrally, but they are certainly related to the asset management strategies and the selected technology (which may well lead to restrictions in case of installation). However, it is important that all aspects are covered and the comprehensiveness and completeness can be proved by certification procedures. The main areas to be covered are:

- Operation of infrastructure:
  Certified maintenance strategy (activities and cycles), e.g., according to Technical Safety Management (TSM) of FNN resp. DVGW.
- Environment:
  In general, an environmental manual for compliance with the regulations of environmental protection act and certifiable according to DIN 14001.
- Work safety:
  Specifications for compliance with the accident prevention regulations and the trade association rules, certifiable by TSM, or by the professional associations themselves.
- Material manuals:
  Catalogs of approved materials of the specific companies to standardize the technology and limitation of material variants (company-specific and not certified).

- Specification for construction and erection:
  Definition of company-specific requirements for equipment and construction projects, usually as a basis for pre-qualification of manufacturers/suppliers declaration of investment goods and service providers, which carry out the projects.
- Catastrophes and emergency management:
  Requirements for the secure flow of necessary processes and the elimination of catastrophes or emergency situation, involving the infrastructure system to be considered.

An infrastructure company organizes its security procedures and processes by a closed internal legislation. Thereby the asset management has not in all areas the leading role, but the total coverage of rules will also ensure that the tasks can be fulfilled. In many cases, the policy competence (ratification and entry into force) or at least cooperation and approval of these departments are required.

2.2.2 National and International Standardization Processes

The basis for the selection of different assets and the design of plants of infrastructure systems are the standardization by various standards. These are so-called product standards on the one hand and construction standards on the other. The core task of the norms that may apply worldwide is to ensure the quality of the product and its safety during operational use, and the characteristic of a norm is usually the long-term validity. This is due to the fact that depending on different decision-making structures, several years pass away, starting from the first description of the contents of the standard to the final publication (e.g., 5 years for the development of the standard, publishing and possibly arbitration and mediation, and finally the validity). In this context, the problem of the discussion should be mentioned about the “safety of the stock.” This means that the construction of a plant or the production of equipment was carried according to the standards valid at the time of construction or production. But, as infrastructure systems usually have a long life and quite new versions and revisions of the standard may occur within this extended period, the question arises whether the systems and equipment must always comply with the latest standard, or is it sufficient, to meet the standard at the time of the erection. A final legal certainty on this issue does not exist with the question, how a complete infrastructure system in case of a new standard version can be converted to the new conditions. If safety concerns play a role in the modification of the existing standard, appropriate measures have to be taken into account of these concerns by the asset management through an appropriate temporal transition period without to rely on the “safety of the stock.” However, more difficult is the discussion in case of the introduction of new calculation methods or additional reserves that are not applicable to the previously established technology. The asset management should have the authority to interpret the agreement with the relevant regulators to ensure a fair and safe continued operation of existing plants.

When developing a standard, all professional concerned circles of experts (e.g., utilities, manufacturers, service providers, government, and universities) should be involved, in this case the cooperation is always voluntary in the expert committees.

Basis for the application of rules and regulations, e.g., in the electricity and gas networks, provides the Energy Act [57], and the requirements for power installations are described by the so-called presumption rule in § 49:

- § 49: Requirements for energy installations

  1. Energy installations shall be constructed and operated that technical security is ensured. In this case, subject to other laws, the generally accepted rules of technology are to be considered.
  2. Compliance with the generally accepted rules of technology is thought, if in case of installations for the generation, transmission, and distribution
     (a) Electricity: The technical rules of the Association for Electrical, Electronic & Information Technologies (VDE)
     (b) Gas: The technical rules of the German Gas and Water Association
     must be observed.

The best-known standards outside of the electricity and gas networks are the German Industrial Standards DIN, which also regulate many other areas, but the example of structures and thus also in infrastructure systems may be relevant.

The main advantage of international standards is the ability to advertise the proposed procurement worldwide, so that the number of potential providers should increase, which manufacture their products under the same conditions.

In addition to the construction and product standards, the issue of operation of infrastructure systems is more and more in the focus of standardization and regulation, in particular with the certification of safety and quality requirements in this area. One of the first organizations engaged in this field was the British Standards Institution (BSI), which met the first requirements for asset management in terms of network in 2004 with the "Public Available Standard PAS 55." A revision of these documents took place in 2008 [44, 45]. A standard is developed at the international level (ISO: International Organization for Standardization), which deals with the topic of "Asset Management." Since January/March 2014, the final editions were published and the following parts are available [35]

- ISO 55000:2014-01/03: Asset management—Overview, principles and terminology
- ISO 55001:2014-01: Asset management—Management systems—Requirements
- ISO 55002:2014/01: Asset management—Management systems—Guidelines for the application of ISO 55001

The ISO standards 55000/55001/55002 describe the generic procedure to conduct the asset management independently of types of assets and application (industries, organizations, etc.).

In Germany, the establishment of standards and operating rules and instructions for use in the power grid was institutionalized by the foundation of the expert Forum Network Technology and Network Operation (FNN) by the VDE in the year 2008. The resulting rules are almost legally binding by the above-described “presumption” rule in § 49 of the Energy Act. Such an official organization, so to speak, which creates a set of rules in network operation as a legal framework, has currently in Europe a unique position.

2.2.3 Standard for Maintenance of Electrical Systems

Before the foundation of the FNN, the following standards of DIN and VDE are developed within the DKE organization (German Commission for Electrical, Electronic & Information Technologies), which cover the maintenance of installations and equipment in transmission and distribution networks of electricity supply at all voltage levels and therefore cover the title of § 49 Energy Act:

- DIN V VDE V 0109-1 (VDE V 0109-1): 2014-09 Maintenance of installations and equipment of electrical energy supply networks—part 1: System aspects and procedures [27]
- DIN V VDE V 0109-2 (VDE V 0109-2): 2014-09 Maintenance of installations and equipment of electrical energy supply network—part 2: Determination of the condition of equipment/installations [28]

The above-mentioned standards are considered as “pre-standard” because there is no parent IEC or CENELEC standard. If such VDE regulations are developed according to [54] as VDE pre-standards and there are no substantive reservations against them, they can gain the status “general accepted rules of technology” like the normal VDE standards. This has been followed in the preparation of this pre-standard.

When developing the DIN standard mentioned above, the starting point was according to the Energy Act, and the purpose of a power supply company is a secure, cost-effective, consumer-friendly, efficient, and environmentally sustainable supply of electricity (Sect. 1.1). The security of a network generally depends on various parameters, such as:

- Network structure,
- Maintenance,
- New investment,
- Spare parts of assets, and
- Number and know-how of the staff.
- …

This means that the issue of maintenance is only one possibility to ensure the security of supply and this has the consequence that in a private organized energy supply market, the selection of various options to fulfill the supply contract should be the decision of any company.

In contrast, the restoration or the solution of a singular problem cannot be the target of a standard, but it is possible that these problems should be clarified with the help of single, specifically tailored maintenance measures between the partners involved. Thus, it has been the goal of the elaborated standard to cover the following steps and the two sub-standards reflect these steps:

- Description of maintenance strategies and processes, documentation and
- Possibilities of condition assessment of assets.

According to Sect. 2.1.1.1, the maintenance activities include the following subtasks: Inspection–service–repair–improvement, wherein the inspection describes the measures taken to identify and assess the current condition of a maintenance object. The inspection can be organized in the following subtasks, which are defined in Sect. 2.1.1.1:

1. Site inspection,
2. Visual inspection,
3. Function control (functional test),
4. Condition determination, and
5. Condition assessment.

While the VDE standard makes a statement to the points 1–4, which is described by the expression "condition determination," the question regarding the condition assessment of equipment remains unanswered. The reason is, as explained earlier, the condition assessment belongs to the responsibility of the company and should not be defined by a standard. The contents of the two standards can be described as follows:

Part 1: System aspects and procedures

The requirements for a standard that describes essential work processes should comply with the following specifications:

- The basic responsibilities of a network operator shall not be affected by the pre-standard.
- Definitions should be equally feasible for all companies.
- The process is divided into eight steps.
- The implementation of the draft standard should be detectable for a company and possibly certifiable.

The essential part of this standard is to define the process that can be divided into various system steps that are listed in Table 2.24.

Table 2.24 Workflow of the maintenance process according [27]

System step	Result
1. Constitution of responsibility and principles	Basic rules, e.g., in form of a guideline
2. Development of maintenance concept	Maintenance concept and basic structure of the documentation
3. Development of the maintenance plan	Maintenance plan
4. Preparation of the maintenance measures	Operation schedule (date, location, resources)
5. Execution of the maintenance measures	Maintenance object is maintained
6. Documentation of the results	Documentation of every maintenance object
7. Evaluation of the results	Updating of the maintenance plan
8. Assessment and improvement	Further development of the maintenance concept

Finally, the main steps and their results are to be documented so that individual decisions can be traced. The maintenance documentation should include at least the following statements:

- Principles of maintenance strategy,
- Catalog of maintenance support,
- Maintenance concept,
- Catalog of maintenance plan,
- Benchmark criteria for the condition of installations and equipment,
- Description of maintenance tasks for every type of object,
- Stock of installations and assets,
- Catalog of implemented maintenance measures,
- Inspection reports, detected minor and major failures and damages,
- Quality requirements of the staff, and
- Training certificate.

Part 2: Determination of the condition of equipment/installations

The second part of the pre-standard is used to support the asset manager to derive a maintenance concept (system step 2 of Table 2.24), because a condition assessment of the assets has to be performed. A catalog is presented for different pieces of equipment to determine the technical condition, which should be supplemented by the asset manager, if necessary. The maintenance activities (e.g., replacement, repair, service, etc.) which have to be derived by the condition determination are not defined by this pre-standard, but this is the responsibility of the asset manager.

The condition determination is performed by site and visual inspection, function control, and measurement. In general, the condition of equipment/installation also depends on the location, the technology, and the production, so that these constraints have to be observed. For this reason, manufacturers' recommendations and operational experience of the user should be additionally considered. This has the consequence that cycles are not part of the norm, but are covered by the responsibility of the asset manager.

As an example, Table 2.25 shows an overview, how the selection catalog of different components is designed. Starting from the component, the criteria are defined, which condition can be determined by a certain measure. If necessary, additional information is listed, e.g., further DKE and IEC regulations.

In summary, it can be said that the requirements of the Energy Act § 49 are met by this pre-standard 0109.

2.3 Securing the Resources

The development of strategies and the identification of the need for action and possible solutions are the higher level tasks of the asset management. Therewith, the proper function of the infrastructure system resp. the secure and stable operation is not guaranteed. For this purpose, also the calculation of necessary funds is required, usually based on fiscal year periods and medium-term planning periods, as well as ensuring the necessary resources for operations. The intensity of the asset management, which is hereby employed directly, varies depending on the organization model starting from pure assignment (general contractor) of a relevant service area up to the selection and allocation of tasks to different internal and external service partners (Sect. 1.5). This will be intensively discussed in Chap. 4. However, securing the resources is an existential part of the management, as the function and the operation are not alone guaranteed by strategies and funding. Figure 2.50 represents the main tasks of the asset management with regard to the implementation of operational strategies.

2.3.1 Material and Service

A variety of materials and resources is required for normal operation, construction, and development activities, which take place within the projects. This splits into consumption items on the one hand and wear materials and construction materials, resources, and equipment sets (accessories, junction equipment, etc.) on the other hand. The first part is usually organized directly by the operating personnel, and the supply for this purpose is ensured, in which a general release and approval is also required in accordance with the internal rules (e.g., cleaner, which is approved only for certain defined surfaces).

However, of greater importance are building materials, equipment, and fittings that have a significant impact on the operability, durability, and the costs (total costs of

Table 2.25 Condition assessments of circuit-breakers, live parts [28], and extract

Component	Criteria	Measure	Additional information
Porcelain (arcing chamber), cement, flange, terminations, pole column (air-insulated substation)	Pollution, damage	Visual inspection	
Flange joints (outdoor circuit-breaker)	Corrosion (not flange corrosion)	Visual inspection	
Contacts	Contact resistance	Resistance measurement	
Arcing chamber	Clearing time, switching speed	Measurement of travel-time, measurement switching time	
Insulating and extinguishing medium	Pressure, density, humidity, dissociation products, filling level, breakdown voltage	Visual inspection, measurement	IEC/TR 62271-303
Embedding pole parts (vacuum circuit-breaker, withdrawable switch)	Crack formation	Visual inspection	
Circuit-breaker (general)	Number of switching cycles	Visual inspection	
Moving parts	Deterioration contact system	Visual inspection	

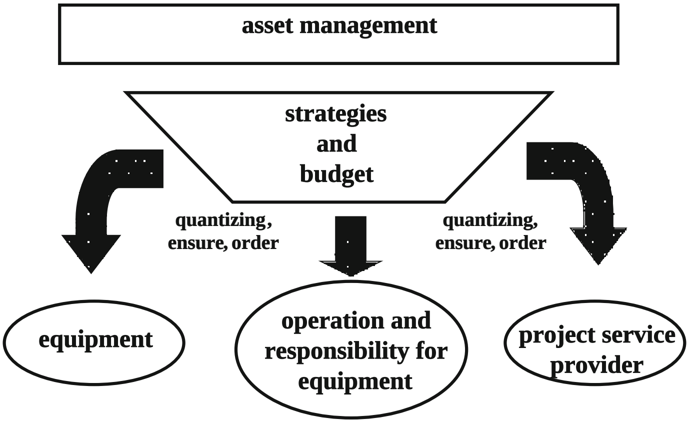


Fig. 2.50 Implementation of operational strategies

ownership TCO, Sect. 3.1.3) within an infrastructure system. The material manuals of various segments are included in the internal regulations that include a detailed description of the approved materials and it is noted, after which test specifications and certificates of the appropriate materials are approved for installations in the infrastructure system. In addition to the types of materials, it may be that not only functions and material properties, but also defined products and models are prescribed for use in individual areas. In this context, it must also be ensured for the technical realization that not only a description of the materials are available, but also a source exists of the procurement market that covers the demand for these materials. For example, if a gas network operator prescribes the component pressure regulator with defined properties for its network, but this component is discontinued by the manufacturer and is no longer available, the asset manager must find a possible solution. This may be due to a change in the strategy that such pressure reducer (if not legally and normatively prescribed) will in future no longer be installed and not be replaced. It can also be the identification of additional suppliers for the approved component or a change in the approved parameters, to bring in use a follow-up technology or other suppliers.

The basic message is, however, that the approval of material itself is a strategic task in terms of technical asset management, which includes responsibility for ensuring the availability of market sources for the approved materials in addition to the compilation, maintenance, and release of material handbooks. In general, the procurement itself takes place by support departments, such as purchasing departments or operational service departments, but this must comply with the material specifications and manuals.

In detail, the investment goods have to be considered which need special explanations (such as circuit-breakers, high-voltage cables, high-pressure pumps). In this segment, there are not only precise specifications and descriptions of the usability available, but usually the manufactures are technically pre-qualified by the company, which is responsible for the procurement, and the manufacturers are approved only after a defined process to deliver. Again, care must be taken that in the context of these processes, sufficient suppliers have to pass through the pre-qualification process not only to ensure, on the one hand, the supply of such investment goods, but on the other hand also to build a market for these goods in order to create the right incentives for competition and innovation. For this purpose, the asset management, together with purchasing and operational service experts, set up a process that leads via specifications to a supplier strategy for product groups, thus ensuring the long-term availability of the necessary technology and capital goods.

Similar to material and equipment, ensuring the availability of service personnel is of great importance and the intensity of labor has particularly to be considered inside an organization. If a service department can fully provide all services and activities, the asset management has achieved his target, because the service department can directly assigned. In general, however, large proportions of service management activities are provided by third parties, and they are directly assigned either by the asset management or by the service department. In this case, a short-term assurance of service capacity is required to ensure future activities, and at least, a mid-market monitoring for the development of the service capacity is necessary.

Service companies have usually a limited economic geographical working radius (travel and organization costs compared to actual activity), and therefore, this analysis has to be conducted on infrastructure territorial level to have access to the corresponding capacity in the medium term with acceptable costs. This part is also ultimately a policy-oriented task of the technical asset management to ensure the implementation of defined activities and projects and thus the sustainable operation and preservation of the infrastructure system.

2.3.2 Operating Staff

The operation of infrastructure systems must always be ensured, and usually, an operating organization is responsible for this charge. The operation is directly linked to compliance with standards and regulations, and thus, a particular qualification and training of personnel is needed. Responsible personnel operating in the electricity and gas network, which carries out the so-called investment responsibilities, is performed, e.g., by so-called professional managers who must provide a certificate of the responsible activity in this network segment for several years for this function. For this reason, there is no real competitive market for the management staff and usually, the human resource capacities for infrastructure operators are directly employed by the companies. If, in a particular case, the management assigned another infrastructure company, this service provider belongs to the same branch, as the barrier to market entry for “free” service companies with this (certainly justified) boundary condition is too high.

In the role of the client for the network operation, the asset management has the responsibility to ensure that the capacity and competence of the authorized operating department are sufficient to perform sustainably and completely the tasks defined concerning the network operating.

2.3.3 Reserve and Special Situations

Disturbances, so-called emergency or disaster situations, are special cases within the operation of infrastructure systems. As the dimensions of an infrastructure system may not be economically designed for all eventualities, it will come to shortages and interruptions of the usability of the systems in case of fault situations. Due to the outages of high-quality and complex components, the restoration will take a long time, so that operational concepts for the personnel capacity as well as reserve and fault-clearing materials for special constructions should be provided for the temporary restoration regarding the usability of the system. The sufficient size of these materials and structures is again a task of the asset management, as on the one hand, the quality of the system (resupply, interruption time, etc.) as well as the used costs for the organization and provision—as part of the business and technical concepts of the infrastructure system—has to be considered. For example, the probability of a (non-short serviceable) line failure has to be defined in consideration of the structure of a high-voltage network. In this case, the situation should be controlled by spare parts of special emergency cables and leverage systems in a suitable time and it has to be considered which personnel (own or external) and the reaction time is able to handle the situation. This aspect of network operation should not be underestimated by the asset management, as these concepts are rarely used and are therefore often neglected.

2.4 Conclusion

This section describes the various fundamentals, based on which the asset manager can solve his tasks. Firstly, a key factor is the representation of the different maintenance strategies, which are used depending on the different equipment groups. In recent years, the RCM is increasingly being used, which allows a prioritization of maintenance activities depending on the condition and the importance of equipment for the entire system. Moreover, the application of fuzzy logic and the use of the “FMEA” are the tools for identifying appropriate maintenance measures. Here, the collection of fault data and their preparation is essential to carry out optimal maintenance of equipment.

Since the assets of infrastructure systems are characterized by a long life, long-term strategies are essential to carry out renewals. In principle, statistical values on the aging behavior of network components can be accepted as reference values to determine the renewals as required in different years as budget value. In addition, the future network development has to be considered in the renewal strategies, and for this purpose, different planning principles have to be defined. The aim of these considerations is to make optimal use of the personnel and the financial resources of a company. These planning principles are to be modified in the field of electrical power due to the decentralized and volatile feed in by renewable energy sources (wind, solar), since a unique load flow is no longer common as in the past. Partly, more renewable energy is fed into downstream voltage levels compared to the consumption, so that a reverse power flow to the upstream voltage levels takes place. The consequence is a change of the electrical boundary conditions for dimensioning. This does require the adoption of different load scenarios in order to prevent overloading of the network components.

Basically, the relevant national and international standards have to be taken into consideration in the performance of the maintenance activity. In recent years, the newly established standard DIN V VDE 0109 (German Standard) is available, in which the various work steps are defined in the derivation of a maintenance strategy, which have to be documented.

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Control Functions

3

Asset management means to develop strategies built on assured knowledge which is generally formulated and defined on valid norms and rules by experts. But additionally the task of implementing these strategies is given as part of a commissioning process and role model (see also Chap. 4), and each implementation must be controlled accordingly. Therefore, the asset management requires appropriate control functions to initiate the implementation of strategies and to measure the success and if required appropriate strategy corrections are implemented. Only with such functions, the achievement of tasks of the asset management can be ensured. Also, the early assessment of the impact of policies through operational experience, simulation, or statistical analysis in this context is an essential basic control function. The various topics are described and analyzed in this chapter in more detail.

3.1 Economic Control Functions

Every company follows a business purpose and is therefore also measured on earnings from operations based on its reciprocal, such a company can continue to operate only with an adequate financial result, so the control of economic variables is essential. In case of an infrastructure company, the use of financial resources is of fundamental importance for the result of the company due to the implemented strategies and must be controlled. So this view also applies to the technical asset management.

The total volume of capital, which is available to the asset management, is usually scheduled, provided, and controlled in a so-called budget. There are, depending on the structure and philosophy of the company and the IT system used for the planning of financial results, different characteristics in the preparation and organization. The clearness of the budget and objectives still remains a fundamental condition for all variations, to use

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exactly this budget for the tasks. Due to the complexity of the task and the duty to report to the owner, the supervisory authority and also according to the regulation, a distinct “enterprise resource planning” (ERP see also Sect. 5.2) is generally used in today’s infrastructure companies, which automatically provides the system-side tools for planning and control.

3.1.1 Budget Planning and Structure

The budget includes the entity of the available financial resources for the tasks of the asset management. The demand for the budget comes from two directions. On the one hand, there is a long-term view with appropriate boundary conditions, in which total financial resource is annually required to meet the processes, projects, and activities from the management of the network, so that the specified objectives of the client are achieved. This value can be represented or developed, for example, by long-term simulations (see also Sect. 3.4). The other direction is roughly determined by what level the asset owner is able to generate revenues in its task to refinance the infrastructure system and thus the asset manager can provide the interest payment after deduction of its costs. The merging of these two directions is usually carried out by the definition of the boundary conditions and by the consideration of long-term needs. In conclusion, this ultimately leads to a certain value that is available each fiscal year during the planning period and which can thus be scheduled accordingly.

The next step is the process of budget planning, which requires a certain handling time due to the long-term nature of the business processes. An example of the sequence of such a planning process is shown in Fig. 3.1. The process starts around 15 months before the scheduled money can officially be put into action. At the end of the process, a coordinated budget of particular segments is the basis for all operational activities.

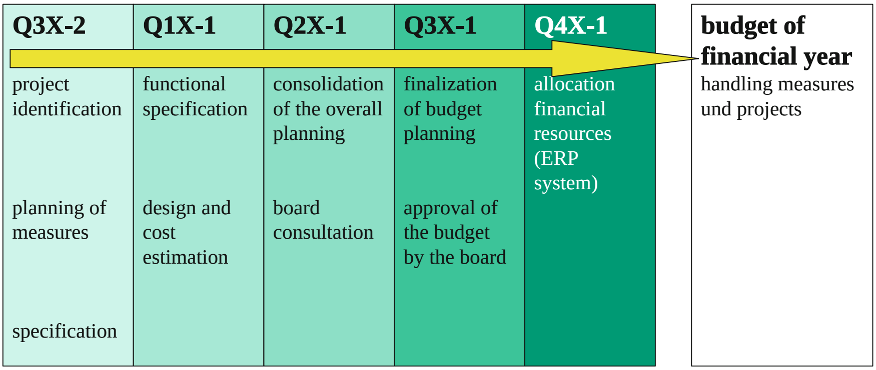


Fig. 3.1 Budget planning process of an infrastructure company

The effective funds during the planning stage can be classified into three areas depending on their effect on the company's results:

- Investment
  Expenditures for buildings or equipment, which are understood as an extension or exchange of capital assets and have to be activated by the accounting department in every case. These expenses appear in the company's results on the so-called amortization period with the percentage which is scheduled by the depreciation. This area is also known as capital expenditure (CAPEX) (see Sect. 3.4.3).
- Operating costs
  Expenses for ordinary operating activities, outages, repairs, etc., as well as the exchange of such pieces of equipment that are not considered as separate capital assets. This capital does not lead to an activation of accounting but acts as a reduction of the financial result with a value of 100 %. This area is also known as operational expenditure (OPEX) (see also Sect. 3.4.3).
- Depreciation of expenses (AfA)
  The so-called depreciation (AfA) is the sum of the annual depreciation related to the year in question depending on the previous investments over the amortization period. The depreciation reduces also the earnings to 100 %. The characteristic of depreciation is that it cannot be influenced in the normal case, i.e., the purchase price and the depreciation period are fixed and thus the annual costs of depreciation per capital assets.

Due to the uncontrollable nature of the depreciation, this is not relevant in the budget planning of investment management and thus will not be considered further. In consequence, the budget and its planning can be split in the first step into two main segments of investment ("Invest") and operating expenses ("Expense"). The assignment to the respective cost pools is not arbitrary, but will automatically be provided at the end of the planning. This is defined by the accounting rules of the infrastructure company, which lead to a certain space within the legal instructions.

The planning itself is determined by two basic cases, which also define the structure of the budget and have a significant influence on the control described in Sect. 3.1.2. These basic cases are defined by the character of projectability on the one hand and on the other hand by the forecast. As the asset manager arranges the planning on its developed strategies such as renewal and network development, so the projectable part will find its basis and the measures are derived from this. The not projectable and thus to be predicted part needs other sources to verify the funds and to create a stable and realistic basis for a budget plan.

The two segments and the planning cases in Fig. 3.2 are the basic elements for all budget planning and thus constitute the general basis.

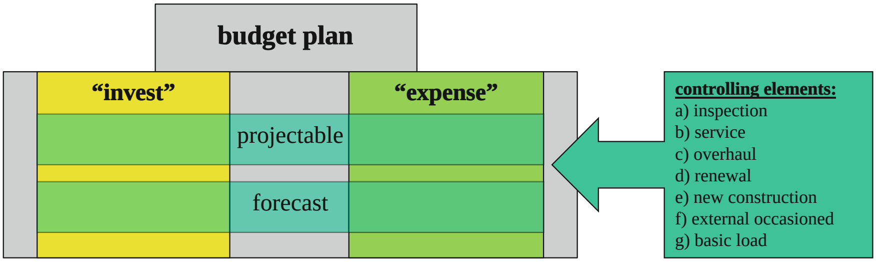


Fig. 3.2 Basic of budget planning with exemplary planning structure

Starting from this basis, it is useful for the handling and also for the creation of groups to divide the budget planning into so-called budget or controlling elements. For such a subdivision, there are no generally accepted nomenclature and definitions as this depends particularly on the company and partially on the division. In the following, an example is shown for such a planning structure and how it can be applied to infrastructure companies, as shown in Table 3.1.

As any classification, there are special cases and border areas that need to be decided in each case according to the assignment, but the identified structure allows the mapping of all transactions in the asset management regarding the budget.

- Inspection
  Equipment and installations have to be inspected regularly. The cycles and activities for each segment will be fixed and commissioned within the maintenance strategy as described in Sect. 2.1. As part of the budget planning, these are evaluated and presented by the entire quantity structure of the system infrastructure with hours and finally with the financial funding. Due to this derivation, the inspection is a fully schedulable controlling element in the budget planning. The inspection is purely a maintenance activity and has not to be capitalized. Therefore, only "expense" funds are planned in this element.

Table 3.1 Example of a planning structure

Element	Attribute			
	Expense	Invest	Projectable	Forecast
Inspection	Yes	No	Yes	No
Service	Yes	No	Yes	No
Overhaul	Yes	No	No/partly	Yes
Renewal	Partly	Partly	Yes	Partly
New construction	No	Yes	Partly	Partly
External occasioned	Partly	Partly	No	Yes
Basic load	Yes	No	No	Yes

Activities of the inspection are, for example, site inspections, condition determination by checklists, control of the oil level, simple function tests.

- Service

  The argumentation for the maintenance activity arises from two sources, on the one hand, the requirements of the manufacturer, and on the other hand, the knowledge and experience of the infrastructure manager regarding the necessary activities of inspection and years of use. The service is also defined by necessary activities and implementing indications during the maintenance strategy and is therefore completely predictable just as the inspection. Short-term and unplanned service is extremely seldom in such a system of predictive and controlled maintenance under the direction of the asset manager and is therefore neglected in the planning stage. The service does comparable to inspections not include investing parts and thereby only "expense" is scheduled in this controlling element.

  Activities of the service are, e.g., replacement of wearing parts, maintenance of the vegetation in the vicinity of plants and lines, checking and lubricating of moving parts, oil fuel or oil change, cleaning of filters and pumps, renewal of the corrosion protection.

- Overhaul

  As outages and damages occur in any infrastructure system with a larger quantity structure and a homogeneous age structure, appropriate funds must be provided for this segment. But due to the fact that finally neither fault locations nor assets, which have to be repaired, are known at the time of budget planning, these are usually unplanned activities. However, there is a gray zone in the segment on the one hand for minor damages, which do not prevent the operation of the equipment, and on the other hand, in principle, very complex repairs resp. long delivery times of necessary spare parts. This gray zone can also belong to the predictable expenses due to the long duration of the repair. This is the reason that additional "partly" is listed in Table 3.1 for the planning of this segment. The damage would remain in the meantime and be mitigated by a provisional generic solution. For this reason, the total budget for this element is part of funds for known damages that are fixed on an orderly repair plan, and on the other hand, are based on predicted part due to the experience. The forecast is usually determined by the outage occurrences due the various asset classes and resources of the infrastructure system and the financial fund that was spent in the previous 3–5 years. It is clear, that in case of the forecast, a historiography and documentation of outages and damages, including the business data, are of major importance for a good future planning of the investment management.

  Another feature of the overhaul is that it can sometimes lead to an unplanned renewal. This fact has to be considered in the segments managing and controlling described in Sect. 3.1.2, since it has implications for the "plan–actual check-up."

  The forecast has to be realistically performed even in case of a tight budget, since the overhaul has to be implemented by force and an "optimization" of the budget regarding a defined upper limit will not be successful in terms of budget compliance by reduction of the position “overhaul” due to unrealistic forecast.

Examples of overhaul activities are repairing the joints of power cables, replacement of defective insulators, refinishing the coating of gas pipes in case of damages, replace defective fuses, waterproofing of roofs of buildings, rewinding of large power transformers at the factory, rebuilding of damaged cable distribution board, etc.

- Renewal

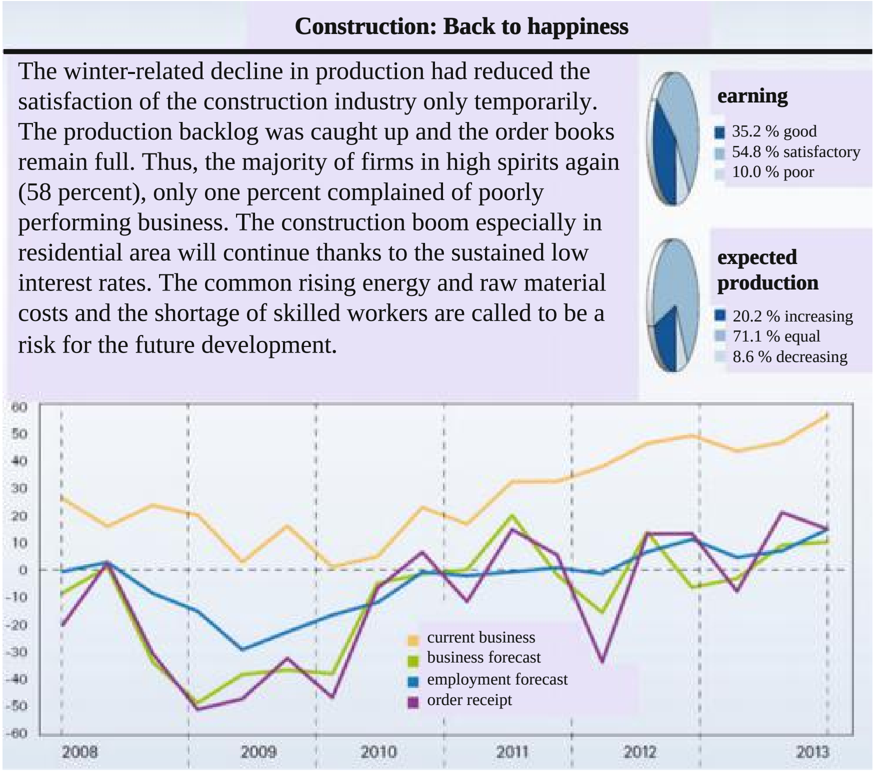
  Another strategy in investment management is the renewal strategy. In general, there are historical investment cycles of assets in infrastructure systems. Even on long-lived capital assets, which the components of electrical power systems belong to, there is the need for continuous renewal in order not to “live from the substance.” The asset manager analyzes the renewal requirements by applying appropriate tools and determines an appropriate annual quantity structure, which is available in various asset classes and components for renewal. This quantity structure results into the corresponding budget plan for renewal, which is weighted by the specific daily value as new. It is clear from this derivation that the renewal budget is completely predictable. There is fact that according to accounting rules in different companies, renewal activities are capitalized as completed assets. The ratio of “expense” and “invest” is determined by the company-specific rules. But it is certain that both areas will always be in renewal budget.

  Examples of renewal activities are the replacement of power transformers, the same construction of a substation, cabling of an overhead line, the exchange of secondary technology by a new generation of IT, the exchange of short pipe sections due leaks.

- New construction

  Infrastructure systems always follow the expansion of the needs of their customers in terms of growth or change. If growth takes place, but also, for example, closure of industrial sites and possibly concentration elsewhere, this leads to network expansion or changes in the target network analysis. This new construction is justified in two areas: On the one hand by the slow growth on the customer side, which leads to sudden investments to expand the capacity of the system after the achievement of the power capacity limits. On the other hand, measures regarding the expansion and new construction of new infrastructure components will be derived by externally initiated specific projects.

  The first part is well-founded in a long-term development of the system itself and thus in the long term to be scheduled regarding the budget of the asset manager. The second part is induced on the other hand usually from the outside. This can even happen for a short term, in fact a larger part of the new constructions is concretized by external factors for periods which do not allow a particular consideration in the budget planning process. This part can only be determined for the budget by a forecast. The basis for forecasting is, e.g., public information such as business climate, contracting in the construction industry (e.g., Fig. 3.3) as well as direct contacts with local building authorities and industrial customers, which can be used by the asset manager.



Construction: Back to happiness

The winter-related decline in production had reduced the satisfaction of the construction industry only temporarily. The production backlog was caught up and the order books remain full. Thus, the majority of firms in high spirits again (58 percent), only one percent complained of poorly performing business. The construction boom especially in residential area will continue thanks to the sustained low interest rates. The common rising energy and raw material costs and the shortage of skilled workers are called to be a risk for the future development.

Fig. 3.3 Business development of the construction industry in the region of Baden-Württemberg [47]

Nevertheless, this part is specifically associated with a high uncertainty, because developments may well occur in the short term which are not influenced by the infrastructure company. Thus, large projects with appropriate budget funds may fail at the last minute due to the public resistance or a short-term government funding leads to a building boom in certain regions. Specifically, companies for the supply of electrical energy have no choice due to the statutory duty, but they have to implement a compulsory network development. Another forcible construction in large scale is given in this area by determinations made by the Renewable Energy Act (REA), with the duty to connect the customers and to expand the system by the system operator. In case of a significant additional financial demand, which is required by these effects, the control of the budget can reach their limits.

As new construction resp. network development may be, for example, the development of new residential areas with infrastructure, installation of a new power transformer due to the load growth, expansion of an industrial terminal in case of a production growth, laying a new gas pipeline to ensure the reliability of supply, grid reinforcements to connect distributed REA generating plants.

- External induced

  Infrastructure systems have many points of contact with customers, other infrastructure systems and public organization, such as local authorities, development agencies, etc. The plants and assets affect their construction projects resp. will be influenced by them. Depending on the type of influence, constitution of the contractual relationship or legal requirements, an infrastructure company needs to change, to remove or to secure temporarily its installations at request of third parties to allow the execution of the actions of these third parties. Regardless of whether the causer can be charged, which would be reflected by the revenue planning, which is not discussed here, such measures of the infrastructure company must also be considered in a budget planning so that appropriate funds are available for the execution. External projects will be registered at the infrastructure companies in a short term, so that these measures cannot be planned but must be predicted during the ordinary budget planning process. Although in addition to the experience of the past fiscal years, the basis is the same compared with the new construction, as furthermore the business climate of the economy has naturally an impact on the amount of third-party projects and thereby determines the emergence of measures initiated by the third parties. The implemented topics usually have "expense"-character but also can be of investing character, for example, if a transmission line is in conflict with a construction project and therefore a new cable connection has to be installed elsewhere. Other examples in this segment are the insulation of electrical service connections at roofs in case of private restoration, changing of lines in road construction, etc.
- Basic service

  In addition to particular measures and precisely identifiable projects, there are a range of activities that are of vital importance for the safe operation on the basis of standards, norms, and laws of infrastructure companies. These overall activities are referred to as basic service. They are not assigned to individual business results, but they present the basis of the regular operation. The scope, what is considered as a basic service in the budget planning, is dependent on the company's management philosophy and the underlying role model in the organization. But it always depends on the existing quantity structure of the system and also on the size of the existing business volume. As these conditions are known in the planning process in sufficient accuracy, the basic services can also be planned exactly.

  New capitalized added value is not created by the basic service, why this is mapped to 100 % in the "expense" area. An overview regarding the necessary expenses is not possible attributed to the asset management responsibility without the mapping of the basic load in the budget planning or at another suitable point.

  Examples of basic services are planning information in case of civil engineering, comments to inquiries from third parties, network planning without specific project, conducting of studies, etc.

A corresponding budget plan can be exemplarily set up with this model, which budgets the necessary funds as the basis of the operational activities, i.e., providing the implementation of the measures. In this context, not only the financial resources to order services from external companies are meant, but also the delivery of internal services are included, for example, charging the infrastructure company’s own employees. Against the background of Chap. 4, which describes the role model, the budget plan represents the financial resources, which are needed by the asset management. These resources are required to commission the asset service to ensure and to conduct all necessary measures, projects, and activities within a fiscal year in case of the operation of an infrastructure system.

3.1.2 Budget Controlling

By completing and delivering an approved budget before the beginning of the considering financial year as shown in Fig. 3.1, the asset management is in a position to conduct the commissioning of projects and activities of the relevant segments, which are covered by “controlling elements.” A part of the positions is planned on the basis of forecasts, as already described in case of the definition of the controlling elements. Furthermore, even exact project planning can be obsolete through influences from third parties or uncertainties during the process. To get an overview about such mechanisms and to be able to act at any time in the sense of responding to unexpected requirements, the management must develop and apply a system for controlling, which is the basis for tools to control the active budget. In case of the technical intensity of controlling, it has to be distinguished whether the budget is to be controlled as a whole or whether particular projects or segments should be observed during the assignment. Another definition, that has to be taken, is the frequency in which a controlling should be performed. These two boundary conditions, intensity, and frequency, are dependent on the philosophy of the company. They are determined by the defined objectives.

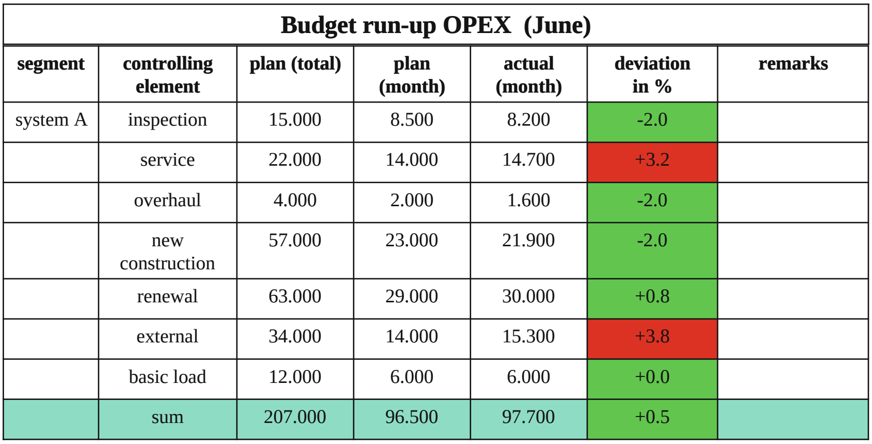
In general, these objectives and minimum achievement are determined by the fact that the asset management does not exceed the budget of the considered financial year, the thematic associated funds (e.g., construction, renovation) are used properly and thus the substance and operating ability of the infrastructure system is preserved as required in the planning. To achieve this rudimentary objective, the asset manager must only keep an eye on the cash outflows of the individual segments and must provide a sufficient safety margin to the total approved budget to cover safely unforeseen situations throughout the year, for example, in each quarter. Toward the end of the year, the probability of such unforeseen projects decreases due to the remaining time. The “normal” projects are forced to implement the planned amounts of renovation and to fulfill the strategy. Therefore, this well-known effect is called “end of the year rally.” Considering the budget utilization over the time, this control system performs a distinct buckle, the so-called hockey stick in the appropriate utilization chart, as a significant percentage of the annual budget is expended in the last weeks of the year. This is the simplest type of control and is still widely used. The resulting disadvantage—such as lacking continuity of processing, bottlenecks in the supply market, reduced reactivity, which are intensified by the fact that this control is also used by other involved partners in the process (e.g., local governments, authorities, local traffic)—require an optimization and also detailing of this process in order to meet the needs of a modern enterprise management system in the infrastructure sector.

Business planning process

The basis of the controlling consists of the plan described in the previous section. The review of the predictable expenditures of the non-projectable segments as well as the pursuit of the projectable projects and activities are regularly conducted in the existing planning intensity. A check of the run-up of budget must be planned over the year in order to submit a plan not only to the attainment of its end value. The run-up of the budget is controlled at each time for each forecast segment, every project, and every action by a plan value, which can be checked in a plan–actual comparison. Also the cycle of review follows the normally monthly cycle of corporate control, i.e., a monthly controlling report will be performed, covering at least the elements of the controlling. The sum of the particular run-up plans can be aggregated over the entire budget, a run-up for each total project and for each infrastructure elements arises gradually starting with the summary and finally the total value of OPEX and CAPEX. An example of such a total run-up curve and controlling of a possible monthly report is shown in Fig. 3.4.

The budget report gives an overview for the technical asset management system on the one hand, how the budget utilization evolves compared to the plan. In addition, the first-level indication will be received, which segments and controlling elements differ from the planning process. The level of detail regarding the key figures, that should be included in this report, depends on the goal of the budget control. Additional information can exemplarily be added as given in Fig. 3.4. The reduction of funds due to external and internal services, payments, commitments, revenue from third parties are just a few examples of additional indicators that can provide information for specific management issues. With this information, the asset manager has the ability to analyze the positions systematically and to determine causes for the plan–actual deviation up to the activity level. Controlling is needed in this context really as a basis for control. If the considered controlling level shows no deviations, the asset manager will not get further into the analysis as the plan–actual deviation is not relevant for the total controlling on the lower level. But, if particular elements and thus in consequence the total value leave the tolerance values of a monthly report, there is the possibility to check the corresponding values on a significant lower level. The possible causes of budget variances can be manifold, as shown below:

- Faulty planning or pricing of individual measures,
- increase of unpredictable projects,



Budget run-up OPEX (June)						
segment	**controlling element**	**plan (total)**	**plan (month)**	**actual (month)**	**deviation in %**	**remarks**
system A	inspection	15.000	8.500	8.200	-2.0	
	service	22.000	14.000	14.700	+3.2	
	overhaul	4.000	2.000	1.600	-2.0	
	new construction	57.000	23.000	21.900	-2.0	
	renewal	63.000	29.000	30.000	+0.8	
	external	34.000	14.000	15.300	+3.8	
	basic load	12.000	6.000	6.000	+0.0	
	sum	207.000	96.500	97.700	+0.5	

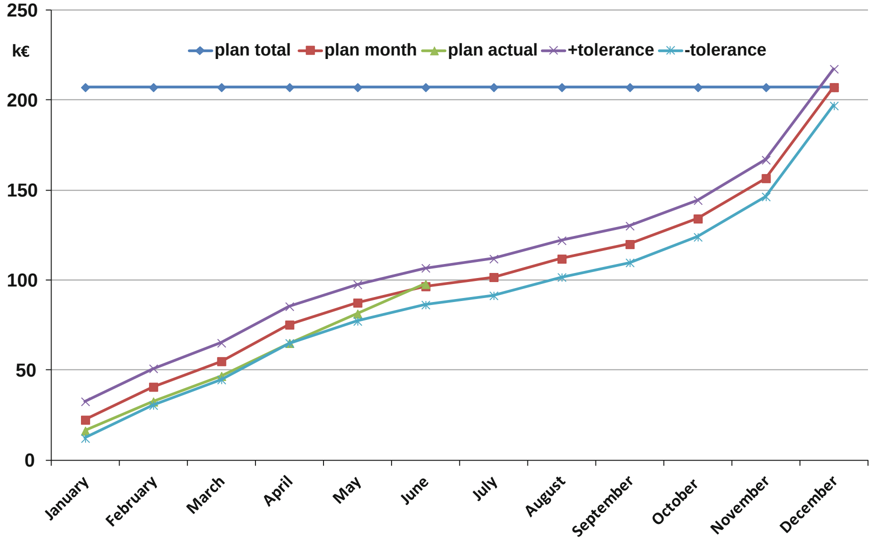


Fig. 3.4 Example for a run-up of the annual budget. a Representation tabular form (monthly). b Yearly representation

- time delay (e.g., building permission, weather),
- shortage in case of suppliers and service providers,
- forecast deviation (e.g., economic activity, commodity prices),
- occurrence of systematic errors.

Singular events, such as hurricanes, floods or other natural disasters, cannot be balanced by a control of budget and are therefore not included and not relevant in this consideration.

The effect can have an impact in the positive direction, that means too early or too high, or in the negative, and thus too late or too low regarding the utilization of the budget. Experiences show, however, that significant differences go rather into the negative direction, as delays occur more often than rapid project processes and more safety resp. unforeseen projects are taken into considerations in case of the project calculation.

Since the exact fulfillment of the plan is an ideal conception, the presence of the above-described deviation is the rule in reality the need to control is given for the asset management. Taking this into account, measures may be initiated, for example, to return budget values of the particular segments or in total to the tolerance band. It is assumed that the utilization of the total budget at the end of the year and also the compliance of the run-up during the yearly period are the premises which are to be met. The allocation of the liquid assets at the right time is an important factor for the financial control, and therefore, the second premise is of particular importance.

Various options are given for control that must appear in positive (accelerated) as well as in negative direction (decelerated) to enable the compliance of the premises. They can be classified into the following categories:

- time-varying measures,
- volume-varying measures,
- additional projects,
- alignment of the budget.

Considering the thematic composition of the budget regarding the controlling elements, the fewest positions are appropriate for the use of control measures. As shown in Fig. 3.5, some of these blocks are constant resp. are not influenceable. Rather controllable compensatory mechanisms arise and the measures are only targeted to the variable parts within the overall budget.

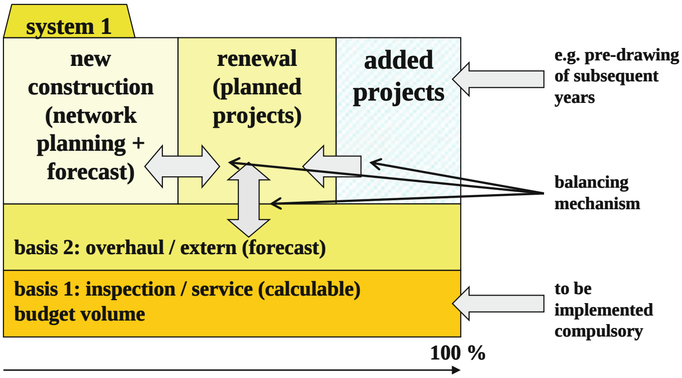


Fig. 3.5 Mechanism of the budget control

Due to basis 1 of Fig. 3.5, the measures resultant from inspections and services have to be applied, which are generally based on liability issues, and this is the reason that the measures should be implemented in volume and time. Basis 2 is based on forecasts and experiences and does also not offer the choice between implementation and non-implementation. Defective or faulty equipment must be repaired and externally requested measures must be implemented which are justified by law or contract. However, if the volumes during the course of the year are differently estimated, either budget funds from other blocks or not used resources of other projects have to be used. As the only really controllable area is the area “renewal,” this block is regarded as a natural variable control area for funds to provide or to be incorporated. This compensation mechanism is described in Fig. 3.5 by the double arrow between basis 2 and renewal. The new area is to be divided into forecast, i.e., measures that result from development of residential areas or industrial location, and network planning, which is used to guarantee the quality and security of supply by adequate infrastructure systems. The planning measures, which arise from the network planning, are at least temporary flexible within narrow limits, i.e., some projects can at least be shift into the next budget year. Thus, a first source of control measures represents the capital within this block and can also be used to compensate the low forecast of the growth which is provided for network planning measures. If the internal balance mechanism is not enough, the block “renewal” is used again as the donating or receiving part of the budget.

If there is a case, that during the planning process, all positions were considered too high, i.e., the outages do not occur as assumed and also the growth projects and external measures are lower than expected, more liquid asset is available as shown in the block “renewal” compared to the original planning of the funds provided for renewals. A delay of projects is also possible within the area “renewal.” As already described, this is the area which offers the greatest potential for the management system and hence the choice of the controller. The measures within the area “renewal” are flexible in time and in the volume with either accelerating or decelerating effects, unless due to outages or safety reasons. Furthermore, additional renewal projects can be quickly defined, usually by slightly earlier time for the renewal of assets which are provided for the following budget year.

The last-mentioned category of control measures, the budget adjustment, does not represent a technical but a business management control. Essentially large-scale projects with earmarked funds as well as projects of clients with high profit share are the focal point. As part of a budget control, it makes technically no sense to compensate for such projects. These topics are subsequently implemented either customer-driven or economically controlled by rescheduling of the financial resources by generation of accrued liabilities. In addition to the planning of the budget, the revenue planning is mostly affected.

Excluding the budget adjustment, the main deviations of the budget face the control options and the combinations, as shown in Table 3.2.

Table 3.2 Control possibilities of budget deviations

Deviation	Balance	Control
Basis 2 too low planned/forecasted	Funds of renewal shift to basis 2	Reduction of renewal, shifting of projects to the following year
Basis 2 is not operated at full capacity	Funds of basis 2 shift to renewal	Time controlled adjustment of the forecast of basis 2 and the realization of renewal projects is shortly possible. Pre-drawing of projects of subsequent years
Construction takes place to a greater extent than predicted, network planning projects are not sufficient to compensate	Funds should be shifted from renewal to construction	Reduction of renewal, shifting of projects to the following year
Construction lags behind the expected range	Funds should be shifted from construction to renewal	Creation of short-term projects, pre-drawing from subsequent years
Planned and budgeted renovation projects are delayed in processing	No reallocation of funds, offset by time-varying renewal measures	Pre-drawing projects from the following year, funding for the subsequent year will be used for delayed projects

Of course, this control according to Table 3.2 can clearly refine the details, but already follows these guidelines consistently in the line of asset management according to a continuous and consistent implementation of the long-term renewal strategy and to avoid large jumps in the budget planning for particular years in the predictable range. This means that any fluctuations in the forecast can be

- the compensation of the renewal block,
- the adjustment of the planning over several years,
- the appropriate pre-drawing or the shift of measures, and however, a technical control is enabled with achieving the approved strategic targets.

A very low actual deviation in the budget is thus a proof of quality that the control processes of asset management can be used effectively.

3.1.3 Calculation of Economics

In case of an investment decision, it is essential to evaluate different solutions from an economic point of view, if the technical and environmental constraints are complied. For this purpose, various methods are available to achieve an optimal investment decision.

3.1.3.1 LCC and TCO

In practice, the two terms life cycle costs (LCC) and total cost of ownership (TCO) are often used synonymously and hereby define the costs of an investment over a specified period. In this connection, the two cost considerations are defined as follows:

- Life Cycle Costs: All expenses for purchase, operation, and disposal of an investment, including the preparatory work during the project phase. This calculation is performed using the present value method.
- Total Costs of Ownership: In addition to the expenses in case of the calculation of life time costs, expenses or indirect cost elements are additionally taken into consideration, which moreover take account of an unproductive use of the equipment or the process or further risks from the entire business process. Since these types of costs are in principle very difficult to quantify, the consideration is generally not easy.

Moreover, in general, the net present value method is used in this case. The procedure is the sum of the present values (Sect. 3.1.3.2) of all expenses and revenues within the useful life, Eq. (3.1).

$$\mathsf{K}_0 = \mathsf{B}_{0\mathrm{E}} + \mathsf{B}_{0\mathrm{A}} \tag{3:1}$$

where

K_0	net-present value (NPV)
$\mathsf{B}_{0\mathrm{E}}$	present value of revenues
$\mathsf{B}_{0\mathrm{A}}$	present value of expense

If the NPV is positive, the investment project resp. the investment option is economically preferable that has the highest NPV. The internal interest rate of p can be determined by the net present value method that the value K_0 according to Eq. (3.1) has the value zero. This calculated interest rate is compared with the interest on capital requirements of an investor. The evaluation of an investment using the net present value method is useful, for example, in case of a power plant project, since the revenue from the sale of electrical energy can be directly assigned to the power plant investment. In contrast, however, the investment of an infrastructure project, such as an overhead line, is not possible to allocate the additional revenue simply to the investment of a single network component.

For the above-mentioned reasons, only the calculation of the LCC is described in detail in the further consideration of this chapter, Sects. 3.1.3.2–3.1.3.5.

3.1.3.2 Life Cycle Costs

The calculation of LCC is today an essential part of the costs analysis to compare different options in case of the construction phase of a plant. Exemplarily, the total expenses of an air-insulated substation (AIS) can be compared with those of a gas-insulated substation

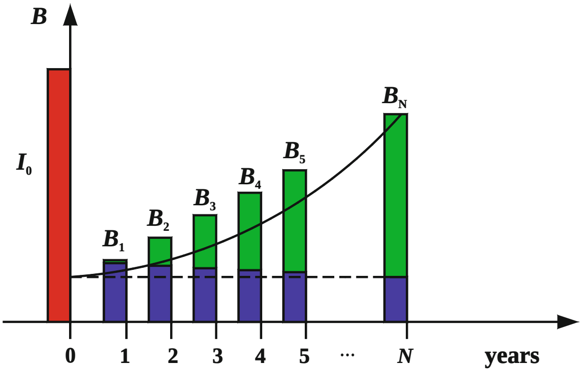


Fig. 3.6 Application of the net present value method (schematically); N end of life

(GIS). Here for each variant, all costs are added that occur during the life of a facility, including the costs of disposal. Subsequently, the relevant present value is calculated using the interest factor, which can be used as a comparison of different solutions.

Using this method, all payments, i.e., one-time investments, losses, taxes, payroll, are discounted or accumulated at a fixed time. Here, future expenses, if they are based on an earlier date, are discounted and vice versa. The basic procedure can be found in Fig. 3.6 as the annual payments B_1 to B_N are plotted over the observed period (green bars). In these cases, it is assumed that payments occur at the end of the year. Subsequently, these amounts (e.g., year "zero") are discounted (blue bars).

The present value of B_0 for the entire period is given by Eq. (3.2) by the addition of all partial payments including the expenses for the initial investment.

$$\begin{aligned} B_0 &= I_0 + B_1 \cdot (1+p)^{-1} + B_2 \cdot (1+p)^{-2} + \cdots + B_N \cdot (1+p)^{-N} \\ &= I_0 + \sum_{n=1}^{N} B_n \cdot (1+p)^{-n} \end{aligned} \qquad (3:2)$$

where

I_0	initial investment
B_n	annual payment of the nth year
p	required rate of return
N	end of life

Under the conditions that the annual payments ($B_n = B_1$) are constant, the equation simplifies (3.2) to:

$$B_0 = I_0 + B_1 \cdot \frac{(1+p)^N - 1}{(1+p)^N \cdot p} \qquad (3:3)$$

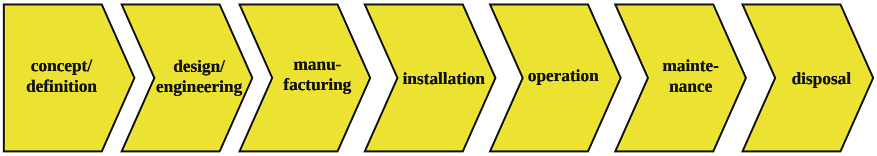


Fig. 3.7 Steps of procedure in case calculation of the life cycle costs

With the help of Eq. (3.2), the calculated present value does not consider a potential residual value of the plant or the equipment that may be still present at the end of life. By contrast, when assuming a residual value R, the present value is considered to:

$$B_0 = I_0 + \sum_{n=1}^{N} B_n \cdot (1+p)^{-n} - R \cdot (1+p)^{-N} \tag{3:4}$$

If the current annual expenditures $B_1, \ldots, B_N$ are only different due to the inflation rate i (no different expenditures are considered each year), then the present value is calculated under consideration of the residual value:

$$B_0 = I_0 + B_1 \cdot \sum_{n=1}^{N} (1+p)^{-n} \cdot (1+i)^{n-1} - R \cdot \frac{(1+i)^{N-1}}{(1+p)^{N}} \tag{3:5}$$

The calculation of LCC is performed according to [35] resp. analogously to the IEC standard 60300-3-3 [33]. In this IEC standard, the basic procedure is introduced in the calculation of LCC in the area of electrical engineering, so that in addition, the application of this general method is applied to the analysis of equipment of the electric power supply, such as high-voltage AIS. Figure 3.7 shows the different cost items which are considered in the calculation of LCC. For better presentation, the operating and maintenance costs are in contrast to [33] record separately so that it is possible to distinguish between the illustrated cost types.

In many cases, it makes sense to differentiate between the higher level segmentations, namely investment costs, costs of ownership, and disposal costs, so that the following assignment results:

• Investment costs	Concept/engineering, manufacturing (installation)
• Costs of ownership	(Installation), operation, maintenance
• Disposal costs	Disposal

Installation costs can be assigned to two groups of costs, depending on a current project and its implementation.

3.1.3.3 Definitions

The following definitions provide an overview of the contents of different types of costs.

Concept/engineering

For the calculation of these expenditures, the time required for the elaboration of concepts, for example the effort at the contracting authority and the engineering of the plant, is considered. In this case, these costs are taken into consideration, which are generated during the specification or design phase.

Manufacturing

These costs include the expense incurred for the production and sales of the product by the contractor. They thus represent the value of the contract for the plant, but without installation and commissioning costs. Separately, the costs of monitoring systems should be broken down, because these costs are additionally to be considered in evaluating the condition-based maintenance of the equipment, where appropriate.

Installation

When calculating the cost of installation, all expenses are taken into account, which have to be provided on-site before the system can go into operation. These include, for example, the following expenses for the different services: Permits, construction, transportation, grounding system, material, test, and assembly.

Operation

All expenses are considered that are necessary for the operation of the system. These are in particular the costs for labor, material and current heat loss of assets (e.g., current and voltage-dependent transformer losses, personnel training).

Maintenance

Basically, different maintenance strategies go into consideration in case of the calculation of the maintenance costs. The following activities can exemplarily be summarized: Inspections, overhaul of the switchgear, route maintenance of overhead lines, inspections, etc. Possible maintenance strategies are, as described in detail in Sect. 2.1.1:

• Corrective	• Time based	• Condition based

The reliability-centered maintenance, as it is used today in many cases, does not lead to a different assessment of the financial costs compared to the condition-based maintenance because the difference is that only the priority of the maintained equipment is changed due to the importance of the equipment for the electrical system. The number of components that need to be maintained, however, is unaffected. Here, it is assumed that the failure rate against the condition-based maintenance does not change.

Miscellaneous expenses for maintenance/inspection or repair in case of a failure are considered depending on different maintenance strategies, these are as follows:

- **Corrective**: As in case of this maintenance strategy, a replacement of the equipment takes place after a failure, only the "major" failure and therefore the probable labor as well as material costs have to be considered based on a year. An inspection or service/overhaul of the equipment does not take place.
- **Time based**: In this case, all activities take place (including replacement) depending on fixed, predetermined time intervals so that all expenses for inspections and overhauls are considered (depending on the time intervals). In addition, the probable labor and material costs for fault-related failures ("minor" and "major") will be considered.
- **Conditioned based**: In case of the condition-based maintenance strategy, maintenance activities are conducted depending on the condition of equipment. The costs of inspections and overhauls are determined (depending on the condition).

  In addition, expenses for the additional investment of a monitoring system and detection or assessment of the technical condition of the component (diagnosis, analysis, condition assessment) must be considered.

Basically, the following expenses have to be considered for different strategies according to Table 3.3. It has to be distinguished between an inspection resp. an overhaul and fault repair in case of "minor" and "major" faults. Table 3.3 indicates which cost items are taken into account depending on different strategies. It is possible, that even in case of components that are subject to corrective maintenance strategies, regular inspections can be performed.

In general, different failure rates for "minor" and "mayor" faults have to be taken into consideration, if the above-described maintenance strategies are applied, as it is in general assumed that the annual occurred outages of the components depend on the used maintenance strategies.

In addition, outage costs occur which can economically be evaluated, such as additional damage to equipment, loss of revenue of the utility and economic losses of energy not supplied (ENS), penalties due to supply interruptions.

Table 3.3 Assignments for calculating the maintenance costs

Strategy	Inspection	Overhaul	Fault repair "minor" fault	Fault repair "major" fault
Corrective	(X)	–	(X)	X
Time based	X	X	X	X
Condition based	X	X	X	X

Disposal

When calculating disposal costs, the following types of expenses are considered: labor, material, and disposal costs. Arising charges for recycling (e.g., copper windings of power transformers) must be deducted as credits of the expenses. Basically, the declaration of disposal costs has critically to be evaluated, as the actual costs incurred will depend essentially on legal principles in the future which are not known today as a rule. For these reasons, it is permissible to take the current regulations of the disposal costs into account.

Additional input value

The following input data are used for the calculation of the costs of the life besides the above-mentioned values:

- Interest rate,
- technical life of the components,
- inflation rate,
- hourly rate (for service of engineers and installation).

Taking into account a predetermined useful life of an entire substation, e.g., 50 years, different single components may have in practice lifespan deviating from the overall value, so that they must be replaced during a shorter time. In these cases, any residual value of the new equipment reduces the total present value of the investment at the end of the period in case of the final decommissioning.

3.1.3.4 Example: Life Cycle Costs of a 380 kV Air-Insulated Substation

The basic procedure of the LCC calculation is shown in the following with reference to the evaluation of a 380 kV AIS [6]. The aim of this calculation is to determine the present value of this investment that all expenses are discounted to the year of investment over the useful life depending on Eq. (3.1). The considered substation consists of five bays and the considered components are listed below (number of considered components):

- plant 1
- circuit-breaker 5
- power transformer 1
- disconnector 25
- instrument transformers 15
- secondary equipment (bay) 5

In this case, the secondary equipment represents the protection and control of the entire substation, whereas the term “plant” comprises all components of the substation that are not individually mentioned in the list: busbar, dead ending, portals, etc.

Maintenance strategies and failure rates

Today, different maintenance strategies are applied for the above-mentioned components of a substation to which each of the various failure rates of the components refer calculating the outage costs. These strategies are provided in detail as a function of the asset groups for further consideration as follows:

• Corrective	– Plant
	– Instrument transformer
• Condition based	– Circuit-breaker
	– Disconnector
• Time based	– Power transformer
	– Secondary equipment

The outage costs of equipment are influenced by the failure rates (major/minor) that are exemplarily listed in Table 3.4 for the different assets. The probable outage costs per years are determined by these values. If the components are treated by the corrective maintenance, each "minor" failure will lead to a "major" failure so that outage costs due to "minor" failures are not possible and are therefore not taken into account (Table 3.3). In case of secondary equipment, it is assumed that only "minor" failures occur which do not lead to a sudden interruption of power supply.

Different costs have to be taken into consideration regarding the fault repair for staff and material expenses (repair costs), which are listed in Table 3.5, depending on different components and fault types.

In addition to the fault-related costs (repair costs), in each case, the time-based maintenance expenses for inspection and overhauls have to be taken into consideration depending on the time cycles. The data of Table 3.6 are used for further calculations. It is assumed that the data of the circuit-breakers and disconnectors for inspections and overhauls are used, although the time-based maintenance is applied.

Table 3.4 Failure rates for different assets (outages per year)

Equipment	"Major" failure	"Minor" failure
Plant	0.220	–
Circuit-breaker	0.025	0.152
Power transformer	0.025	0.050
Disconnector	0.0015	(1)
Instrument transformer	0.001	–
Secondary equipment	–	0.010

(1) in general negligible

Table 3.5 Typical personnel and material costs in case of an outage

Equipment	"Major" failure		"Minor" failure	
	Working hours (h)	Material costs (k€)	Working hours (h)	Material costs (k€)
Plant	16	5	–	–
Circuit-breaker	24	25	8	0.5
Power transformer	40	150	8	5.0
Disconnector	16	5	(1)	(1)
Instrument transformer	16	10	–	–
Secondary equipment	–	–	8	0.5

(1) in general negligible

Table 3.6 Data for the calculation of the expenditure in case of a time-based/condition-based maintenance

Equipment	Overhaul			Inspection		
	Interval (a)	Time (h)	Material (€)	Interval (a)	Time (h)	Material (€)
Circuit-breaker	12	48	1500	6	4	100
Disconnector	4	24	200	(1)	(1)	(1)
Power transformer	6	8	1500	2	4	1000
Secondary equipment	4	8	1000	2	1	100

(1) in general negligible

The fundamental data of this chapter are used in case of the calculation of the maintenance costs.

Concept development

The number of working hours to prepare the specification of high-voltage substation can be estimated to about 48 h in this example. This presupposes that sufficient prior knowledge from other projects already exists.

Engineering costs

The development of the final layout for the considered plant, including the engineering activities, requires a time exposure of approximately 160 working hours (engineering services); also true is in this case that these parameters depend on the prior knowledge in a particular case.

Manufacturing costs

The manufacturing costs for different components of a substation are roughly estimated according to Table 3.7, and the total sum can be determined to about 12.6 M€. In this case, the greatest impact on the total value of the manufacturing costs has the "plant" with 45 %, while the circuit-breakers have only a part of about 5 % (Table 3.7).

Installation costs

Different particular costs belong to the installation costs of a substation, such as construction, material, assembling, and transportation costs, and expenses for installation of earthing system and testing. The amount of installation costs can thereby be estimated to about 1.5 M€, whereby the plant accounts for the largest share with 54 % (Table 3.7).

Operation costs

The operation costs per year (131 k€, Table 3.7) includes the following activities or expenses for the entire substation depending on the type of equipment:

• Plant	Site inspection of the AIS, lawn cut, snow removal, etc
• Power transformer	No load and short-circuit losses
• Secondary equipment	Upgrade of the software

A load factor of 0.4 is taken into account for the calculation of short-circuit losses of the power transformer, which are depending on both the operating voltage and the current flow. The electric power generation costs are assumed to 3.5 cents/kWh in case of the assessment.

Maintenance costs

In case of the maintenance costs, the today's strategies for the different types of equipment are considered according to the subsection "Maintenance strategies and failure rates."

- The probable maintenance costs of equipment, which are treated according to the corrective strategy (plant/instrument transformer), add up to an annual amount of about 1.1 k€. Here, only outage costs are considered due to "major" failures, as each "minor" failure leads to a "major" failure due to non-executed maintenance activity.

Table 3.7 Partial costs depending on the equipment (percent values)

Equipment	Manufacturing	Installation	Operation	Disposal
Plant (%)	45	54	2	22
Circuit-breaker (%)	5	5	–	25
Power transformer (%)	26	7	94	11
Disconnector (%)	8	16	–	23
Instrument transformer (%)	12	10	–	14
Secondary equipment (%)	4	8	4	5
Total costs (M€)	12.6	1.5	0.13[a]	0.27

[a] Total operation costs per year

- It has to be differentiated between the following expenses in case of the time-based maintenance considering the maintenance costs:
  - Costs for inspections and overhauls (Table 3.8),
  - probable annual repair costs due to “major” or “minor” failures
- When calculating the maintenance costs of assets, which are subject to condition-based maintenance (circuit-breaker/disconnector), the same types of costs are considered as compared to the time-based maintenance.

The annual expenses for maintenance activities are valued according to Table 3.8, while in case of the determination of the repair costs, the failure rates as well as the required expenditures for the elimination of the outage according Tables 3.3 and 3.4 are taken into consideration. From these data, the probable annual repair costs of outages are determined taking into account the number of components:

- Circuit-breaker: 4.5 k€
- disconnector: 0.23 k€
- power transformer: 4.1 k€
- secondary equipment: 0.1 k€

The calculation of probable annual repair costs, both damages to other components and costs for ENS at a system node will not be considered. The reason for the latter is, because it should not come to an immediate supply interruption in the downstream voltage levels due to the topology of the 380-kV network.

Disposal costs

Credits for different materials (such as copper in the case of the power transformer) are considered calculating the disposal costs for equipment. The value of the disposal costs is therefore approximately 270 k€ for the entire switchgear, Table 3.7.

Table 3.8 Expenditures for overhauls and inspections of the components, which are serviced by the time-based and condition-based maintenance, per k€ (the number of components is taken into consideration)

Equipment	Overhaul (k€)	Inspection (k€)
Circuit-breaker	25.5	1.3
Disconnector	45	–
Power transformer	3.3	1.2
Secondary equipment	5.5	0.9

Calculation of the present value

The calculation of the present value of an investment option gives an overview of all payments during a specified period, discounted to the year of installation, Eq. (3.1). The following data are used for the calculation:

• Interest rate	6.5 % resp. 10 %
• Inflation rate	2 %
• Useful life	
– Primary equipment	40 years
– Secondary equipment	20 years
• Time of depreciation (equipment)	25 years
• Repair costs	See subclass: maintenance costs
• Service costs	See subclass: overhaul/inspection
• Service cycles	Table 3.6
• Considered period	40 years

For simplification of the analysis, a maximum useful life of equipment is assumed to 40 years, with the exception of the secondary equipment; in this case, it is expected due to the technology at a lower maximum operating life. The exchange is after 20 years, so in this case after 40 years, no residual value of the secondary systems must be considered. For an assessment of the LCC of the entire system, the present value (Sect. 3.1.3.2) of all components is added in the following, so that on this basis, the importance of various components can be represented with respect to the incidental financial expenses. The present values represent the total expenses of an investment over the period under consideration.

Present value of the substation

Figure 3.8 shows the segmentation of the present value of the investigated substation (17.3 M€) regarding the particular components with an interest rate of 6.5 %. In case of an increase of the interest rate to 10 %, the total present value decreased to 16.1 M€, as the present value of the annual costs is much lower due to discounting effects. It is obvious that both the plant and the power transformer with 39 and 34 % have the greatest impact on the total present value, whereas the other components are of minor importance.

Present value of the components

Figures 3.9 and 3.10 show the present values of two different components (circuit-breaker and power transformer), which are maintained by the time-based strategy in each case based on the different partial costs. The investment costs have a share of 84.7 % based on the total present value in case of the circuit-breakers, while the inspection costs are of minor importance (0.2 %). The probable outage costs (repair costs) go with a total of 10.2 % into the calculation.

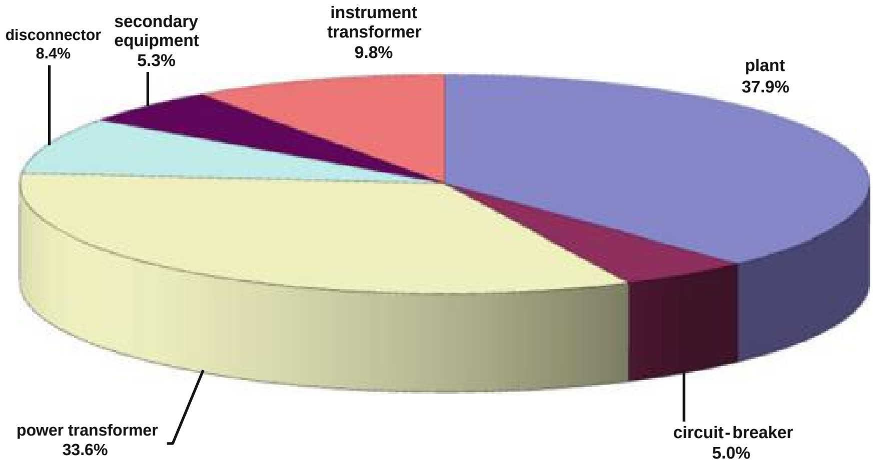


Fig. 3.8 Present value of the 380 kV substations in case of an interest rate of 6.5 % [6]

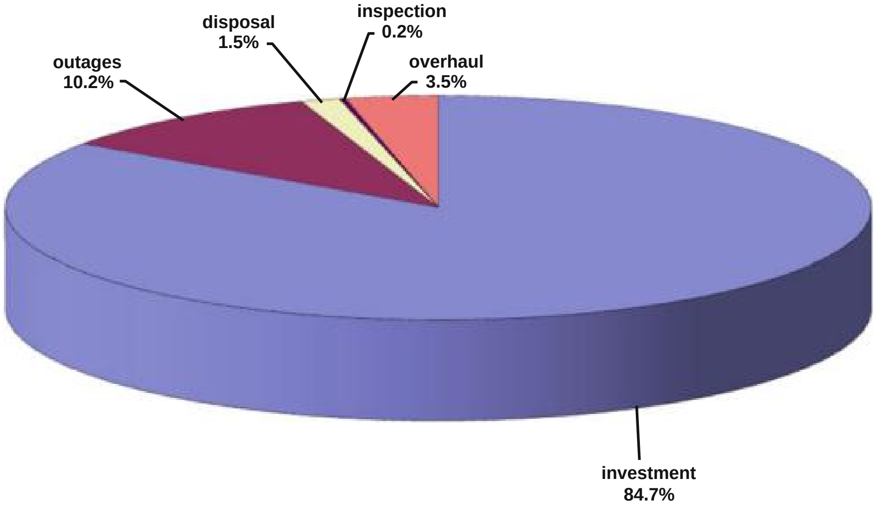


Fig. 3.9 Present value of circuit-breakers (interest rate 6.5 %) [6]

On the contrary, the operation costs (active losses of the power transformer) have a significant impact on the total present value of 41.5 % in case of power transformers, while the capital costs account for only a part of 56.7 %. The other portions of costs are of minor importance.

Therefore, the final conclusion for asset managers is that the costs of power losses of a transformer are essential besides the investment costs in case of an investment decision. In principle, the partial costs of “inspection/overhaul” and “outages” can be used for a

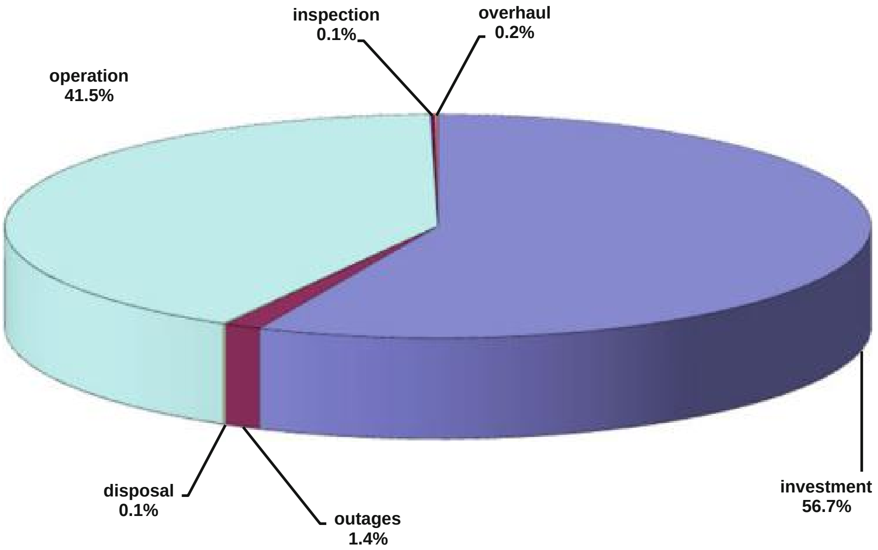


Fig. 3.10 Present value of a power transformer (interest rate 6.5 %) [6]

consideration of the variation of maintenance strategies, since the maintenance activity has a direct impact on the partial costs and hereby also the financial framework of a change of the maintenance strategy is described. This means that a reduction of maintenance costs below a defined level will lead to an increase of the failure rate and higher failure costs and vice versa.

Influence of the maintenance strategy

In general, it is possible to investigate the impact of a change of maintenance strategy due to the present value with the help of the LCC calculation. Basically, the variation of a maintenance strategy and thus the cycle of an inspection/overhaul correlate with the failure rate of equipment. This means t, for example, the transition from a time-based to a condition-based strategy should result in a change of the failure rate (major/minor).

In this case, the basic approach in order to show the influence of a change of the strategy is shown with reference to circuit-breakers. A transition from a time-based to condition-based maintenance usually requires the installation of a monitoring system and an additional expense for the assessment of the condition of the measurement results. If the advantage of a monitoring system has to be evaluated, two extreme variants are possible because the financial costs of a condition monitoring (installation of a monitoring system) inevitably increase the investment costs. These additional expenses can be absorbed either by reduced outage costs (variant a) or by reduced overhaul and inspection costs (variant b). Moreover, in practice, a combination of both variants will occur, but this is not considered in the following.

The same effect arises, if a piece of equipment with an increased quality requirement should be used instead of an additional monitoring system for the condition assessment. In this case, the advantage of the additional investment can be assessed on the basis of reducing the outage costs.

In the following, it is assumed that considerations, for example, expenses for the condition assessment can be compensated by a reduction of the outage costs depending on a lower failure rate. There will be an additional economic advantage in favor of a transition to a condition-based maintenance strategy due to a further reduction of the failure rate. In any case, these variants specified above must be compared with the present value calculation according to Fig. 3.9.

- Variant a: reduced outage costs
  If the manufacturing costs of a monitoring system are assumed in the order of 3 or 5 % related to the total investment costs of the original equipment, the failure rates and the outage costs have to be reduced accordingly, whereas the ratio between the "major" and "minor" failures as well as the maintenance cycles are assumed to be constant. Failure rates for circuit-breakers are assumed 0.025 %/year ("major"-failure) and 0.152 %/year ("minor"-failures) according to Table 3.4. The following changes of the failure rates appear in order to achieve cost parity depending on the investment costs for the additional condition detection (monitoring system):
  - 0.025 to 0.0195 %/year (in case of 3 % investment costs) or
  - 0.025 to 0.0155 %/year (in case of 5 % investment costs).
- Variant b: reduced overhaul and inspection costs
  It can be distinguished between two cases depending on the additional investment costs of the condition detection, if the failure rate is considered as constant and the existing inspection and overhaul cycle is to be extended (Table 3.6):
  - 3 % investment costs: Extension of the cycles to 10 years for an inspection and 20 years for an overhaul instead of today's 6 years (inspection) and 12 years (overhaul).
  - 5 % investment costs: From an economic perspective, there is no advantage to use a monitoring system because the additional capital and operating costs are higher than the present value of the overhaul and inspection costs.

The last result can be derived from Fig. 3.9, as the sum of the present values of the maintenance costs of 3.7 % based on the total value is less than the present value of a monitoring system with 5 %.

The costs of monitoring and evaluation have to be taken into consideration calculating the present value in addition to the consideration of the investment costs of a monitoring system, so that the exclusive part of the investment costs for a monitoring system is reduced even further.

However, the results of the calculation essentially depend on the interest rate on equity capital, as the investment costs of a monitoring system are immediately incurred, however, the avoided outage costs at a later date, so that in these cases the present value is lower depending on the discounting. It should also be noted in the illustrated consideration that in case of a change to a condition-based maintenance strategy, in general, only a part of the occurred faults can be detected by a condition monitoring, e.g., in case of circuit-breaker, Sect. 3.2.5 [10].

3.1.3.5 Example: Life Cycle Costs of a 110 kV Overhead Line System

Following the same procedure, the present value of an entire network can be determined, as it is shown for example in [35]. In this connection, the 110 kV network consists of various components (number of components):

- plant: 66
- circuit-breaker: 334
- power transformer: 83
- disconnector: 393
- secondary equipment: 252
- shunt reactor: 5
- instrument transformer: 168
- length of route (km): 523
- overhead line towers: 2093
- circuit length (km): 1151

The overhead line system is fed by the upstream 380 kV network and has in total 66 AISs. Calculating the present value, it is assumed that the network will be installed at the time $t = 0$. Taking into account the necessary data (investment costs, failure rates, maintenance costs, outage costs, etc.), the present value of the entire network is approximately €500 million, if an interest rate of 8 %/year and an inflation rate of 1.5 %/year are assumed and an observation period is provided by 50 years.

The partition of the present value regarding the particular components is shown in Fig. 3.11. It shows in this case that the overhead lines (towers, circuits) have the greatest impact on the present value (59 %). It is assumed in this analysis that the length of routes already exist, so that expenses relating to the approval process and route planning are not included. The power transformers represent the second part (19 %), followed by the other components.

For the selection of a maintenance strategy of the entire network, the present value of the outage costs (repair costs) of the various components is an important factor for the

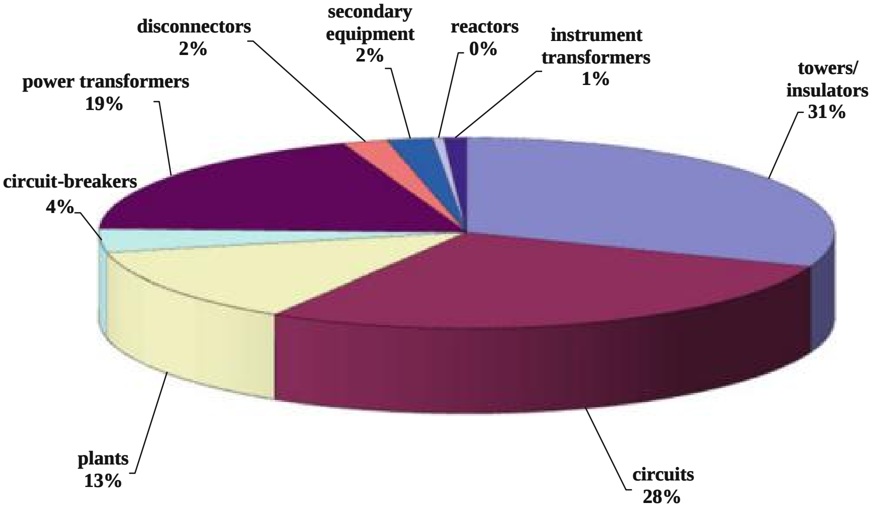


Fig. 3.11 Present value of 110 kV overhead line system [35]

determination. Figure 3.12 shows the present value of the outage costs (3.5 M€) for the network, and in this case, it also results that the overhead lines (54 %) and power transformers (29 %) have the largest share, while the remaining components participate with 17 % of the total value. In this analysis, the costs of ENS are not included, which

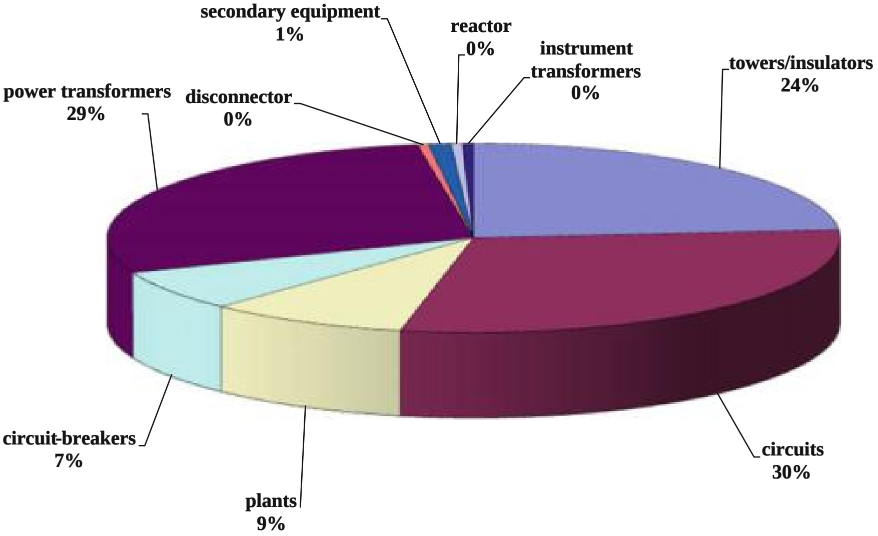


Fig. 3.12 Present value of the outage costs of 110 kV overhead line system [35]

Table 3.9 Assessment of the present values outage and maintenance costs

Equipment	Outage costs (OC) T€	Maintenance costs (MC) T€	Factor OC/MC
Towers/insulators	836	19,417	0.0413
Current circuits	1051	9852	0.1067
Plants	304	9548	0.0319
Circuit-breakers	248	3599	0.0689
Power transformers	1018	1083	0.9400
Disconnectors	18	1160	0.0155
Secondary equipment	31	352	0.0881
Shunt reactors	0	18	0.0000
Instrument transformers	15	2191	0.0068
Total	3522	47218	0.0746

perhaps have to be paid to customers when a supply interruption has occurred. This value depends on the particular case of the topology of the network and the contract between the different partners.

For a better assessment of the costs for outages and maintenance measures, Table 3.9 shows the absolute amount of the present values of various components and a factor (OC/MC), which relates the total outage costs to the maintenance costs. In case of small values of the factor (e.g., <0.1), the maintenance expenses are significantly larger than the expected outage costs. This can basically be caused by the following:

- Outages are avoided due to the high maintenance costs, and
- The outages are independent of the maintenance measures at a low level.

A comparison of the ratio “OC/MC” (outage costs related to the maintenance costs) shows that in case of the power transformer this ratio 0.940 is much higher related to the entire network and especially compared to the disconnectors (0.016), which is below the average value of the network. This raises the fundamental question whether the maintenance costs are justified in each case depending on the equipment group.

Although the calculation of LCC leads to a meaningful consideration what components significantly affect the costs of a network and the identification of the relationship “OC/MC” gives an indication of the efficiency of the maintenance activities. An optimization between different asset groups does not take place, however, and the calculation could only iteratively performed by the repeated starting with modified maintenance costs and failure rates. For this purpose, methods from the field of “operation research” are suitable which are presented in Sect. 3.5.

3.2 Technical Control Functions

It is important for an optimal performance of asset management to have a sufficient knowledge of the failure behavior of the used equipment. The main options are presented below.

3.2.1 Outage Statistics

According to DIN EN 13306:2008-10 (draft) "Maintenance—Definition of Maintenance" [23] in general, two different types of outages of plants and systems are defined. These are as follows:

- Outage (interruption)
  Performance of a unit, characterized by its inability to fulfill a required function for any reason. Here, an outage means either a functional condition or downtime (internal to the plant) of a single unit, Sect. 6.8 of [26].
- External outage
  Part of the fault of a working condition unit; a condition which occurs due to a lack of an external tools or planned measures with the exception of maintenance measures, Sect. 6.9 of [26].

In addition, the term "fault" is still divided into two further groups, which describe the effect on the overall goal of the supply reliability and thus give information on the following questions:

- Outages at singular components: How often does an equipment fail or its functioning is disturbed. Which causes are responsible for this? From this response, a maintenance measure can be derived to avoid such disturbances. This category is referred to in the nomenclature of energy companies as "damage."
- Outages at system nodes: How often does a supply interruption at system nodes occur, so that a connected client is unserved? In these cases, it has to be clarified, if the interruption is allowed, so that considerations have to be applied in terms of improvement, for example, by a redundant power supply or higher reliability of equipment.

There is another way of classification into the following categories in relation to the effect of the function on the one hand and within the framework of supply reliability on the other hand:

- Damages without functional interruption: It describes a damage of the infrastructure/ equipment which does not result in a functional failure and is usually identified only by an inspection/site inspection (e.g., damages to wooden towers, leakage of power transformers).
- Damages with functional interruption without outage of the energy supply: The damages are listed in this category which do lead to an outage of part of the infrastructure/equipment, but does not affect the function of the system and the customer supply.
- Outage without damage: In this case, the impact on the customer supply is in the main focus, but the infrastructure is not damaged (e.g., lightning strikes without damage, switching off by a fuse in case of overload).
- Outage with damage: All other outages that also result in damage of the equipment and a repair/exchange.

Statistics, e.g., in the area of electric power supply, are published by the FNN (forum network technology/network operation within VDE) in the Federal Republic of Germany for many years [2, 17] and also published by the Federal Network Agency as a regulatory body. In this sector, these statistics reflect the outage behavior in public networks. In terms of definitions according to DIN EN 13306, only the first listed fault category (outage/ interruption) and their effect on the customers is recorded so far. Four different fault classes are recorded presenting the statistic, which are differentiated by the following features:

1. Outages with supply interruptions: Outages, in which a supply interruption has been occurred.
2. Outages with switching off operation without supply interruptions: In these cases, it is a matter of outage in which the equipment was switched off without a supply interruption has occurred.
3. Successful "automatic reclosing" (AR): In this case, an outage is meant which is cleared by an AR.
4. Without switching off operation: In this case, an outage is meant which does not lead to a switching off of equipment.

In many cases, the term "major" failure and "minor" failure is used for damage to equipment (e.g., Sect. 2.1.5.3). According to the above definitions, the failures have the following error mappings:

- Definition of outages 1 and 2: "major" failure
- Definition of outages 4: "minor" failure.

In case of the definition of outages 3 (successful AR), no damage on an equipment occurred, as, for example, an outer arcing is extinguished after the interruption of the power supply by itself without damages to the equipment.

Exemplarily, Fig. 3.13 shows the outages of the year 2008 per 100 km circuit length of [17] for different voltage ranges (MV, HV, and EHV), including the causes of faults.

In general, it is useful regarding the analysis of various outages to make a classification concerning the different causes of faults, types of faults, and fault locations to determine appropriate measures for avoiding an outage in the particular case. The following classifications have been proven in the area of electrical power:

- Causes of fault:
  - Atmospheric effects (lightning, storm, fog, humidity, etc.),
  - external influences (people, birds, other animals, digging and earth work etc.),
  - auxiliary devices (protection devices, other auxiliary equipment),
  - reactions (from the own or other systems, power plants),
  - other effects,
  - no identifiable cause.
- Types of fault:
  - Single line-to-earth fault (single line-to-earth short-circuit current),
  - Multi-pole short circuit,
  - switching off operation without short circuit (defected equipment, reactions, overload, etc.),
  - further types of faults (lack of voltage, interruption of the conductor).
- Fault location:
  - Overhead line, cable,
  - substation, secondary substation,
  - power transformer,
  - further fault locations (protection devices, reactions, other).

The failure rate of equipment (fault location) can be derived using the information of the FNN fault and availability statistics. Because of the data set, however, only an average failure rate of the collective asset group can be determined as the age of the equipment is

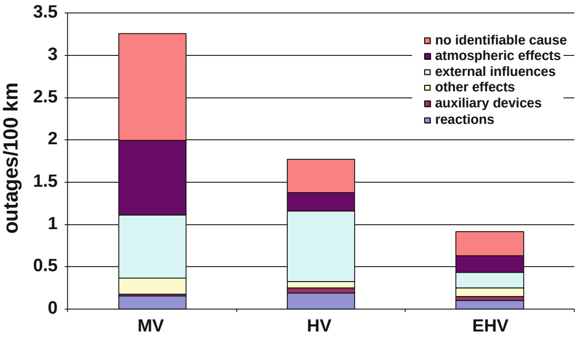


Fig. 3.13 Outages with interruption of the power supply and switching off operations without interruption of the power supply, 2008 [17]. MV medium voltage, HV high voltage, EHV extra high voltage

not recorded at the time of the fault. In any case, a list of outages according to Fig. 2.33 is appropriate for an application of a time-based maintenance strategy, as this figure describes the fault behavior between maintenance measures as a function of time.

In contrast to the deduction of the failure rate of equipment, it is useful to evaluate other parameters for the fault behavior at system nodes in case of the assessment of the quality of supply. In addition, the today's commonly used indicators to describe the quality of supply are listed (SAIFI, SAIDI, and CAIDI) (Table 3.20; Sect. 3.3.3). These are the following parameters [17]:

- Frequency of interruption H_u: Value, how often the end customer is yearly affected by an interruption of supply on average (sum of customer interruptions/number of supplied customers), Eq. (3.6).

$$H_u = \frac{\sum_j n_j}{N_{ges}} = \mathrm{SAIFI} \quad [1{=}a] \tag{3:6}$$

- Duration of interruptions T_u: Average duration of a supply interruption of the end customer (accumulated duration of customer interruptions/total number of customer interruptions), Eq. (3.7).

$$T_u = \frac{\sum_j n_j \cdot t_j}{\sum_j n_j} = \mathrm{CAIDI} \quad [\mathrm{min}] \tag{3:7}$$

- Non-availability Q_u: Product of the interruption frequency H_u and interruption duration T_u. Parameter for the average duration of a supply interruption per year of the end customer (accumulated duration of customer interruptions/number of supplied customer), Eq. (3.8).

$$Q_u = \frac{\sum_j n_j \cdot t_j}{N_{ges}} = \mathrm{SAIDI} \quad [\mathrm{min}{=}a] \tag{3:8}$$

Values of Eqs. (3.6)–(3.8):

n_j	number of interrupted end customers
N_{ges}	number of total supplied customers
t_j	duration of interruption
SAIFI	System average interruption frequency index
CAIDI	Customer average interruption duration index
SAIDI	System average interruption duration index
CAIFI	Customer average interruption frequency index

The listed data of the failure statistics are primarily used as input variables for reliability calculations to determine the reliability of supply resp. to identify appropriate network measures during the planning phase, allowing an increase of the reliability of supply, if it is necessary. A commitment of a maintenance strategy for asset groups by these statistics is not possible, because on the one hand, equipment is usually assembled of various components and the maintenance action is always performed to the components, and on the other hand, the damage is not recorded in this context in the electric energy sector. For example, when a flashover takes place in air on an insulator, which is next interrupted by the protection system, no damage will be caused to the insulator which will lead to a maintenance activity. The consequence is that for considerations of a maintenance strategy, it is essential to provide a data file for the collection of damages (Sect. 3.2.2) which are the basis of any quality analysis, for example, in the pipe network area.

3.2.2 Data Files of Outages

As explained in Sect. 3.2.1, there is a need for fault statistics to determine the characteristics of a network in terms of supply reliability. In addition, input parameters are determined for the reliability calculations. However, outage values are of limited use for the derivation of a maintenance strategy, since the equipment may have an outage without any permanent damage present to this equipment or the component. The FNN fault and availability statistics for 2008 present that no damage occurred in about 70 % of the outages in a high-voltage overhead line network, since the supply was maintained by an AR and the operation could be continued.

In contrast to an outage, a damage may be defined that a component or the entire unit is faulty, which may lead to functional failure of the equipment (but not necessarily).

In general, it can be distinguished between the following categories in case of damages:

- The damage leads to an unplanned maintenance measure.
- The damage leads to a planned maintenance measure, and the operation can be continued.

Maintenance action can lead to a repair, a replacement, or a renewal. The advantage of using a data file is to optimize both, the provision of personnel and the financial resources on a medium- and long-term period. The results of the outage analysis can be used for two different tasks:

• Long-term strategy	Performing of asset simulation, Sect. 3.4
• Operational optimization	Usage of FMEA method. Selection of suitable maintenance services for the asset groups, Sects. 2.1.4 and 2.1.5

When creating a data file in detail, the following steps are taken into account resp. has to be provided:

- Age of equipment or components at occurrence of damage,
- developing the equipment model with different levels, design according to Fig. 2.31, Sect. 2.1.5,
- consideration of various technologies in case of asset groups,
- information regarding “internal” causes , e.g., aging, wearing, stress (mechanical, electrical) etc.,
- information regarding “external” causes, e.g., storm, thunder storm, earth work, and digging, etc.,
- used maintenance strategy and cycles,
- listing of the subsequent maintenance actions resp. renewal and its expense.

The frequency of damages can be determined as an average value for an asset group with the help of technological damage mapping. If the age of equipment is listed in case of the occurrence of the damage, this can be used to determine an age-depended failure rate according to Figs. 2.34–2.38. This approach allows concretizing the maintenance strategy for components in order, for example, to define a time-based or condition-based maintenance strategy. The age-depended failure rate is also an essential input value of the asset simulation, as described in Sect. 3.4.

Already, the damage statistics are essentially collected, analyzed, and systematized for asset management in the pipe network area. The rules for this have been described by the German Association for Gas and Water (DVGW) and are used by the infrastructure operators in this area. This classification of damage is described as follows:

- A-damages: Imminent danger, the damage must immediately be repaired, the pipeline, and the equipment have to be transferred in the proper condition, unplanned overhaul.
- B-damages: planned damage, the repair has to be done in a reasonable short period of time, usually fitted at the next maintenance or construction project, planned overhaul.
- C-damages: minor importance, the repair can be planned and implemented, for example, in the next year’s program (optimized overhaul).

3.2.3 Assessment of the Network Asset Value

A higher level indicator generates the asset value of the entire system infrastructure. In this context, higher level means that long-term strategic decisions are controlled and monitored by this indicator. If a company decides due to a negative outlook in the business and therefore reduced return to live on the substance resp. to extract value from the infrastructure system, this is not a short-run strategy due to the long-live cycle of the equipment. In fact, this temporally follows the natural aging process of the equipment. By means of reduced renewal rates and other handling of outages by increased repair instead of replacing components or entire groups, the average age of the equipment group is increased, and the remaining service life of the infrastructure system is shortened with maintaining the assumed technical life. Simply expressed, the average age will increase total per calendar year for one year in the hypothetical case without any renovation and new construction within the system. Since this hypothetical case does not occur, there are always some new buildings or renovations, even from outside induced, so that the "achievable" aging per year is realistic less than a year. The strategic implications and pitfalls are later analyzed in detail that arises from this for the asset management.

An appropriate data base on the age structure and the life consumption of equipment is required to define such a measure and form. It is made by the data from the quantity structure for each segment rated with age and daily value as new, aggregated into an overall system value. The plant asset value A_S is calculated according to Eq. (3.9):

$$A_S = \frac{\sum_j \sum_i R_{ij} \cdot A_{Vij}}{\sum\limits_j \sum_i T_{ij} \cdot A_{Vij}} \tag{3:9}$$

where

A_V capital assets
R remaining useful life
T technical useful life

The index i represents the particular equipment group, while the index j represents the different equipment groups of the entire system, i.e., aggregated from the particular segments. The remaining useful life can be determined by the age distribution of equipment in relation to the assumed technical useful life. The influence of an implemented investment strategy by changing the fixed assets on the plant asset value over a certain period (e.g., 10 years) can be calculated accordingly, so that the change of the plant asset value A_{S10} becomes for an equipment group i in 10 years:

$$A_{S10} = \frac{\sum_i A_{Vi10}}{\sum_i A_{Vi}} \tag{3:10}$$

In addition, the residual value A_{VR} and the investment needs A_{V10} become in 10 years:

$$A_{VR} = A_S \cdot \sum_i A_{Vi} \tag{3:11}$$

$$A_{V10} = A_{S10} \cdot \sum_i A_{Vi} \tag{3:12}$$

The plant asset value as an indicator has a range between 0 and 1, complete asset value consumption would result in a value of 0, and a completely newly built infrastructure has the value 1. Both extremes are not realistically achievable in complex and large-scale infrastructure system, even an approximation to one of these values is extremely unlikely.

Figure 3.14 shows as an example of the relationship between the capital assets of historical production and asset costs AHK and the daily value as new resp. the replacement value TNW, starting from the current year 0 and the past 40 years. It turns out, that in general, the current replacement value is higher than the historical asset costs.

It has to be considered in this context that the asset management does not use financial parameters such as investment and book values and also does not allow referring to the historical acquisition and manufacturing costs. The technical analysis of the plant material should not be based only on the assumed technical life that will be different, for example, compared to the financial amortization period very well. Any improvement of the plant asset value in the area of OPEX will disappear in case of the consideration on the basis of the depreciation values (AfA), which will thus not properly reflect the real asset value. Also a mixture of historical costs, usually an age structure over decades, does not lead to a clearly and therefore incorrect determination of the parameter. For this reason, the current replacement value is always used as a quantity of the costs that must be expended for a latest change of the asset value in case of a given task and current technology.

The development of the asset value of a plant is a very slow reacting parameter in the area of the technical control. As already described, the system aging per calendar year is included in the parameter with less than one year (statistic), even at extremely low costs of renewal. With an average useful life of 40 years or more, this means that the consequence of actions of a renewal strategy in one year or even over a period of several years does not have a significant influence on the parameter. Only the trend over a range of, e.g., 5 years

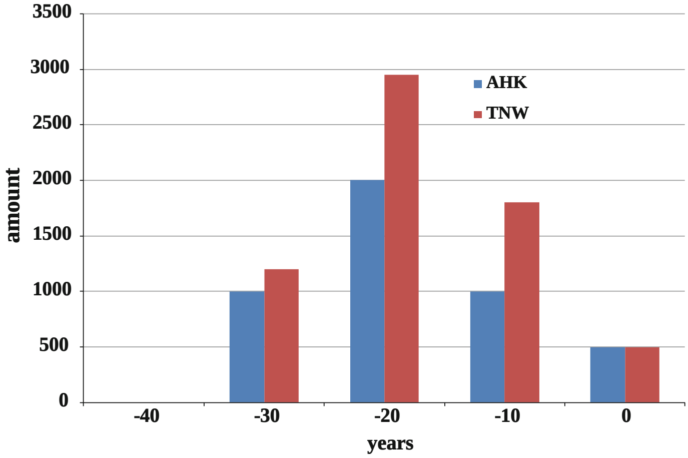


Fig. 3.14 Age structure and plant asset value. AHK historical acquisition and manufacturing costs. TNW daily value/replacement value

reveals something about the sustainability of the strategy. If a case study of an infrastructure system is considered, where in the past the strategy of continuous renewal has been applied, which has an asset value of 0.5 (average) assuming a technical life of 40 years and furthermore a very low renewal activity is assumed (only caused by outages for safety reasons or external causes), consequently, this will lead to an aging of the entire system of 0.8 years per calendar year. In other words, only about 20 % of the assets will be replaced which are no longer in technical use. Considering this approach over a period of 5 years, for example, the average age of the system increases from 20 to 24 years, the parameter of the asset value of the plant changes from 0.5 by 0.1 to about 0.4, and thus on the first glance not necessarily dramatic. A continuation of the strategy on other 5 years leads to an asset value of about 0.3 and thus with a good distance from the extreme value 0 of a system without any asset value. However, if the procedure is analyzed, the following statements can be made:

- In 10 years, all assets would have to be renewed,
- only 5 % of the assets were renewed,
- 20 % of all assets have exceeded their technical life and must be multiply repaired and extensively serviced, and
- if the technical life is correctly considered, the technical quality of system life decreases rapidly and costs of maintenance and repair increase massively.

In case of the economic analysis, at first, probably it saves renewal costs applying this strategy, but a break-even point is eventually reached due to the increased outage probability as well as the increased maintenance costs, while the saved renewal costs and the increased operating expenses are in balance. The further development leads to inefficiency with increasing speed. This phenomenon is referred to as a “breakdown catastrophe.”

The effect in the direction of reducing the asset value is also reciprocally seen in the direction of improving the value. For example, if the asset management wants to balance the loss of asset value after a period, in general, the double renewal costs have to be spent for the preservation for asset value per calendar year. Even in this case, the asset value will be changed by only about 0.1 in 5 years, i.e., the influence of measures is extremely low on the parameters.

Another consideration, when using this parameter as a management tool, is to consider the technical and service life-related homogeneity of the system. For example, the merger of an extremely new with an extremely old infrastructure may lead to a visually acceptable parameter, but a control with this value is hardly possible. Therefore, the development of the parameter should always be done in case of largely homogeneous systems. Several segments should be created and be individually controlled until the homogeneity of the overall system is achieved.

A detailing and segmentation of parameters of the asset value are possible and useful even for a downstream system. Thus, for example, a management can be fitted to run the asset value of a plant in the segment to “0” during a defined period in a technological area that should no longer be continued. Consequently, the tasks of this segment are carried out by another technology with a parameter value of “1” starting in its segment in the direction of the ideal value. An example of this is the conversion of steel pipes in water distribution networks to plastic pipes and to manage the own parameter of both technologies and the asset values can be formed.

The task of asset management in the use of the asset value is to identify the impact of the strategy with the tendency of the parameters with respect to the asset owners and to illustrate the consequence of short- to medium-term optimizations. In case of a required sustainable management of the infrastructure system, a temporary loss of the asset value always leads to lag of a renovation, which must be compensated again during a certain period. A permanent savings effect in this case does not arise.

The potential ideal value of the parameter concerning the asset value is dependent on the nature of the overall system and must be identified by appropriate boundary conditions. The asset management can definitely define that a subsequent renewal makes sense with slightly higher expenses in operation. Certainly, in this case, values between 0.3 and 0.5 are possible, higher values indicate, that the renewal was too early. The tendency of the parameter is, however, of importance. If an appropriate strategy-related ideal value has been identified, it should be kept with minimal fluctuations and thus demonstrates the implementation of the strategy. Sustainable developments in a different direction are an alarm signal for the asset management and must be counteracted.

3.2.4 Assessment of Condition

Concerning many topics that are related to asset management process the condition of equipment and system components plays a major role. Starting with the maintenance strategies until the control of the overall development of an infrastructure system, the assessment of the condition performs the essential data base for the development and decisions.

Furthermore, the assessment of the condition is ultimately a parameter. It describes the condition beginning from, e.g., “like new” to the end of life with “exchange.” The condition “outage/defect” will not be understood as an explicit part of the parameter as the cause of the outage is not necessarily consistent with the control information (such as causing a disturbance by third parties). A possible definition, which occurs repeatedly in practice, consists in a scale of four values:

1. As good as new: The equipment has just been installed and still shows no signs of wear.
2. Used with no service requirements: The equipment shows no vulnerabilities and requires no action to fill up the “wear reserve.”

3. Used, service required: The equipment must be maintained, wear parts must be replaced, and the wear reserve is depleted.
4. Replace: The equipment has reached the end of its life and should be replaced on schedule, maintenance measures for continued operation is no longer useful.

The above-mentioned condition assessment, which is classified into different classes 1–4, is corresponding to the allocation of the condition ranges I–III according to Sect. 2.1.2 (Fig. 2.3) in case of the implementation of the RCM strategy. Here, the assignment is valid:

- Section I: class 4 (renewal resp. exchange)
- Section II: class 3 (service)
- Section III: class 2/1 (new, inspection).

In reflection of particular components or groups of assets, a value for the condition assessment is deposited so that a statement can be made, in which measures are needed in the short- and medium-term. The registration of the condition is usually performed at the lowest level of the infrastructure system and is carried out by means of checklists. The parts to be evaluated and the criteria to be used are specified by the asset management to ensure that the necessary values are recorded for the aging models. The recording itself is done by the operating departments or by authorized, external service providers as part of the normal inspection activity. Consequently, the continuity of the condition detection is assured in appropriate cycles. In order to neutralize the detection of the action and, if necessary, to counteract the motivation for the generation of renewal orders, the description of the detection is carried out as detailed as possible and samples have to be taken concerning the assessment. In addition, the recorded checklists require an objectification by a superior comparison with the ratings of the same assets in other parts of the infrastructure system and other persons, which collect the data.

A group of assets will be merged by these particular evaluations into one overall assessment of a logical unit. For example, the evaluation of all circuit-breakers in a substation will be combined to a value for the circuit-breaker segment. The particular segments will be merged to the largest, individual crucial asset unit (e.g., a substation or water storage) and a single value for the condition will be assigned. This value is evaluated by the asset management aggregating the particular values to an overall assessment of the unit and therefore is also referred to as “central assessment.”

All condition values are stored in appropriate databases in the technical documentation and thus are available for automated and intelligent analysis. This database thus leads to transparency and avoids a “blind flight” of the asset management in case of the plurality of assets in a complex and extensive infrastructure system. In addition, a reporting of the condition of the infrastructure system, as well as regularly required by the regulator, is possible by this approach.

For the control of the renewal, the central review is the first indication, whether the considered unit must be replaced, which would lead to a condition assessment value of 4.

With a rating of 1 or 2, no deeper considerations must be performed because no immediate action is needed. Condition 3 of the central assessment requires a breakdown of the unity in various segments and analyzing how activities in this stage are required. If there are still no clear reviews, it is analyzed in the last stage up to the equipment level of the segments, if there are activities necessary to maintain the operating capacity of the entire unit. Thus, there is a condition assessment of the smallest unit up to the central evaluation of a total unit and subsequently a specification of the measures in the reverse direction and back to the particular equipment.

The aim of the procedure is the management of the whole system by the assessment of particular components and control of the life consumption until the date that the total unit can be replaced as a whole. To remain in this example of the substation, asset management can perform the renewal of protection as a segment. The circuit-breakers are serviced again until a certain time, both, circuit-breakers as well as the protection and the building will reach the condition value 4 and the substation can to be replaced as a whole.

The models for condition assessment also find their way into the simulation of the infrastructure system using IT systems to determine the need for development and renewal in the coming years and decades. The stored aging models describe the transition of the condition values from 1 to 4 and provide, as already described, also the basis for the strategy development of the overall system.

3.2.5 Monitoring/Diagnostic

The increased use of monitoring systems in networks is an essential basis to increase the degree of automation. While the use of information has progressed in electrical networks of high and extra high voltage levels, the medium- and low-voltage systems are characterized by the following initial situation:

- Low level of automation (e.g., switching operations have to be performed by hand on site in case of a fault as a general rule).
- High number of faults in medium-voltage systems (over 95 % of the supply interruptions have their origin in medium-voltage networks).
- The capital and operating costs are very high due to the number of installed assets.

As a result of the above-listed characteristics, in general, a very high potential for improvement exists by applying a higher level of monitoring system. Herewith, the objectives are summarized as follows

- Operational: Optimization of different processes is fault location, load monitoring and load management, remote switching of assets, etc. In particular, this area gains massively importance due to the increasing use of distributed generation in distribution

networks and thus the shift to so-called active networks. For example, smart meters have to be classified in this segment.
- Strategic: Future optimization opportunities based on detailed information, such as outage frequency of equipment (failure analysis), component monitoring, defining the maintenance strategy, optimization of network losses.
- Regulatory: Legal security and statistical basis for the regulator in terms of security of supply, measurement, and monitoring of power quality (voltage quality).

The tasks of a monitoring system consist in the transmission of messages, measured values, and control functions and in principle, the monitoring systems can be divided into two different categories, according to the duties:

The monitoring of components is an essential basis for the commitment of a maintenance strategy. In each case, the expenditure for the installation and operation of monitoring and the operational benefits in financial terms compared to savings is weighed against each other, as this is exemplarily shown on the basis of circuit-breakers in the following sections.

• Network monitoring	Provides information about the instantaneous network condition and the switch position, e.g., current, voltage, active and reactive power, switch on–off as a basis for network management and remote control
• Component monitoring	Used for monitoring control variables and conditions of assets, e.g., number of switching operations, level of capacity, temperature as the basis for condition detection and derivation of maintenance measures

3.2.5.1 Condition Monitoring Using the Example of a Circuit-Breaker

The current condition of the most important system components, such as the circuit-breakers, is essential for the reliability of the electrical system. To save a good technical condition of the equipment, appropriate maintenance measures are performed, whose cycles are defined by time-based, condition-based, or reliability-oriented strategies, Sect. 2.1.1. However, condition-based and reliability-centered strategies require the knowledge about the current condition of the circuit-breaker, which must be provided by different monitoring devices or on the basis of generally available data of experts [39].

In addition, evaluations of outage events of circuit-breakers show [10], Sect. 2.1.5.4 that the probability is high to have a fault in the same year in which a maintenance action has taken place. Basically, this phenomenon allows two conclusions in order to achieve an improvement of the fault behavior:

- Intensive training of maintenance personnel, possibly, the origin of the outage was not found,
- better diagnosis and monitoring procedures to indicate clear fault localization.

This means that a further improvement of maintenance activities could be possible, if a better and faster localization of the fault is possible due to additional instruments. It is of particular importance which fault of the equipment can be already detected during the appearance by various diagnostics and monitoring procedures. The ability to detect initiating faults by a trend analysis is a necessary requirement for the transition, for example, from the time-based maintenance to condition-based. Consequently, the probability is important that outages of the assets can be avoided, as the additional efforts for the condition detection (measuring devices, evaluation) must be covered by the avoided outage costs, as described in Sect. 3.1.3.1.

In addition, the possibility to detect a fault in the initial stage has advantages due to operational reasons, because in these cases (“minor” fault), a scheduled maintenance may be performed without interruption of supply, so that a “major” fault will not occur with an immediate switching off operation of the device.

Several methods are possible for the condition determination, which can be divided into two different groups as follows:

• Diagnosis	Investigations for the condition determination that require an out of operation of the device (off-line)
• Monitoring	Investigations for the condition determination that can be conducted during operation of equipment (online)

Which method is used depends in detail on several circumstances; this includes components, operating experience, the costs of condition identification and evaluation and of course, and the efficiency to detect faults at the devices. For this reason, the probability of faults at components is shown below, which can be detected, e.g., high-voltage circuit-breakers, and which efficiency can be expected by applying different measurement methods for condition evaluation.

3.2.5.2 Efficiency of Diagnosis and Monitoring Procedures

For testing the diagnostic methods of circuit-breakers, a database is used, which is described in detail in [28, 41, 42], and in total, 6000 faults or damages are registered. Figure 3.15 gives an overview of the faults contained in the database, in this case SF_6 and minimum oil circuit-breakers are considered with mechanical and hydraulic drives. It is visible that 38 % of faults refer to the drives, of which again 95 % belong to the hydraulic type, which is in accordance with Table 2.15, Sect. 2.1.5.3. The other comments refer to the illustration in [42].

An efficient diagnostic method is characterized by the detection of a large number of faults during the development which actually occur. In this case, different values are monitored this includes continuous signals (e.g., current of the tripping coil) or discrete signals (e.g., status of the auxiliary contacts). All measurement methods, which are currently used in practice, were described in the study regarding the necessary input variables to assess an outage. In addition, there is a definition, by which variables different fault classes are basically detectable according Fig. 3.15. Finally, the effectivity of the measurement method could be derived on the basis of the outage collective.

Figure 3.16 shows the efficiency of various diagnosis methods referring to the fault detection of circuit-breakers with a hydraulic drives. The picture represents a matrix: a number on the x-axis is assigned to each outage according to the frequency, as listed in Fig. 3.15, and in total 5294 faults are taken into account. All diagnostic methods are

function group	faulty component in %				
drive	38	hydraulic drive	95	leakage	72
				pump	12
				motor	4
				valve	2
				others	10
		spring drive	5	damper	28
				latch	24
				spring	8
				motor	9
				others	31
control	30	pilot switch			26
		relay unknown			7
		density watcher			7
		heating			6
		relay heating			5
		others			49
life parts	12	grading capacitor			43
		breaking unit			15
		SF6 filter			14
		high current contacts			12
		drive insulator			9
		piston rod			4
		others			3
insulator	8	different			100
others	6	different			100
unknown	6	different			100

Fig. 3.15 Fault behavior of SF_6 and minimum oil circuit-breakers with hydraulic and mechanical drives [42]

applied on the y-axis, which can be generally used in case of minimum oil and SF_6 circuit-breakers with the hydraulic drives for fault detection. If a particular outage can generally detected by one or more diagnostic procedures, this indicated by a “green” bar. The efficiency of a diagnosis can be derived by summing up the green bars relative to the total number of faults and on the right-hand side, the percentages illustrate the probability that this process is able to discover the occurrent faults. In addition, all outages are sorted with respect to their detection ability.

Figure 3.16 shows that about 60 % of the faults are detected of these circuit-breakers with all sorts of monitoring methods. In case of a circuit-breaker with a hydraulic drive, the very high number of failures is characterized by various leakages at the hydraulic drive and for this reason methods are particularly efficient that can identify this type of fault. These include:

- Position of the energy storage (32.8 % of the actual occurred failures),
- motor current profile (26.3 %),
- motor start-up frequency of motor starting (18.1 %), and
- oil level in drive reservoir (28.7 %).

However, it is recognized that this diagnostic or monitoring procedures partially recognize the same problems, as can be seen by the overlapping of the green bars. In addition, methods are of great importance which detect

- SF_6 leakages of the switching chamber resp. and
- N_2 leakages of the energy storage.

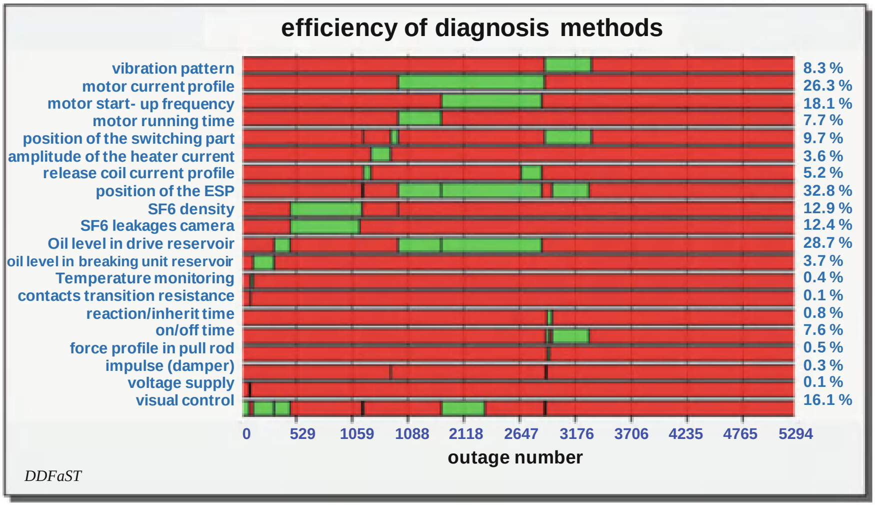


Fig. 3.16 Efficiency of diagnosis parameter of SF_6 and minimum oil CB with hydraulic drives [42]. Green detectable failures; red non-detectable failures

A surprisingly high number of failures, such as external leakage, corrosion, or broken parts, can be detected by a visual observation (16.1 %). This leads to the conclusion that the periodic visual observation of the circuit-breaker may be quite efficient due to this requirement.

While the efficiency of failure detection is shown by various methods in Fig. 3.16, the additional information is of interest for the assessment under which boundary conditions the failure detection is possible. For this reason, Fig. 3.17 is similar to Fig. 3.16, but the additional information for failure detection is shown on the y-axis, this includes answering the following questions:

- When can the failure be detected?
- Can the faulty component be identified?
- Is a development of the failure discoverably (trend detection)?
- Does the failure lead to an outage of the equipment?

Figure 3.17 shows that 56.6 % of all failures can be detected during the down time of the circuit-breaker, which is a consequence of the detection of leakages. This type of failure can be relatively well localized (43.9 %), and this strongly influences the rate to detect a failure trend already during the development (38.1 %).

In addition, it is essential that in case of the considered collective, 55.8 % of the failures do not result in an immediate break down of the equipment at the moment of failure identification.

Different results can be observed in case of the evaluation of a changed collective, as Figs. 3.18 and 3.19 show for SF_6 and minimum oil high-voltage circuit-breakers with a

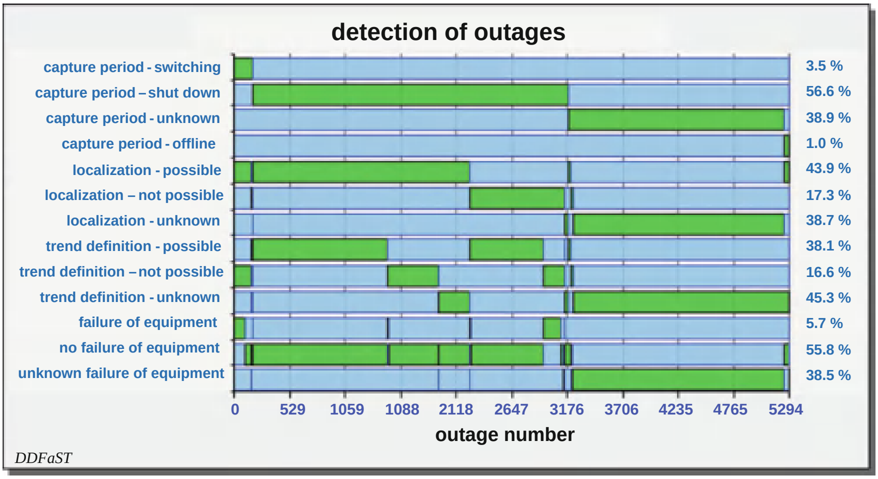


Fig. 3.17 Additional data for the capture of failures for SF_6 and minimum oil CB with hydraulic drive [42]. Green yes; blue no

mechanical drive. But only 923 failures have been evaluated, because of the low failure rate of mechanical drives. Unlike circuit-breakers with a hydraulic drive, a total of only 40 % of the actual failures of the mechanical drives are recognized by diagnostic or monitoring procedures. The lower percentage is a consequence of the typical failure in hydraulic drives that are well detected by suitable sensors. It shows that methods, which are able to detect mechanical problems, are particularly suitable in such cases. The most efficient diagnostic parameters of the actual failures are as follows:

- Position of the switching part (18.3 %),
- on/off time (11.2 %),
- reaction/inherit time (10.5 %), and
- visual control (12.0 %).

Nearly all failures that can be detected by sensors are properly localized (38.0 %) according to Fig. 3.18, in other words, an accurate failure location makes it easier for the subsequent maintenance. The trend detection, however, is in most cases not possible (9.1 %) and furthermore, the failures that lead to plant outage (9.1 %) and the number of failures is greater than compared to a circuit-breaker with a hydraulic drive.

3.2.5.3 Assessment

The investigations show that basically not all failures, for example, of a circuit-breaker, can be detected by diagnostic or monitoring procedures. So that in case of a circuit-breaker with a hydraulic drive, about 60 % of the actual occurred failures can be detected, while this proportion decreased to about 40 % when mechanical drives are considered.

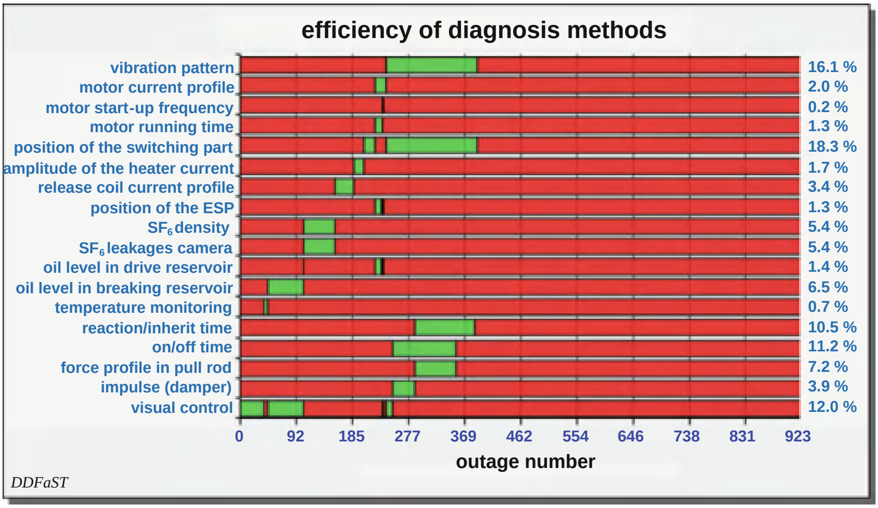


Fig. 3.18 Efficiency of diagnosis parameter of SF_6 and minimum oil CB with mechanical drives [42]. Green detectable failures; red non-detectable failures

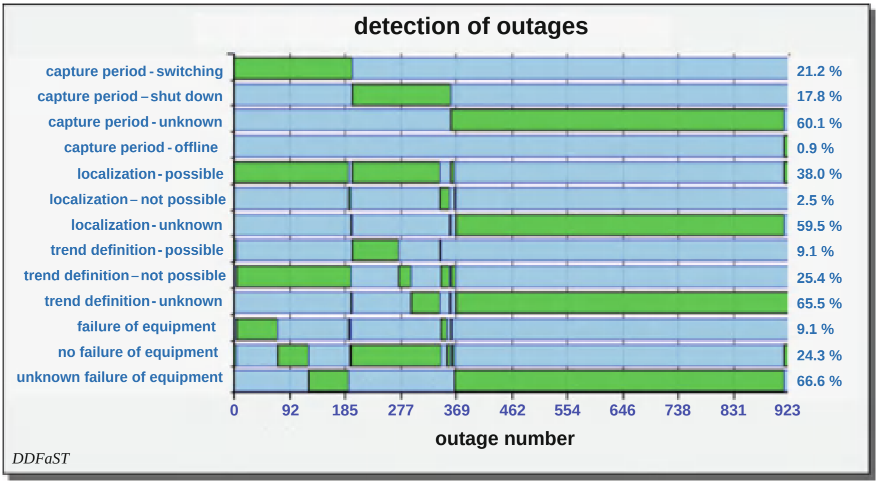


Fig. 3.19 Additional data for the capture of failures for SF_6 and minimum oil CB with mechanical drive [42]. Green yes; blue no

This situation is always to be taken into consideration when the condition-based maintenance for equipment should be introduced because not all failures can be detected in the form of a trend analysis. This means that the financial costs of the condition detection cannot be fully achieved by reducing the outage costs, as this is shown in Sect. 3.1.3.1 [6].

It has to be taken into consideration that not only the investment costs of the condition devices but also the data analysis and data management costs must be taken into consideration compared to the expected annual outage costs caused by failures. In this case, the reduced expenses must be deducted due to the saved maintenance measures. In addition, the reliability of such diagnosis or monitoring systems is to be considered as not to worsen the availability of the overall system. For this reason, for example, an expensive online monitoring of a circuit-breaker will not be useful, but it should be used for particular cases as support for an off-line diagnosis instead of an area-covering installation.

In the future, it will automatically come to a stronger data generation due to the change of the energy systems in the context of the energy turnaround in Germany, the planned expansion of smart meters at feed-in plants as well as more customer connections and the expected increasing degree of automation, especially in the local network stations and in the medium-voltage network. On the one hand, new components for condition or function detection will go into operation in distribution networks, but also corresponding communication networks and data storage for the transport and processing of these data. With the emergence of this total new infrastructure with intelligent components in the coming years, the use of observation (monitoring) will have to be evaluated newly and economically in medium- and low-voltage networks, since additional monitoring functions can be realized with little additional costs.

3.2.6 Risk Analyses

The risk analysis is generally the part of asset management, which is subjected to the greatest misunderstandings. By this, it is not meant that risks are deliberately accepted to meet the business objectives, but the task is to identify risks within the entire business process to initiate subsequently and implement appropriate measures to reduce the risks. At the same time, a ranking of the necessary maintenance measures will be developed as a ranked list of projects is created with decreasing risks. The advantage of a risk assessment is therefore to start with the project, which leads to the greatest risk reduction from the company's perspective.

The reliability calculation as a basis of a maintenance strategy leads to the result that assets are critical in terms of an interruption of supply. However, this is only a first step toward a decision in terms of an optimized maintenance measure, as a cost assessment of all expenses, arising from a failure, is not listed. Therefore, a subsequent risk assessment includes not only the consideration of the ENS but also other costs of an outage to be compared with the financial expenses for maintenance. Following, a risk assessment of equipment is performed, and the required information for such a process is listed.

Basically, the risk analysis and the risk management are one of the essential tasks of the asset manager regarding the functionality and reliability of the infrastructure system.

In general, three different risk areas can be distinguished, which describe different goals in detail. These risk areas are as follows:

- Risk of the investor: The interest is to get in a certain time the invested capital back, including an appropriate rate of return.
- Risk of the project: In this case, the target is whether the project is able to provide the desired performance in a designated time, considering the costs.
- Risk of the system: In this area, the "performance" of the entire system is understood; this means the availability resp. the reliability of the network.

Considering the role model, the first bullet point relates more to the asset owners, the second point is usually a case-specific management tasks at the macro level. Therefore, the following comments refer to the last of the above risk areas, as the supply task of the system operator is regarded as the target value of a risk assessment.

3.2.6.1 Procedure for the Risk Management

The aim of a risk assessment is to find the combined optimum of several ranges of influence and it is generally not the case that this optimum results from the sum of the sub-optima. Due to Fig. 3.20, the areas, asset/equipment, system, and economic/finance, can be defined, which are essential for a risk assessment, so that the "Triangle of Risk Management Process" can be formed. The influences have to be assessed by the subsequent process:

- Asset/Equipment: Technical condition of the equipment (in terms of standards and legal requirements) resp. the accepted technology of the equipment and
- System: Impact on the quality of supply resp. the duty of supply of the company, and
- Economic/Finance: Low LCC, optimal ratio of capital and operating costs, financial situation of the company, and cash flow.

Here, it is useful to choose a uniform scale for the summing up assessment so that all sub-risks are expressed on the basis €/per year. If in contrast, a reference of risks to a common basis is not possible, a multi-criteria optimization is useful, as this is described in Sect. 3.5 using the example of game theory.

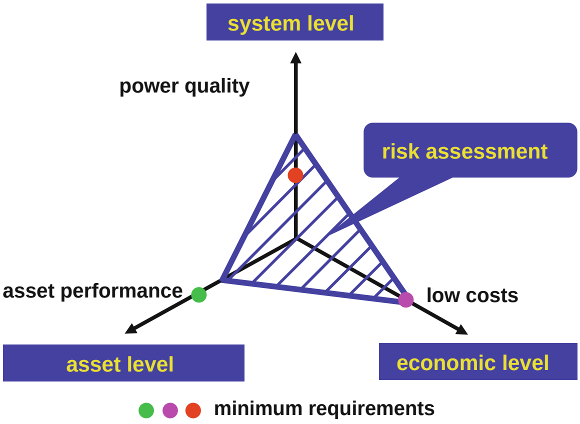
The basis of a risk analysis includes both, the detailed knowledge about the condition of various assets, the influence, and impact of a maintenance measure on the failure behavior; and the feedback to the non-availability of electrical energy of the entire system.

Moreover, in general, other influences have also to be evaluated, which include, for example, the environmental and social components, and can be described as society (public opinion, corporate image).

The requirements of corporate governance are highlighted in Fig. 3.20 by points on the respective axis, which represents the minimum requirements that must not be exceeded. For example, corporate targets could be as follows:

- Asset/Equipment level: Determination of minimum technical requirements or exclusion of risk technologies (e.g., no installation of oil-filled cables).
- System level: Definition of reasonable outage duration of electrical energy or specifications of the regulator or standards.
- Economic/Finance level: Limitations imposed by the maintenance budget and the impact of measures on the funding possibilities.

Fig. 3.20 Triangle of the risk management process [4]. Green circle, pink circle and red circle minimum requirements



The current values can be joined to form a triangle determining the combined optimum taking into account the company specifications.

When a risk analysis is performed to decide future maintenance decisions, it is assumed that the future development of the network is taken into account in each case. This is given when defined system questions in terms of network development have clearly to be answered, similar to the procedure in Sect. 2.1.3.2. These include, for example,

- Future change of feeding nodes (new construction or deconstruction of a power plant).
- Change of the power output in the near future due to changed supply nodes?
- Is a change of rated voltage provided, e.g., reduction of the 220 kV transmission level and extension of the 380 kV level?
- Are there changes in technical requirements (short-circuit currents, performance, reliability, customer requirements, specifications of the regulator, revision of laws, standards, etc.)?
- Is a merger provided with another company or is a change of ownership expected?

The above-stated questions can be company-specific, extended, or reduced, and mean that a maintenance task is not performed or special considerations are necessary in individual cases if any of these questions is answered with “yes.”

Definition of a risk

A risk assessment attempts to give an answer to the following essential questions [34]:

- What can be done and why?
- What are the consequences?
- How likely is the occurrence of the event?

In general, a risk is defined as the product of two parameters, namely the probability of a failure and the resultant consequences of a failure, so that the definition is valid:

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

related to the outage event. In this connection, only outages with damage are used according to the definition in Sect. 3.2.1. Figure 3.21 shows the general workflow when performing a risk assessment and the subsequent consideration to reduce risks, if this is necessary.

• Asset, system	Based on the assets of the entire network, the significant variables are analyzed with regard to an outage of components or a supply interruption at a network node
• Outage: consequence	The consequences are in particular to define and to describe for each possible outage
• Outage: probability	Failure rates from the history must be derived for the disturbed equipment
• Risk: identification	Calculation of the different risks in case of different outages (based on €/per year), alignment of a list of priorities, representation in a risk diagram Fig. 3.22
• Risk: assessment	Assessment of the risks in respect of the objectives of the company
• Assessment of measures	Assessment of maintenance measures to reduce the risks to acceptable values
• Risk: treatment	Implementation of the appropriate maintenance measures

The probability of a failure depends on the failure rate of the equipment, which is in operation, while the consequence is a question of the outage impact, for example, the costs of renovation, the ENS, personal injury. Risk diagrams are used in order to visualize the relationships, as this is illustrated by Fig. 3.22. Here, each fault is evaluated based on the probability of occurrence (y-axis) and on the possible consequences of a failure (x-axis). While the dimension of the probability is uniformly determined: failure per equipment and year (1/a), but under certain circumstances, the classification in terms of consistency is difficult because a financial assessment is not always possible, such as for personal injury and image of the company. Nevertheless, the financial evaluation of risks and thus establishing a basis for decision making remains the goal of the risk management. Here, it is still possible to achieve a refinement by gradation of the consequence in occurrence of the risk, such as high damage, medium damage, and low damage.

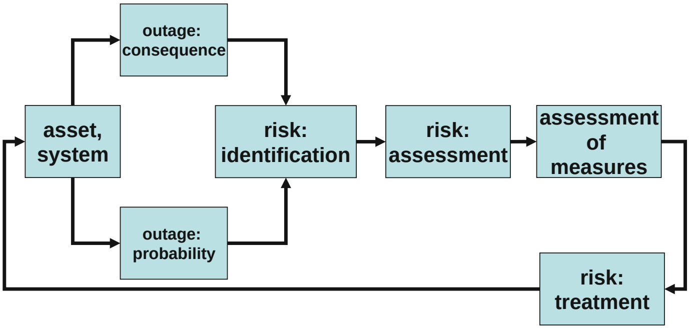


Fig. 3.21 Workflow of a risk assessment

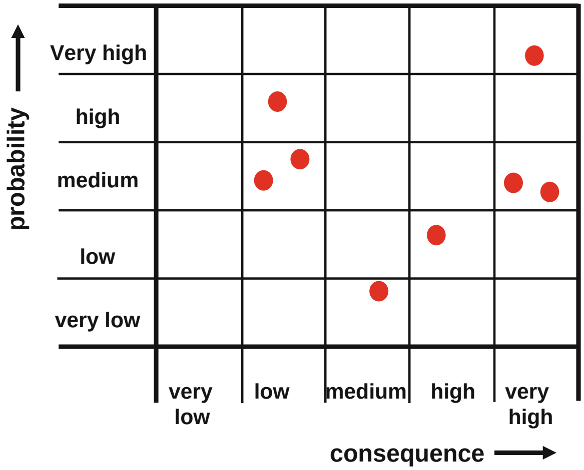


Fig. 3.22 Risk diagram for the assessment of outages

The classification of the two axes can be carried in defined classes starting with "very low" until "very high." Thus, the representation according to Fig. 3.22 helps to identify the risks in the network, such as an outage should be registered with a high probability and large consequences in the upper right half and vice versa in the lower left half.

In addition to the representation (Fig. 3.22), tolerance zones can be introduced according to Fig. 3.23 which can be visualized by different risks, for example,

Low risk	Medium risk	High risk

If an outage assessment is within a field that cannot be accepted, appropriate action is to be applied to reduce the existing risk to an accepted level.

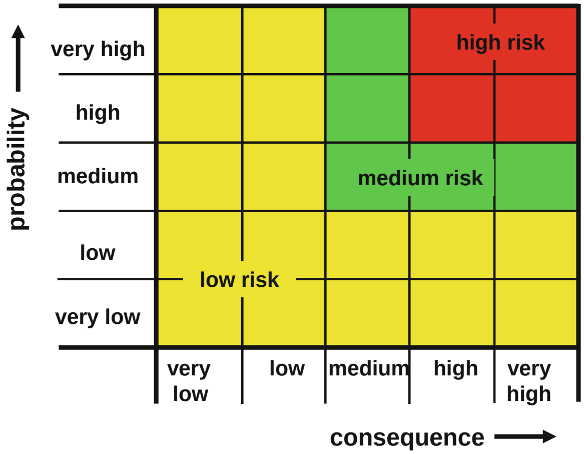


Fig. 3.23 Risk classification

The following maintenance tasks can be assigned to the risk classes according Fig. 3.23:

- High risk: The risk is to be reduced by appropriate measures within a specified time, such as 6 months, to a medium risk.
- Medium risk: The risk is to be reduced by appropriate measures within a certain time, such as 12 months, so that no further actions are necessary.
- Low risk: No action is necessary.

Assessment of measures

Based on a risk diagram according to Fig. 3.22, it is possible to evaluate different maintenance activities of equipment, which is exemplarily shown for the equipment (red dot) in Fig. 3.24.

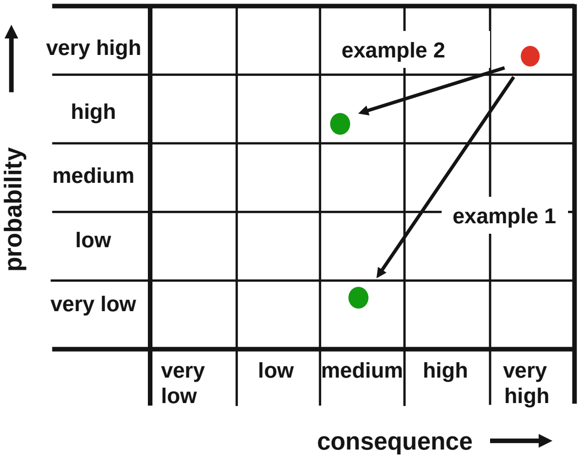
It is assumed according to Fig. 3.24 that two variants for a maintenance action are possible related to the equipment (green dots), which lead to a reduction of the risk and is characterized by two examples 1 and 2. It follows, that example 1 leads to a greater risk reduction (Drisik_1), but the financial burden is taken into consideration for a final evaluation. Consequently, the effectiveness of a measure can be evaluated according to Eq. (3.13) by the risk reduction related to the financial expense involved.

$$g = \frac{\mathrm{Drisk}}{\text{costs of the measure}} \qquad (3{:}13)$$

A sequence can be performed in case of different projects by rating according to Eq. (3.13). In any case, however, it has to be ensured that the new risk assessment can be accepted after the maintenance action for the operation of a network.

The basic procedure of the evaluation is that the maximum permissible risk of a probable equipment failure is previously defined. When exceeding this limit, a maintenance action will be required. An optimization in this case is only possible, if two maintenance measures are available, such as replacement or overhaul/service.

Fig. 3.24 Assessment of risk measures



Example for risk classes

In principle, a risk diagram can be derived according to Fig. 3.22 for different areas, for example, [20, 22]:

• Finances	The company evaluates a failure-free financial situation. The indicators are, for example, EBITDA, EBIT, ROIC, liquidity
• Quality of supply	In this context, the following quantities are evaluated: interruption time, power quality, timely delivered, or supplied energy, etc.
• Safety	Evaluation of safety in relation to the individual employees and third party: number of industrial accidents
• Jurisdiction	Evaluation of activities related to legality, for example, expected introduction of laws
• Image	Evaluation of corporate image in the public, e.g., newspapers, television, customer satisfaction, price performance ratio
• Regulator	Evaluation of the activities in accordance with the requirements of the regulator, increasing efficiency, etc.
• Environment	Impact on the environment, such as environmental damage (leakage of oil, etc.), value of energy not supplied, etc.

Exemplarily, the risk classes listed above demonstrate some ways that can be considered in a risk assessment. But, depending on the company management, it will be often useful in practice to focus exclusively on the segments “financial, quality of supply and the environment,” because, for example, risk in the area “safety” will not be accepted due to the laws.

Starting from these areas, a classification of the consequences and the probability of failure are determined, which depends in general on the individual assessment of the company. As an example, Figs. 3.25 and 3.26 show different ways according to [20]. A difference is made due to the figures between “hard” and “soft” facts because the risk classes differ in assessing the consequences.

The risk chart can be used for the final risk assessment according to Fig. 3.23, as this is generally marked in Fig. 3.27 as the vertical line represents the failure probabilities and the horizontal line the degree of failure consequence (moderate, serious, difficult, and catastrophic).

In terms of risk classifications (VH, H, M, L, VL), various activities can be defined to reduce the risk due to the specification of the company. According to [20], the following measures are used in this case:

• VH	Very high	A maintenance action is immediately necessary
• H	High	A maintenance should be carried out as part of normal maintenance cycle
• M	Medium	Should be pursued over the next few years
• L	Low	Need not be considered at the moment
• VL	Very low	Can be neglected

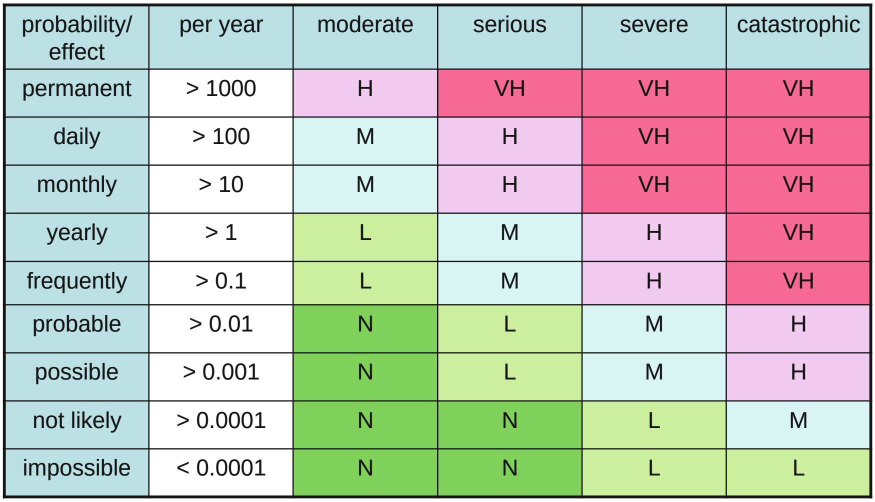
per incident	financial "damage"	quality "1.5*kW*min"	safety "victims"	legal "penalty"
catastrophic	> 10 M€	> 10 Mmin	several death	loss of license
severe	1 – 10 M€	1 – 10 Mmin	1 death/ heavy handicap	imprisonment
serious	0.1 – 1 M€	0.1 – 1 Mmin	1 disabled	heavy fine
moderate	< 100 k€	< 100 kmin	longlasting absenteeism	condemnation

Fig. 3.25 Example of the assessment of consequences [20], “hard factors”

per incident	image "attention in press"	regulator "corrections"	environment "clean-up-costs"	image "authorities"
catastrophic	> 1 month (national)	structural clashes	> 10 M€	structural clashes
severe	weekly national, month regional	single conflict	1 – 10 M€	single conflict
serious	TV-program: national article, week regional	dozens of corrections	0.1 – 1 M€	dozens of corrections
moderate	regional article, complaint in newspaper	< 10 corrections	< 100 k€	< 10 corrections

Fig. 3.26 Example of the assessment of consequences [20], “soft factors”

According to Fig. 3.27, it is thus possible to evaluate particulary the different risk classes according to their urgency and to arrange the appropriate action. If a uniform assessment standard is possible, for example, “€/per year,” the individual results can be combined to an overall result, which may have a different weighting.



probability/ effect	per year	moderate	serious	severe	catastrophic
permanent	> 1000	H	VH	VH	VH
daily	> 100	M	H	VH	VH
monthly	> 10	M	H	VH	VH
yearly	> 1	L	M	H	VH
frequently	> 0.1	L	M	H	VH
probable	> 0.01	N	L	M	H
possible	> 0.001	N	L	M	H
not likely	> 0.0001	N	N	L	M
impossible	< 0.0001	N	N	L	L

Fig. 3.27 Example of the resultant risk assessment, risk diagram [20]

3.2.6.2 Extended Risk Assessment

The specified method of risk assessment, described in Sect. 3.2.6.1, using a risk graph, represents the relationship between the probability of failure and the consequences. However, a comparison is missing related to the expenses which may prevent the outage, for example, by a maintenance resp. overhaul or by a replacement of equipment ahead of schedule. For this reason, an extended evaluation is possible, which allows the consideration of the failure and the maintenance costs. Figure 3.28 shows the principle flow chart [4, 5].

The basis for the evaluation is the outage probability of equipment, so it is essential to know the failure rate as a function of the time after commissioning or after the last maintenance or overhaul [11]. In parallel, the energy not delivered or not fed—which is caused by the failure of the equipment—is determined by a reliability calculation. During both actions, company-specific requirements in terms of equipment (e.g., technology) and the system (e.g., network reliability) are taken into consideration. The outage costs are the result of this calculation, taking into account any expenses that might be regarded as a consequence of failure (repair, replacement, evaluation of energy, etc.) and thus the result represents the value of the risk according to Eq. (3.13). Finally, the probable annual failure costs can be compared with various maintenance costs. In this case, in principle, it can be distinguished between different maintenance strategies resp. the transitions to renewal strategies [45]:

- Extension of the useful life by an overhaul: Realization of an intensive overhaul to shift a replacement investment for a certain time period.

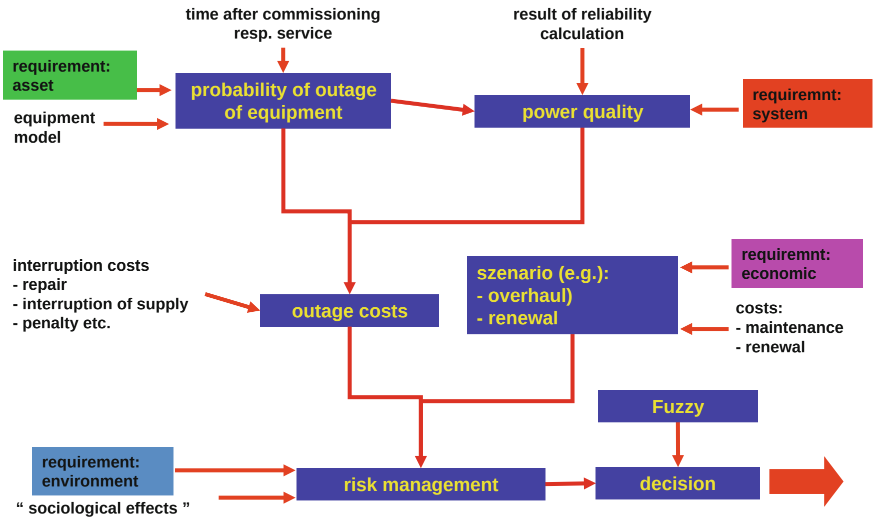


Fig. 3.28 Flowchart of the risk assessment procedure [4]

- Renewal by replacement: All components of a system will be replaced the network remains unchanged regarding the structure.
- Renewal by a partial replacement (retrofit): Some components of a plant will be replaced, so that these parts can be considered as new, the network remains unchanged.
- Upgrading or renewal: Partially, the network is technically upgraded, for example, by increasing the current capacity or short-circuit strength.
- Redesign of the network: The structure of the network is partially modified, e.g., changing the voltage or any other network connection of the plant.
- Corrective maintenance: No maintenance is performed, because the failure of the equipment does not affect the supply essentially ("wait and see").

Finally, an evaluation of these costs takes place using the "sociological effects" according to Fig. 3.28 ("soft" factors according Fig. 3.26, e.g., social consequences and loss of image due to a failure, frequency). Even in these cases, company specifications are included in the analysis in terms of finances and the environment. If a decision regarding a scenario is defined, considerations for the implementation are necessary, for example, more components of a plant have to be replaced in order to keep the total expense low. In this context, decision techniques are helpful under consideration of fuzzy logic when complete substations are assessed, Sect. 2.1.3.

The basis for the risk assessment is the consideration of the probable failure rate of the component in the next year, in conjunction with the resulting financial costs (outage costs). These costs are compared with the maintenance costs for different scenarios of the equipment in order to avoid this outage or to restore the functionality of the system. In each case, the costs of various scenarios include the expected failure costs of the new or the serviced equipment, generally, outages will occur even after a repair/replacement. If these maintenance costs are less than the probable outage costs, a maintenance activity is useful to that extent. The basic procedure is shown by the following example for the evaluation of high-voltage circuit-breakers.

Basically, this assessment procedure should be performed in two steps to derive the optimal maintenance action:

- Variant A: Comparison of risk (original condition) with the risk after the maintenance action “overhaul/service” including the outage costs of the serviced equipment,
- Variant B: Comparison of risk (original condition) with the risk after the maintenance measure “replacement,” including the outage costs of the new equipment.

This takes into account that only the maintenance tasks “extension of useful life by an overhaul” and “renewal by replacing” are considered due to the present description of the maintenance scenarios. While the corrective maintenance of risk calculations corresponds to the original state.

The appropriate maintenance action can be selected for the particular equipment by the comparison of these two assessments, whereby the transition to a corrective maintenance for this equipment is also possible. This is appropriate, if the likely outage costs are always lower than the expected costs of the maintenance action (replacement or overhaul/service of the equipment).

In case of the risk assessment and the determination of maintenance activities, it has always to be considered that risks, previously defined by the organization, should not be exceeded regardless of the cost-effectiveness of the maintenance action independent of the risk reduction.

In the following, in total 14 high-voltage circuit-breakers are considered with different extinguishing medium, the following types and voltages are assessed according to Table 3.10.

The condition and importance evaluation leads to the values of c and i according to [9] or Sect. 2.1.2.2, Table 2.2. In total, 23 criteria are answered for the condition evaluation,

Table 3.10 Equipment collective regarding a risk assessment

No.	Voltage (kV)	Type
1–6	123	SF_6
7–8	123	Minimum oil
9	123	SF_6
10	123	Air blast
11	245	Air blast
12	420	SF_6
13	245	SF_6
14	420	Air blast

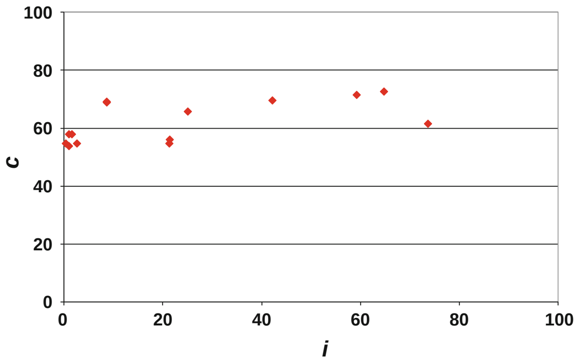


Fig. 3.29 Condition—importance assessment of different circuit-breakers

which describe the condition of a circuit-breaker sufficiently. The following criteria are considered for the evaluation of the importance: voltage level, interrupted active power of the circuit-breaker in case of outage, failure rate, and location in the network. The result is shown in Fig. 3.29. If the condition with a rating of $c > 50$ is recognized as a threshold to replace a circuit-breaker, it can be seen that all the circuit-breakers exceed this value and a risk assessment is useful to determine the actual need for action and the order.

Various possibilities are considered in case of the following risk assessment:

- Corrective maintenance ("wait and see"), this means no maintenance action is applied,
- improved service of the equipment to shift the replacement, and
- immediate replacement of the equipment.

In the following, two different types of costs (outage and maintenance costs) are determined in order to make subsequently a comparative assessment.

Outage costs

The failure rates λ of circuit-breakers have a significant impact on the calculation of the probable failure costs which are to be expected due to the results of a "major" or "minor" failure. Starting from an outage statistics in Germany in the time range from 1991 to 2000, the following failure rates ("major" failure) are used depending on the voltage level and type of circuit-breaker, Table 3.11.

Table 3.11 Failure rate λ (failure per circuit-breaker and year) for "major" failures

Type	123 kV	240 kV	420 kV
Minimum oil	0.0021	0.0104	0.0203
Air blast	0.0039	0.0114	0.0319
SF_6	0.0024	0.0144	0.0260

The ratio depending on the voltage level can be specified for the correlation between "minor" (mf) and "major" (MF) failure according to [19]:

- 123 kV: 7.0 mf/MF
- 245 kV: 8.6 mf/MF
- 420 kV: 6.4 mf/MF

This means that, for example, 7.0 "minor" failures occur on an average related to a "major" failure for a 123-kV circuit-breaker. The information in Table 3.11 has been used to determine the probable annual failure costs, which include the costs of repair and the costs of the ENS. If the repair costs of a "major" failure are recognized on average with about 25 % of the investment costs for a new circuit-breaker, it is possible to estimate the annual repair costs depending on the failure rate λ. Repair costs of 1.0 k€ are assumed for a "minor" failure, regardless of the installed type of circuit-breaker.

In general, the calculation of the ENS takes places with the help of a reliability calculation for the entire network, so that the effects of the equipment failure on the network nodes can be determined. The result is that the ENS at the network nodes is substantially depending on the topology and the redundancy of the network (e.g., radial, meshed). For simplicity in this context, the interrupted energy E is determined by the following relationship in the case of an outage by a faulty circuit-breaker,

$$\mathsf{E} = \mathsf{P} \cdot \mathsf{T}_\mathsf{S} \cdot \mathsf{k} \tag{3:14}$$

where

E energy not supplied,
T_S switching time, e.g., 20 min,
λ failure rate of the considered equipment

The determined value according to the Eq. (3.14) should generally be estimated on the conservative side and can only be applied for radial networks. In principle, two different approaches exist for the evaluation of the ENS, which must be considered in each individual case:

• Loss of revenue	The amount of energy not supplied leads to loss of revenue of the energy company. It is possible that the energy can be sold depending on the customer behavior at a later time, so the loss is reduced. The evaluation is based on billing costs, e.g., 0.1 €/kWh for the low-voltage level
• Economic loss	A financial loss arises on the customer side in dependence on the production process due to the interruption of the energy. The evaluation depends specifically on the supplied customer structure and is evaluated in this case, with 5 €/kWh as a mean value

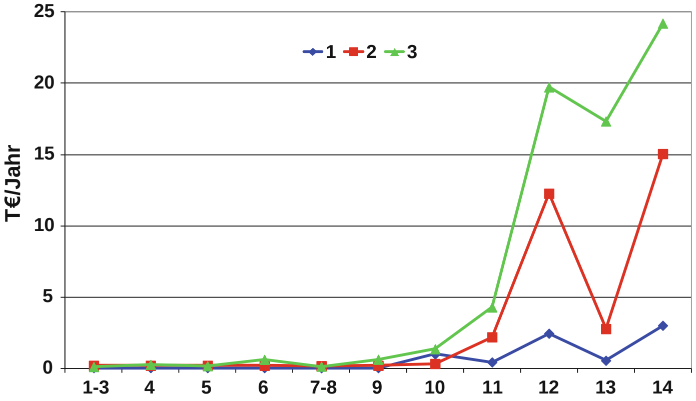


Fig. 3.30 Annual outage costs of different circuit-breakers (1–14). 1 Actual failure rate λ according to Table 3.11, costs of energy not supplied are not considered. 2 Fivefold failure rate λ according to Table 3.11, costs of energy not supplied are not considered. 3 Current failure rate λ according to Table 3.11, costs of energy not supplied are considered

The economic loss is exclusively considered during the further consideration, as contrary, the loss of sales is of minor importance in case of the financial evaluation. In addition to the above-mentioned costs, damages to other components are assumed, which have an average value of 15 % of the investment costs for a new circuit-breaker. The outage costs as a function of various parameters are shown in Fig. 3.30.

In case of a fivefold failure rate, it is assumed that an increase in the failure rate can be expected as a result of the poor condition and the age of equipment. It can be seen that the costs of ENS have the greatest impact on the outage costs (curve 3, Fig. 3.30), if a value of 5 €/kWh will be assumed, whereas the repair costs of the circuit-breaker can be almost neglected. This is even true, if a 123-kV circuit-breaker (circuit-breakers no. 3 and 6) is observed with the current failure rate (curve 1, Fig. 3.30).

Maintenance costs

According to the above explanations, in total three different maintenance scenarios are possible, but in the following, only two strategies are evaluated

• Variant 1 (overhaul)	Improved maintenance for shifting the replacement investment by a certain time period (e.g., 6 years)
• Variant 2 (replacement)	Immediate replacement of the equipment, no overhaul, and inspection costs have to be taken into consideration in the period under review

The strategy “corrective maintenance” results automatically because no maintenance costs will arise in this case.

Table 3.12 Maintenance costs (k€) of aged circuit-breakers (exemplary)

Type	123 kV	240 kV	420 kV
Minimum oil	10	15	30
Air blast	15	25	50
SF_6	5	10	20

The financial costs of an improved maintenance for the different circuit-breakers can be taken from Table 3.12. In addition, it is assumed to determine the present value that a modern SF_6 circuit-breaker requires an overhaul after 12 years (maintenance costs: 123 kV: 2.5 k€; 245 kV: 4 k€; 420 kV: € 5 k€) and an inspection is required after 6 years (costs: * 800 €).

In determining the expected annual costs, a useful life of the equipment of 25 years is assumed. This means that for variant 1 (overhaul), the circuit-breaker is depreciated after 25 years and only the yearly annuities of maintenance expenditure are considered for the period of 6 years. In the other case (variant 2), shifting the reinvestment for 6 years by a single overhaul, a net book value results in accordance with a useful life of the new circuit-breaker of 19 years. An interest factor of $p = 6.5\ \%$ is applied for the calculation of the annual costs. In addition, it is assumed that in case of a replacement of a circuit-breaker, in any case a new SF_6 circuit-breaker of the same voltage is taken into account. The financial costs of a new investment are depending on the voltage level:

- 123 kV: 25 k€
- 245 kV: 75 k€
- 420 kV: 215 k€

Figure 3.31 shows the maintenance costs for the considered circuit-breakers over a period of 6 years. The annual costs for a replacement of the 420 kV circuit-breakers (curve 2, No. 12, 14) comes to about 18.5 k€ as a result of the high investment costs for a new equipment. In contrast to this, the costs of an overhaul for the devices no. 1–6, 9 are higher than the investment costs.

Assessment of the result

Different costs (maintenance, outage) must be compared with a final evaluation and the results are shown in Figs. 3.32 and 3.33. The bars, contained in these images, illustrate the costs according to Figs. 3.29 and 3.30 and the risk that arises from the difference between the two types of costs. Here, the following combinations are compared, in each case taking into account the financial evaluation of the ENS due to an outage:

• Variant A	Outage costs (curve 3, Fig. 3.30) versus costs for overhaul (curve 1, Fig. 3.31)
• Variant B	Outage costs (curve 3, Fig. 3.30) versus costs for replacement (curve 2, Fig. 3.31)

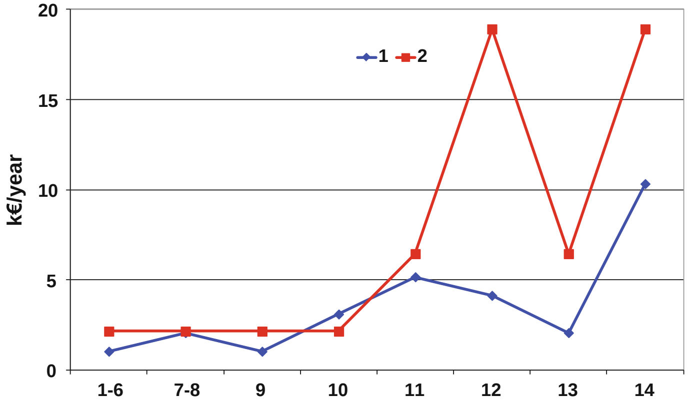


Fig. 3.31 Annual maintenance costs for different circuit-breakers (1–14). 1 Overhaul. 2 Replacement

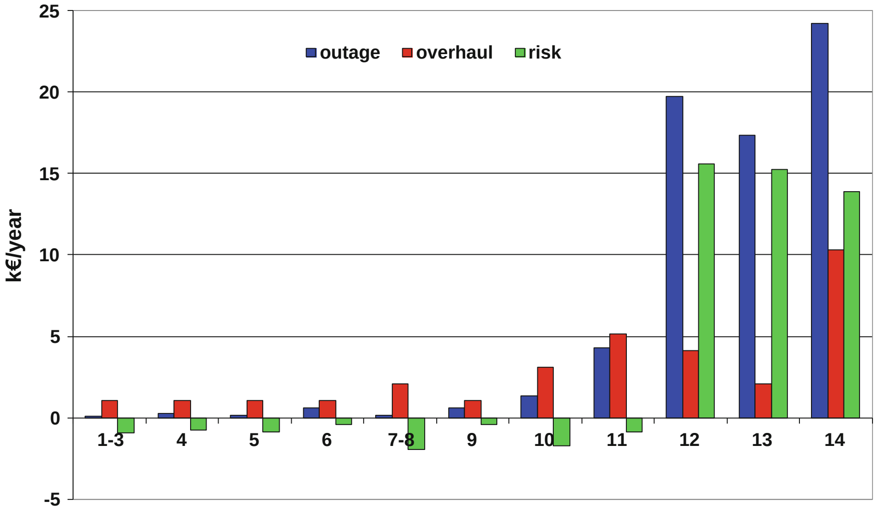


Fig. 3.32 Result of the risk assessment depending on variant A (overhaul)

Figures 3.32 and 3.33 show the final result of the cost analysis depending on the used parameters. In this case, an evaluation will lead to the measures for various circuit-breakers in accordance with Table 3.13. While the components no. 1–11 need a corrective maintenance, an overhaul should be applied for the circuit-breakers no. 12–14.

The calculations confirm that the results are highly dependent on the ENS, which is a consequence of the network topology, the protection system, and the financial assessment of the ENS. However, it would generally be difficult, to determine the probable interruption costs.

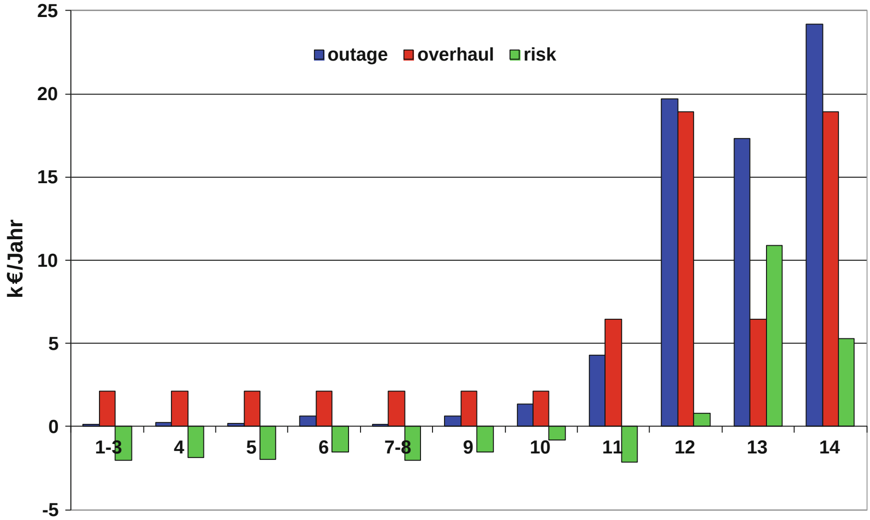


Fig. 3.33 Assessment of the risk assessment depending on variant B (replacement)

Table 3.13 Result of the risk assessment of circuit-breakers

Cb no.	Measure	Ranking
1–11	Corrective	–
12	Overhaul	1
13	Overhaul	2
14	Overhaul	3

3.2.6.3 Derivation of a Risk-Optimized Maintenance Strategy

Following, an optimal maintenance strategy (selection of appropriate maintenance intervals) is determined as a function of the failure frequency of equipment. This means that the lowest risk (Min{R}) can be solved taking into account of boundary conditions according to Eq. (3.15).

$$\mathrm{Min}\{R\} = f_1(p;x) + f_2(p;x) + f_3(p;x) + \cdots + f_n(p;x) \qquad (3{:}15)$$

where

R	risk of the entire system
$f_n(p, x)$	partial risk resp. risk classes
p	probability of risk classes
x	consequence of the risk class

Different risk classes can be defined by the probability and consequence in case of occurrence according to Eq. (3.15). If the assessment of risks cannot be performed with the help of a financial dimension, a multi-objective optimization is basically useful and in these cases, it may be appropriate to set different weighting factors. This procedure is described in Sect. 3.5.

The basic procedure can be shown by a simple example as the optimal maintenance cycle n is determined by a switching device. Here, it is assumed that the failure rate λ results according to Fig. 3.34 and can be described by Eq. (3.16), depending on the cycle rate n.

$$k = F1 + F2 = e^{-n=2} + e^{+n=25} \qquad (3:16)$$

where

n maintenance cycle per time unit

It is assumed according to Fig. 3.34 and Eq. (3.16) that the resultant failure rate λ is composed of two components:

- Improvement of the failure rate as a result of more intensive maintenance (F1), this means that the failure rate is reduced,
- as a result of more intensive maintenance, an increasing number of outages can be expected due to poor maintenance (additional failures may be assembled, F2).

In this case, the parameter "n" (maintenance cycle) has a two-fold impact on the costs, namely the following:

- The maintenance costs K_M per unit of time increase due to an increased service (larger number of cycles n),
- the failure rate λ influences the outage costs K_{St}, including the economic costs of ENS, per unit of time.

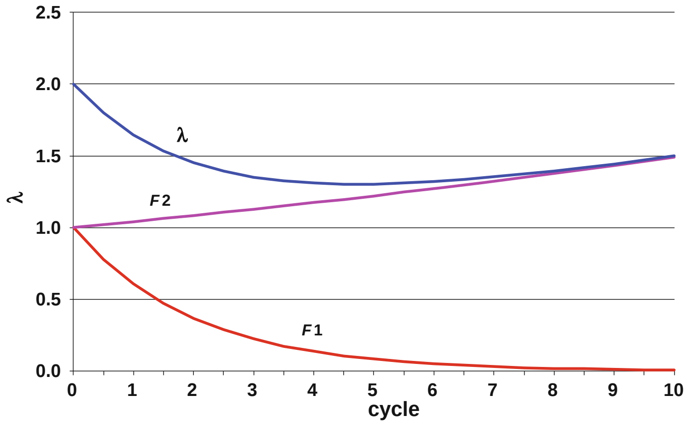


Fig. 3.34 Failure rate λ of a switching device depending on the cycle per time unit

The risk is calculated as the sum of the financial evaluation of the particular risk classes according to Eq. (3.17) using the above probable portion of costs.

$$R = K_M + K_{St} = k_M \cdot n + k_{St} \cdot k \tag{3:17}$$

where

k_M	costs per service
k_{St}	repair expenditure and costs of the ENS per outage
λ	failure rate $(k = e^{-n=2} + e^{+n=25})$ per time unit (Eq. (3.16))

After insertion of Eq. (3.16), the risk becomes

$$R = k_M \cdot n + k_{St} \cdot \left[e^{-n=2} + e^{+n=25}\right] \tag{3:18}$$

The minimum of Eq. (3.18) can be obtained by the first derivative with respect to “n”:

$$\frac{d\,(R)}{dn} = k_M + k_{St} \cdot \left[-0:5 \cdot e^{-n=2} + 0:04 \cdot e^{+n=25}\right] = 0 \tag{3:19}$$

$$\text{resp.} \quad 12:5 \cdot e^{-n=2} - e^{+n=25} = 25 \cdot \frac{k_M}{k_{St}} \tag{3:20}$$

The following values are assumed related to Eq. (3.20):

- k_M = 5 k€ costs per service
- k_{St} = 27 k€ outage costs

Figure 3.35 shows the result of Eq. (3.18) with an optimum of about 1.5 services per unit time. If higher maintenance intervals are applied, the increasing failure rate according Fig. 3.34 has a higher impact on the result, so that the total costs per unit time R increases again. According to Eq. (3.20), a more accurate value for the cycle can be calculated to n_{opt} = 1.5724 in case of annual probable costs of R_{min} = 48.9 k€, this means that the minimum total costs (maintenance and repair) are expected to 48.9 k€.

Of course, the above-performed calculations assume that the repair costs do not change when larger maintenance cycles are provided (i.e., damage as a result of a failure does not change). However, if this is not the case, for example, if a reduced number of maintenance activities lead to higher repair costs as a result of the outage, a dependency on the repair costs k_{St} has additionally to be considered as a function of the cycle n in Eq. (3.17).

3.2.6.4 Value-at-Risk Method

In case of a failure, the risk is generally a sequence of more or less serious consequences for the network operation and for the failure frequency of equipment according to

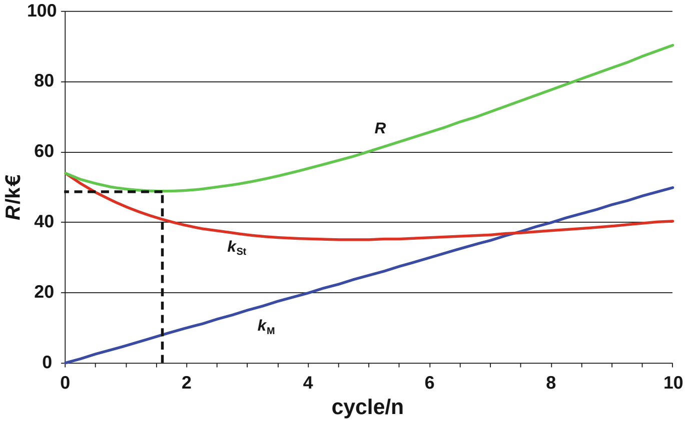


Fig. 3.35 Total risk depending on the maintenance cycles n per time unit

Sect. 3.2.6.1. For this reason, the question of risk management is to identify, to qualify and if necessary to reduce the different risks. Using the value-at-risk (VaR) method, it is in principle possible to estimate the risk, which arises from the operation of a network [12, 43, 44]. VaR demonstrates the probable added value or depreciation of the portfolio at the end of the observation period, which is not violated by a given confidence level.

The term “value-at-risk” was used for the first time in the financial world about 40 years ago to increase transparency in the investment business. Nowadays, the VaR data are used to hedge the investor, to analyze the sources of risk, to check the benchmark of securities and portfolios, and to increase the transparency of the investment activities of financial institutions. In addition, the VaR method is used in recent years in the area of the energy economics.

While a portfolio of the financial sector consists of different commercial papers, the transition to the area of asset management of infrastructure systems is possible that the portfolio consists of various components with different failure frequencies and consequences.

With the help of reliability calculation, it is possible to estimate the outages of a network and to determine the parameters for the expected supply interruptions at network nodes. However, in this calculation, the expected mean values of outages are used. On the contrary, these variables are used in case of the VaR method as stochastic distribution functions.

The VaR model

In the area asset management of power grids, the portfolio value will be compared with the expenditure and the income of the operation of the network, in particular, the costs of the unreliability of network components have a direct influence on the availability of the entire system and thus on the value of the portfolio for the VaR calculation. It is essential during

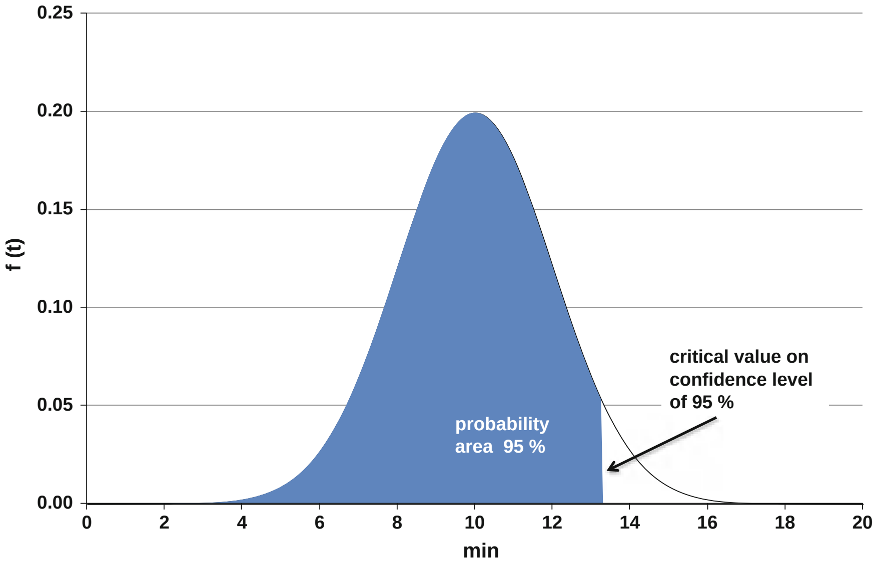


Fig. 3.36 Graphical representation of the VaR using the example of a normal distribution (time duration of an outage)

the calculation that the value of the portfolio is subjected to stochastic processes due to the influence factors, which are also stochastically distributed.

Exemplarily, a normal distribution is assumed for the explanation of the VaR concept, which is described by the expected value μ and the standard deviation σ. Figure 3.36 shows the density function of a normal distribution with an expected value of $\mu = 10$ min, when the duration of an interruption is considered as an influencing variable. The colored area covers a total of 95 % of the outages. The associated time range, in this example 13.25 min, is referred to as VaR with a confidence interval of 95 %, whereas only 5 % of the outages exceed this value.

The calculation of VaR requires the development of a VaR model [32] and according to [30] the entire process can be subdivided into several steps, which is also illustrated in Fig. 3.37.

- Work step: Mapping (Illustration of the portfolio value): Creation of an appropriate equipment portfolio, which is equivalent to the portfolio of commercial papers, i.e., consisting of various components and which influences the availability of the system by their reliability parameters and the costs of repair. These are the influencing factors.
- Work step: Inference (Deduction of a stochastic distribution): Stochastic description of risk factors (distribution of statistical values) and, finally, statistical distributions and their dependencies of the risk factors are available as a result of this process.

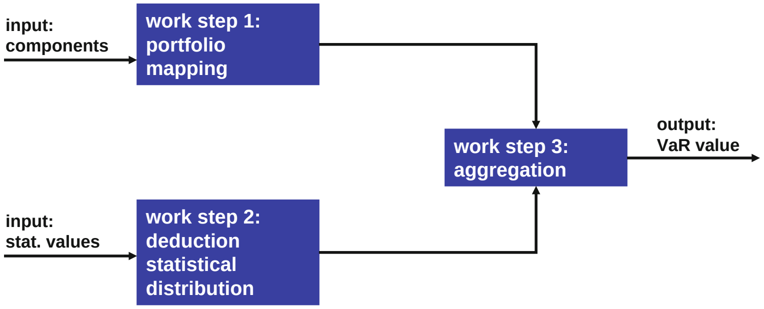


Fig. 3.37 Fundamental workflow of the VaR methodology

- Work step: Transformation (Aggregation): Combining the results of both upstream operations and derivation of the portfolio value.

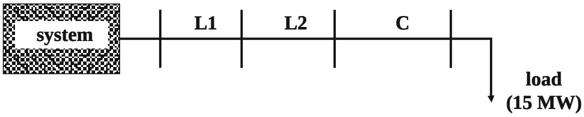
As a result of the process according to Fig. 3.37, a VaR value is available at the end of the procedure this means upon what probability a certain value for outages is not exceeded in a certain time range.

Application of the VaR model for an electrical network (example)

The basic procedure for determining the VaR is shown below for a simple example, and the components of this network, including their uncertainties, represent the network's portfolio. Figure 3.38 shows a 20-kV radial network on which the calculation is exemplarily performed.

The 20-kV network supplies the connected load (e.g., 15 MW) via two overhead lines and a cable according to Fig. 3.38, and both the voltage source and the busbar are assumed as ideal, so that the availability of supply is exclusively affected by the overhead lines and the cable. In this case, the value of the portfolio is influenced by the energy supplied, the capital invested, and the operation and outage costs. The calculation of the risk, which depends on the condition and the importance of components for the system, is determined taking into account the failure rate and the fault consequences [5]. The result of the step "portfolio mapping" is a mathematical formulation of the portfolio value and consists of two different parts U_E and W_A, which represent the financial impact on the company and the present value of the invested pieces of equipment. A distinction is made between fixed factors, which represent a constant value and stochastic factors that are associated with uncertainty and must be included as statistical distributions in the calculation.

Fig. 3.38 20 kV radial network with overhead lines (L1, L2) and a cable conjunction (C)



$$P_N = U_E + W_A \tag{3:21}$$

where

P_N value of the network,
U_E financial impact on the company,
W_A present value of the components.

Different risk factors influence the “financial impact on the company” (U_E):

- Price of the electrical energy,
- consumption,
- failure frequency of system node*,
- penalties in case of a failure*, and
- interruption duration in case of a failure*.

The second part (W_A) of Eq. (3.21) represents the present value of the equipment and includes the following risk factors:

- Financial value of equipment,
- investments (e.g., planned replacement),
- outage costs (e.g., costs of repair and damages)*,
- failure rate of equipment*.

The risk factors which are indicated by an asterisk (*) are subjected to a stochastic distribution and are therefore important for the VaR calculation.

Result

The value of the network portfolio can be divided into two parts: The first component consists of the value of the operating components and the expected revenues, both values are constant during the first approximation and for this reason not of interest for further consideration. The second part consists of stochastic factors and probabilistic costs, which affect the value of the portfolio negatively and are subjected to stochastic processes (indicated by an asterisk *). The last class will be considered in the following and typical input data for the various risk factors are used [5].

The following characteristic values of a normal distribution μ and σ and the components related risk factors are assumed (Table 3.14): Failure rate, interruption duration, repair costs, and damage to other equipment. The values are used for U_E according Table 3.15.

For simplification, it is assumed that these factors are normally distributed. Taking into account various transformation processes, the statistical uncertainties of the risk factors can be mapped in case of the portfolio value. The distributions of the failure rates and

Table 3.14 Characteristic data of risk values (component level)

Risk value	Mean value (μ)		Deviation (σ)	
	L1/L2	C	L1/L2	C
Failure rate (1/a)	0.2	1.1	0.1	0.1
Interruption duration (min/yr)	40	50	50	50
Repair costs (k€)	1.1	4.5	5.0	10.0
Other costs (k€)	0.0	0.0	5.0	5.0

Table 3.15 Characteristic data of risk values (system level)

Risk value	Mean value (μ)	Deviation (σ)
Costs of electrical energy (ct/kWh)	0.06	–
Power (MW)	15	–
Failure rate of network nodes (1/yr)	0.15	0.15
Interruption duration (h)	0.76	0.76
Penalties (€/kWh)	5.0	5.0

failure durations are combined using Monte Carlo simulation and as a result, the unavailability of the network is derived as a statistical distribution. Finally, in various failure scenarios, the distributions of repair and overhauls costs of the components are combined with the distributions of the failure rates. Finally, the costs of repairs/overhauls are derived as a statistical distribution for the period. The combination of failure durations, the costs per failures, and the failure rates of the equipment (transformation process) are illustrated in Fig. 3.39 for all network nodes.

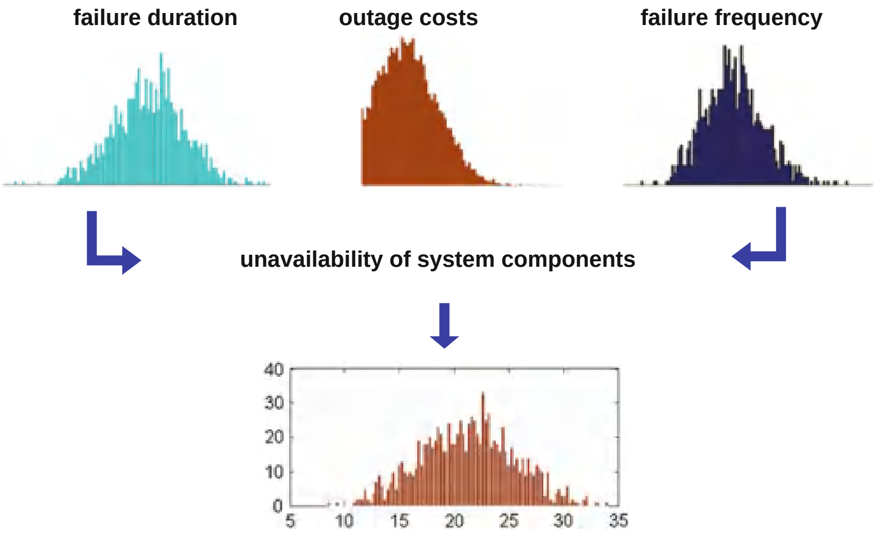


Fig. 3.39 Combination of the work step portfolio value and risk factors (transformation process)

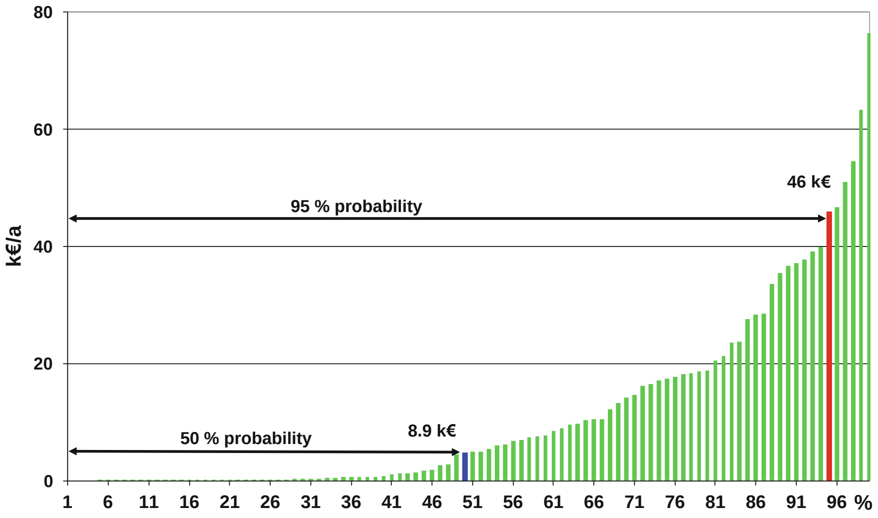


Fig. 3.40 Result of the VaR calculation

Finally, the total outage costs for the period are calculated and presented as a distribution, Fig. 3.40. The red bar represents the VaR with a confidence level of 95 %, this means that 95 % of the possible outage costs will not exceed a certain value, in this case 46 k€ per year. On the contrary, the conventional reliability calculation, that takes into account only the mean values, leads to probable outage costs of 8.9 k€ (blue bar according Fig. 3.40), which covers a confidence level of 50 %, and this amount is around 37 k€ less than the value of the calculated VaR.

Assessment

The advantage of the VaR calculation is that the potential outage costs, e.g., per year, can be determined with a confidence interval. In addition, an assessment is possible by what means the minimization of the risks is associated. Additionally, it can be evaluated, which risk factors and components influence the VaR essentially. Out of this, the strategic decisions can be made concerning the use of maintenance measures, so that the maximum outage costs can be reduced with the least financial expenses.

3.2.6.5 Information for the Assessment

Many data are required for a risk analysis, which can be divided into different groups, which are described below. In this case, it is possible that some information can be assigned to different groups.

Component level

The basis for determining the component outages is the failure rate of the equipment depending on life. The general problem is that these data are available under the exclusive condition of particular resp. different maintenance strategies. But, if the maintenance strategy should be changed, these fault data are not a reliable basis, but must be used as a parameter in each case. In general, the following information is required at the component level:

- Number of outages per year and causes,
- description of the occurred damages,
- type of failure (“minor” resp. “major” failure),
- time duration of outages,
- age of equipment and history (applied maintenance in the past),
- result of measures: diagnosis and monitoring.

System level (reliability calculation)

The reliability calculation determines the ENS or not fed in at different network nodes that are important for the supply task of the utility regarding the customer’s requirements. Various data are necessary on both the equipment and of the system:

- Failure rate of all the components of the network level including off-duration,
- system design and supply philosophy, $(n - 1)$ principle,
- possible failure cause (single or common mode failure),
- design of selective protection,
- repair time of the faulted equipment,
- switching time,
- supplied loads.

Also, it is necessary to use an age-dependent failure rate of equipment in order to determine the importance of the equipment at the system level.

On the contrary, constant failure rates can be used for reliability calculations, if different network types should be compared with each other at the system level. The comparison is done regardless of the age of the used equipment, as only different network topologies are considered.

Outage costs

Due to the failure rate of the equipment, the probable annual costs can be determined which occurred due to an outage of equipment. In addition, costs have to add representing the economic loss of the customer. In addition, expenses (penalty) should be considered which arise due to the contracts with customers or the requirements of a regulator. On the contrary, the loss of revenues of the utility may generally be neglected due to the ENS. The following information should be available:

- Repair costs of faulted equipment,
- liability costs by effects on third parties,
- possible damage to other equipment,
- failure rate of equipment (minor, major),
- ENS,
- loss of revenue of utilities,
- financial assessment of ENS of the customer,
- customer contracts (penalty), prescription of the regulator.

In determining the outage costs, a basic distinction has to be made between two different failure scenarios, which consequently lead to another financial evaluation:

- “major” failure: Immediate unplanned failure of equipment (e.g., flashover inside the circuit-breaker) with and without supply interruption which can only be corrected by an unscheduled repair,
- “minor” failure: Failure can be corrected by a scheduled maintenance procedure and will not cause a failure of the power supply.

Maintenance costs

As a consequence of different maintenance scenarios, the expenses can be estimated for these scenarios and compared to the likely outage costs in case of failures. The following information is relevant for an assessment:

- Maintenance measure resp. maintenance scenario,
- service costs and time interval,
- investment costs of a new equipment,
- usual useful life,
- depreciation method and depreciation time,
- interest rate, and
- disposal costs.

Environmental conditions

For the final decision, the environmental and social impacts are taken into account. In general, however, these effects are not expressed in monetary values and depend on company specifications. Among other things, the following information is of interest:

- Personal injury in case of a failure,
- property damage in case of failure,
- social aspect of the customer during a supply interruption,
- image of the own company,
- land use,
- electric and magnetic fields,
- environmental damage, and
- use of right of ways.

3.2.6.6 Example for the Implementation of a Risk-Based Maintenance

The following example represents a procedure how to implement a risk-based maintenance for an electrical medium-voltage system starting from the specifications of the regulator.

Requirements of the regulator

For example, different criteria were described by the regulator, which define the quality of supply and thereby the network reliability regarding maintenance of a network (see Sect. 3.3.3, Table 3.20):

- Duration of the supply interruption,
- the frequency of supply interruption,
- amount of ENS,
- amount of lost load.

The network reliability is defined according to international practice by the following reliability figures that are to be considered for further definition (see also Sect. 3.2.1, Eqs. 3.6 and 3.7):

- Customer average interruption duration index (CAIDI),
- System average interruption frequency index (SAIFI),
- Energy not supplied (ENS),
- Volume of lost load (VOLL).

Here, the quantity of the lost load is not a new criterion, since it can be derived from the ENS and the interruption duration. Since the first two quantities are relative values, the absolute values are obtained based on a network by the reliability characteristics frequency (H) and duration (T) as the mean of all network nodes.

Definition of risk classes

In practice, it has proven itself to define different risk classes for evaluating a consequence of an event. In principle, a risk diagram can thus be derived according Fig. 3.22 for different areas. This includes exemplarily (see Sect. 3.2.6.1):

- Finance: Financial expenses in case of outage
- Quality of supply: Supply of network nodes
- Safety: Number of Employees accidents
- Jurisdiction/laws: Conflict with legal requirements
- Image: Appearance in public (newspaper, radio, television)
- Regulator: Compliance with the requirements
- Environment: Environmental damage, such as oil leaks.

Depending on the specification stated by the company's management, it may be advisable to take only the following classes of risk into account for further consideration:

Finance–Quality of supply–Image–Environment:

Whereby the risk classes influence each other, so, for example, the assessment of the risk class "environment" may be covered by a financial evaluation, such as the effort to remove oil leakage from equipment. The particular risk classes can be influenced by the following parameters, which are to be considered by a calculation of consequences as a result of an outage or a failure of equipment.

- Finance:
  - Loss of revenue,
  - disposal costs of faulty components,
  - repair, replacement of equipment, subdivided into "major" and "minor" failures (MF/mf),
  - damage to other previously unaffected components, and
  - expenses due to environmental damages.
- Quality of supply:
  - Energy not supplied (ENS),
  - volume of lost load (VOLL),
  - interruption frequency per supplied customer (SAIFI): Sum of the customer interruptions/number of supplied customers,
  - unavailability per supplied customer (SAIDI): Accumulated duration of customer interruptions/number of supplied customers,
  - interruption frequency per interrupted customer (CAIFI): Sum of the customer interruptions/number of interrupted customers,
  - average duration of a supply interruption of a customer (CAIDI): Accumulated duration of customer interruptions/total number of customers' interruptions.

Table 3.16 Influence of the failure rate on outage consequences

Consequence	MF	mf
Repair	x	x
Replacement	x	–
Damage to other components	x	–
Energy not supplied, duration, frequency	x	–
Loss of revenue	x	–
Disposal costs	x	–
Image	x	–

- Image, assessment of an outage in public (each nationally and internationally):
  - Newspaper,
  - radio, and
  - television.

Determining the probability (failure behavior of the equipment)

In this example, the probability is determined that an event takes place due to the description of the failure behavior of the considered equipment. Distinction is made between a "major" failure (MF) and a "minor" failure (mf), which triggers a scheduled repair without a supply interruption, as defined in Sect. 3.2.6.5. Based on this definition, two types of failures have a different influence on the consequences of an outage, Table 3.16.

According to Table 3.16, the "major" failure may thus cause an outage with damages also to nearby components, which leads to a supply interruption with the resultant implications. In contrast, a "minor" failure will not lead to a supply interruption and the affected equipment is repaired by a planned maintenance. A replacement of the equipment is not necessary under these conditions.

In general, the failure rates of equipment in the statistics are given as mean values, regardless of age at the time of failure, e.g., FNN statistics. To differentiate the equipment, however, it makes sense to use an age dependency due to the operational experience according Fig. 3.41. In this case, it is sufficient to consider an increase of the end of life, as failures, which occur immediately after commissioning, should be covered by the warranty. Thus, the financial costs of a failure are covered by a third party. Exemplarily, the aging characteristics of a "major" failure could be simulated for simplicity according to Eq. (3.22) by an exponential function that represents the failure behavior according to Fig. 3.41.

$$k_{MF} = a + e^{bt} \tag{3:22}$$

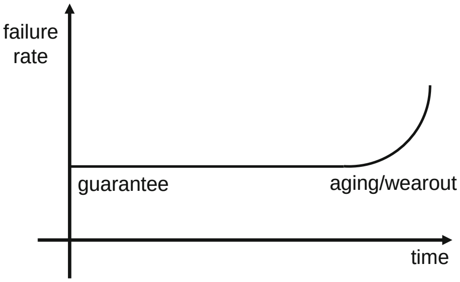


Fig. 3.41 General aging behavior of components (example)

A similar description or a fixed ratio of mf/MF should be chosen for simplicity for the frequency of a “minor” failure. In case of determining the failure rate, outages should be disregarded, in which the resulting damages have to be paid by causing third parties in contrast to Fig. 3.41.

Procedure

The principle problem of implementing a risk-based maintenance at the component level is that

- the regulatory description of the quality of supply is related to network nodes at which customers are connected while maintenance can only be made to components of the network.

In reality, however, the maintenance of equipment has only an indirect influence on the supply reliability of the network, as an example, the network topology is essential to determine the ENS and is not only depending on the failure rate of the installed devices.

The associated risks of different scenarios according Fig. 3.24 are calculated and finally compared to the risk assessment in accordance with Sect. 3.2.6.2 and the derivation of a suitable maintenance action.

- Risk of the original condition (scenario 1): Calculation of the probable failure costs per year of the equipment without overhaul/service. A corrective maintenance strategy is assumed in this case.
- Risk after replacement (scenario 2): The considered equipment will be replaced and the investment, maintenance, and failure costs of the new device are calculated (conversion of investment and maintenance costs to annual values).
- Risk after overhaul/service (scenario 3): The observed equipment is subjected to an overhaul, so that the life is extended for a certain period (e.g., 5 years). It takes into account overhaul and outage costs, in each case converted to annual values.

The risks after a maintenance action (replacement or overhaul/service, this means scenario 2 and 3) are finally compared to the risk of the original condition (scenario 1) in order to derive an appropriate maintenance action. According to Fig. 3.28, the following pools of costs result for the different risks:

- R1 (risk of scenario 1): Probable outage costs of the considered equipment (red bar),
- R2 (risk of scenario 2): Replacement costs, including outage costs of new equipment (blue bar),
- R3 (risk of scenario 3): Overhaul/service costs, including outage costs of the serviced equipment (not presented in Fig. 3.28).

The following rules can be derived by the determination of optimal maintenance strategy based on a risk orientation:

$$R_1 - R_2 \; [\; 0 \rightarrow \text{Replacement of equipment} \tag{3:23}$$

$$R_1 - R_3 \; [\; 0 \rightarrow \text{Overhaul=service of equipment} \tag{3:24}$$

If both Eqs. (3.23) and (3.24) have a positive value, then

$$R_2 \setminus R_3 \rightarrow \text{Replacement; otherwise overhaul=service} \tag{3:25}$$

Basically, the risk of the original condition R_1 has to be compared to the maximum permissible risk $R_{1\max}$ (e.g., Fig. 3.24) whose exceedance cannot be accepted regardless of the assessment according to Eqs. (3.23) and (3.24), even if both equations lead to a negative result. In these cases, the risks R_2 and R_3 can be calculated without the annual expense for replacement or maintenance of the equipment, which are indicated according to Eq. (3.26) with R_{C2} and R_{C3}. The effectiveness of the required maintenance action is finally determined by Eq. (3.13) resp. (3.26), e.g.,

$$g_{12} = \frac{R_1 - R_2 - R_{C2}}{R_{C2}} \quad \text{resp:} \quad g_{13} = \frac{R_1 - R_3 - R_{C3}}{R_{C3}} \tag{3:26}$$

The evaluation of the effectiveness of the maintenance measure—reducing risk by Eq. (3.26)—is applied to the case that the initial risk of the equipment exceeds a permissible value $R_{1\max}$ and yet the assessment under Sect. 3.2.6.2 does not lead to a conclusion that a maintenance measure is required.

3.3 Indicators

For decision making, various indicators are used by a company and the groups involved in the process, which have the aim to make the commitment transparent and understandable. Herewith, the choice of indicators depends on the groups ("stakeholders") which are involved in the decision. In general, these groups consist of owners, customers, employees, legislators, environmental groups, traders, etc. In this chapter, different indicators are presented that can be used depending on the conditions in the particular field.

Moreover, there is an increasing need for companies to publish sustainability reports, in which the influence of the operation of systems is evaluated on the environment. International standards, such as ISO 14001, the "Global Reporting Initiative" (GRI) and the "Global Compact" (United Nations, UN) give instructions for this section regarding the assessment.

3.3.1 Target Values of the Participating Groups (Stake Holders)

The groups involved in the supply process have fundamentally different interests that may be contrary as well, so that in general rules should be made, how the energy supply of the public can be assured in the long term. The basis for this is in any case for the area of the Federal Republic of Germany, the Energy Act in the respective valid version (in this case the Energy Act, July 7th, 2005) that specifies the following requirements (§ 1):

- (1) Purpose of the act is the most secure, cost-effective, consumer friendly, efficient, and environmentally sustainable supply of electricity and gas to public transmitted via network lines.
- (2) The regulation of the electricity and gas distribution network will be aimed at ensuring effective and fair competition in the supply of electricity and gas while maintaining long-term performance and reliable operation of energy supply networks.

In addition, the company of energy supply systems are committed to provide a safe, reliable and efficient energy supply system to operate free from discrimination, to maintain and expand according to the needs, as far as it is economically reasonable (§ 11). The requirements for energy systems are controlled in accordance with § 49 as follows:

- (1) Energy installations shall be constructed and operated in a manner that ensures system technical security. In subject to conformance with other laws, the generally accepted rules of technology have to be respected.
- (2) Compliance with the generally recognized rules of technology is assumed if in case of installations for the generation, transport, and distribution are applied.
  - Electricity, the technical rules of the Association of Electrical Engineers (Verbandes der Elektrotechnik Elektronik Informationstechnik e.V.; VDE)
  - Gas, the technical rules of the German Association for Gas and Water (Deutschen Vereinigung des Gas- und Wasserfaches e.V.; DVGW)

It is the task of various groups to define the essential targets taking into account the boundary conditions prescribed by law, that are important for a decision-making process.

Some examples of target variables are listed in various sections that are of interest for different groups in Table 3.17. The criteria listed in Tables 3.17 and 3.18 were partially developed by a working group CIGRE B3.06. Whereupon, the economic criteria are especially important for those whose business processes are in competition. On the contrary, public companies are more interested in technical issues, such as quality of supply and reliability. Political organizations, such as the regulators, have the task to make the balance between the market forces: public interests and customer needs.

Table 3.17 Participating groups and their targets (economical, technical, sociological)

Groups (“stakeholder”)	Economical	Technical	Sociological
Trader, salesman	Maximal profit	–	–
Power plant operator (private)	Maximal profit	Availability, efficiency	–
Power plant operator (public)	Profit	Reliability, low risk	Energy from renewable sources, safety
Asset owner	Maximal profit	Availability, condition of assets	–
Industry	Maximal profit	Quality of products/price relationship, efficiency of energy consumption	–
Service (private)	Maximal profit	Quality of service/price relationship	–
Service (public)	Profit	Reliability, power quality	Safety, image
System operator	Profit	Reliability, low losses	Solidarity, low environmental influence (CO_2, noise, etc.), cooperation, safety
Employee	Salary	–	Employment, motivation, security
Political organizations	Market structure, well balanced price	–	Market economy laws
Regulator, legislator	Controlled price	Sufficient technology, benchmark	Accordance with laws
Consumer (private)	Low price	Availability	Safety, comfort, efficiency
Consumer (public)	Low price	Availability	Safety
Environment	–	–	Existence, safety

3.3.2 Selection of Indicators in Case of a Maintenance Measure

If an asset manager determines to replace older equipment or an entire plant, different scenarios are fundamentally possible depending on the technical conditions:

- Life extension (scenario 1: life),
- replacement of all equipment (scenario 2: replacement),
- renewal by exchanging individual components (scenario 3, exchange), and
- redesign of the system (scenario 4, redesign).

Depending on which maintenance strategy is determined by the asset manager, different indicators will be of particular importance. Herewith, the indicators can be assigned to different areas (technical, economical, sociological), as it is exemplarily listed in Table 3.18.

The indicators listed in Table 3.18 represent a simplified selection of the total possible figures, which can be exemplarily selected as indicators. In addition, other criteria are useful, which are additionally stated below.

- Technical area: Basically, information of single equipment as well as and of the entire system belongs to this area. Specifically, this can be:
  - reliability resp. availability of components,
  - age depending probability of failures,
  - outage behavior in the past,
  - currently applied maintenance strategy,

Table 3.18 Selection of indicators in case of different maintenance scenarios (example)

Scenario	Indicator		
	Technical	Economical	Sociological
1. Life	Failure rate,	Maintenance costs,	Environmental influence
	remaining life time	costs of life cycles	
2. Replacement	Condition assessment,	Reinvestment costs,	Safety, environment,
	reliability	commercial advantages	public image
3. Exchange	Condition assessment,	Reinvestment costs,	Probability of failures,
	reliability	follow-up costs	environment
4. Redesign	Security of supply,	Follow-up costs,	Motivation of employees,
	availability	costs of life cycle, commercial advantages	public image, environment

  - condition of equipment,
  - residual life,
  - amount of losses,
  - assessment of efficiency,
  - ENS or not fed in at system nodes,
  - volume of lost energy,
  - duration and frequency of interruption,
  - service know-how,
  - availability of spare parts,
  - etc.

- Economical area: Financial expenses are required as a result of the implementation of different maintenance measures, which can be assigned to different criteria. These include as follows:
  - Costs for the life of equipment,
  - operating costs versus investment costs,
  - expenses for additional damage liability,
  - loss of revenue due to an outage,
  - costs of ENS or not fed in,
  - penalty payments to customers due to a supply interruption,
  - outage costs (repair resp. replacement),
  - maintenance costs,
  - business cases,
  - etc.
- Sociological area: Basically, outages or interruptions of supply are influenced not only by technical or economic information, but they may also have a significant impact on the behavior of the company or on the public. As an example may be:
  - customer satisfaction,
  - personal safety,
  - compliance of legal requirements,
  - damage to property in case of failure,
  - public facilities, such as schools,
  - motivation of employees,
  - environmental impact, such as land use, pollution, electric and magnetic field,
  - confidence in the public,
  - image of the company,
  - reduction of CO_2 emissions,
  - etc.

3.3.3 Benchmarking

A survey of various international energy companies was conducted by the Cigre Working Group C1.11 with the objective to identify key indicators that will be used by the companies to control the business activities [21]. In total, 19 companies around the world participating in this survey. In the following, some characteristics are described in detail, which are used in different degrees of intensity. Basically, it makes sense that the various indicators are assigned to appropriate areas; these include the following: Finance—reliability—customers—safety/staff, Tables 3.19, 3.20, 3.21 and 3.22.

In addition, Table 3.23 describes figures which are relevant for an assessment of system availability and to assess activities of service providers (internal/external).

As already mentioned briefly, the representation to reduce environmental impacts for the various companies is gaining more and more importance. This means that for the evaluation of the pieces of equipment also their influence on the environment is important and therefore on the selection of the maintenance measure. For this reason, two Cigre reports [23, 24] have been published that describe this problem in detail. Table 3.24 illustrates some indicators, which are also listed in [24, 25].

Table 3.19 Finance/economy [23, 24]

Indicator	Description
Earning before interests taxes (EBIT)	Revenues less operating expenses, before interest and taxes
Operating expenditure (OPEX)	All expenses that are necessary for the operation, maintenance and non-capital renewal of a network, such as personnel and maintenance costs, depreciation, loss
Capital expenditure (CAPEX)	All capitalized expenses that are necessary for building and renewing the equipment and systems, such as manufacturing and engineering costs, estate
Specific operation costs (operating, maintenance, administration)/(energy × line length)	Operating costs are divided by the product of the energy supplied and the circuit length
Controllable unit costs/line length	The sum spent in a specific period for the purchase of a defined equipment group, based on the purchased pieces of equipment
…	

Table 3.20 Reliability [23, 24]

Indicator	Description
Energy not supplied (ENS)	The accumulated value of the energy not supplied per unit time due to interruptions in the network or at nodes (MWh)
Volume of lost load (VOLL)	Calculated from the energy not supplied in relation to the duration of interruption (MW)
Average interruption duration (AID)	The average time of interruption at a node or the entire network (min/interruption)
Average interruption frequency (AIF)	Average number of interruptions at a node (interruption/year)
System average interruption duration index (SAIDI)	Accumulated time of interruptions based on the number of supplied customers (min/customer)
System average interruption frequency index (SAIFI)	Sum of the customer interruptions based on the number of served customers (interruption/customer)
Customer average interruption duration index (CAIDI)	Accumulated durations of customers interruptions based on the total number of customer interruptions (min/customer)
Customer average interruption frequency index (CAIFI)	Sum of the customer interruptions based on the number of interrupted customer's (interruption/customer)
Unavailability	Product of the frequency and the duration of interruptions, which is the probability that a customer will be affected in a year by an interruption of supply (1, 100 %)
System average interruption time (AIT)	Corresponds to the unavailability, however, related to one year (min/year)
Mean maximum resupply time	Outage time until all customers are again completely supplied on average after a supply interruption (min/interruption)
System minutes lost	Energy not supplied of a network related to the peak load (MWh/MW)
…	

Table 3.21 Customers [23, 24]

Indicator	Description
Customer satisfaction survey	Survey of customer satisfaction among the groups involved in the supply process
Market share	Customer share in different supply areas
Wrong invoice rate	Number of customer invoices that have been issued incorrectly
Complaints	Number of customer complaints
…	

Table 3.22 Employee/safety [23, 24]

Indicator	Description
Accident severity rate (ASR)	Ratio of working days that fail due to work accidents multiplied by 200,000 based on the total number of working hours of employees
Serious incidents	Number of accidents, a classification into different categories is useful
Lost day rate	Number of accidental work days, based on total work days
Occupational disease rate	Number of sick days, based on the total work days
Number on employees	Number of employees, depending on education
Employee wages	Total financial personnel expenses
Demographic factor	Age structure, population pyramid of employees in relation to the operating know-how
Productivity	Number of hours per year which can be paid for at an hourly rate in the internal cost allocation
Training hours	Number of days of training based on the total available work hours
…	

Table 3.23 System availability [23, 24]

Indicator	Description
Availability index (AI)	Ratio of the time that components were not available based on the number of components during the entire time range
Reliability index (RI)	Related time of the random failure of components
Unavailability index of system (UIS)	This ratio describes the non-availability of the components of a system
Maintenance costs index (CI)	Maintenance costs based on the number of equipment
…	

Table 3.24 Environmental impact [24, 25]

Indicator	Description
Used materials	Description based on weight or volume
Recycled materials	Percentage of materials which can be recycled
Energy consumption	Representation of the energy efficiency of new equipment resp. reduction of transmission and distribution costs
Greenhouse gas emission (e.g., CO_2, SF_6, SO_x, NO_x)	Details of the gases with CO_2 potential
Vegetation impact	For example, land use or land reduction by maintenance measures
Hazardous waste	Register of hazardous substances in t
…	

3.4 Asset Simulation

One way to estimate the effects of technical and financial boundary conditions for the infrastructure is to consider the total costs of a group of equipment in a network, taking into account the unavailability of the network nodes over a long-term period of time [2, 14, 15]. The following sections of this chapter relate to these references. Using this approach, it is possible to estimate the effects under consideration of essential boundary conditions due to the maintenance and investment strategy, e.g., extension of service cycles or the useful live. Exemplarily, the ENS or not fed in belong to this as well as personnel and material resources. For this reason, the derivation of an established and effective asset strategy with the aid of dynamic simulation provides a practicable and stringent approach that consistently supports the asset management in its task to manage the supply networks holistically and sustainably.

Thus, the result of simulation represents the statistical behavior of the entire asset group for a long period. However, single equipment can no longer be identified in order to derive individual operational decisions.

3.4.1 Development of a Long-Term Strategy

The aim of this analysis is to develop a long-term strategy for maintenance and investment decisions of a network with the aid of suitable equipment models. These models should be capable of considering the asset behavior in any time range, for example of 30–60 years, according to the useful life of various components. Thus, the following steps result in a dynamic asset simulation:

- Condition assessment and fault behavior of an asset group of a supply system (Sect. 3.4.1.1),
- derivation and implementation of an aging model for different types of equipment (Sect. 3.4.1.2),
- development of different cause-effect chains with the aid of computer simulations taking into account the personnel and financial constraints (Sect. 3.4.1.3),
- preparation of the required input data (Sect. 3.4.2),
- execution of dynamic simulations, and
- assessment of the results.

The basic fundamentals for creating the data model and the necessary input values are described in Sects. 3.4.1.1–3.4.1.3 and 3.4.2.

3.4.1.1 Condition Assessment of Equipment

A method has implemented in recent years for the evaluation of equipment, which takes into account both the condition and the importance of equipment for the entire system, Sect. 2.1.2 [7, 8]. In this procedure, the condition of equipment is determined using different criteria which can be assigned to various assessment classes, for example:

- General data (type, installation point, etc.),
- Age-dependent data (age, know-how, spare parts, etc.),
- operating data (load, temperature, switching frequency, etc.),
- financial data (maintenance expenditure, etc.), and
- technical data (corrosion, wear-out, etc.).

The assessment classes listed above thus indicate that not only the technical condition of a component is acquired, but also additional quantities that are of crucial importance for the decision-making process regarding the exchange of components. These various classes are subjected to different aging processes during the useful life of a device, which must also be taken into account in case of the application of an aging model. For example, a sufficient know-how and if applicable, also spare parts will be available for newly installed equipment during the first years, which may no longer sufficiently guaranteed toward the technical end of useful life. This has the consequence that an exchange of these components can be useful before the actual end of their life, although this device may yet meet the operational requirements.

As a result, the condition assessment of equipment consists of two different sets of criteria that have an impact on the aging behavior and can be defined as follows:

- Technical aging of equipment: In this context, criteria are considered that describe an aging or wear process.
- Strategic ("artificial") aging of equipment: Criteria, that force the premature replacement of the equipment, for example, the number of used components of an asset group is too small so that the required service know-how is not available within the company.

A condition assessment derived from this aging model thus has to take into account these two fundamental components with different aging behavior.

3.4.1.2 Aging Model

Simplifying, the failure rate of equipment can be exemplarily represented in dependence of the life according to Fig. 3.42 [3]. If the annual failure rate is divided into different aging groups, four different areas can be identified due to the failure performance that determine the number of condition classes of the Markov model for further considerations according to Fig. 3.42. The failure behavior of these four regions (I–IV) can be specified as constant for simplification. The failure rate corresponds to the definition in Sect. 3.6.2.8, as the damage per unit time can be based always on the components that are still in operation. In this example, four age groups are assumed; however, other groups can be defined as needed.

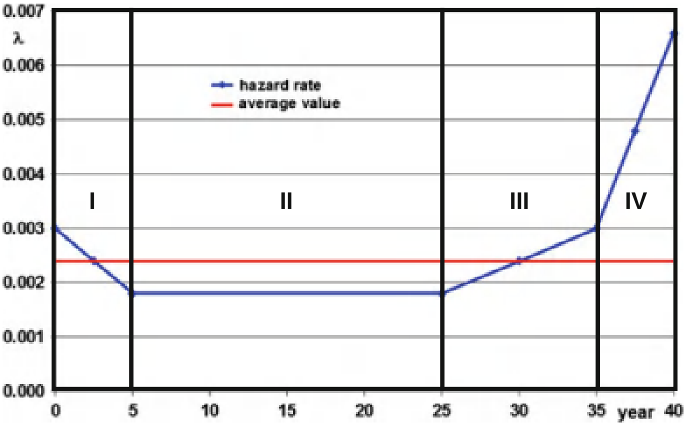


Fig. 3.42 Typical failure rates of equipment (example) [3]

Based on the failure rate λ, the reliability and the availability of equipment can also be estimated, as is exemplarily shown in Fig. 3.43 [18]. In this case, it is assumed that after 20 years a noticeable change of the condition occurs, thereby a decreasing reliability. If no maintenance action is performed on this equipment, it is assumed that after 35 years the “reserve of life expectancy” is completely consumed (reliability is equal to zero). The useful life of the equipment is extended taking into account a required reliability by a periodic maintenance measure. It is essential, however, that no improvement of the condition and thus the reliability is achieved after a normal maintenance operation. However, this is the case when it comes to the maintenance activity with replacement of wear parts or components of units. For example, the condition evaluation and thus the reliability of a complete overhead line can be significantly improved by replacing the conductors, which will result in a sudden improvement of the reliability of the equipment.

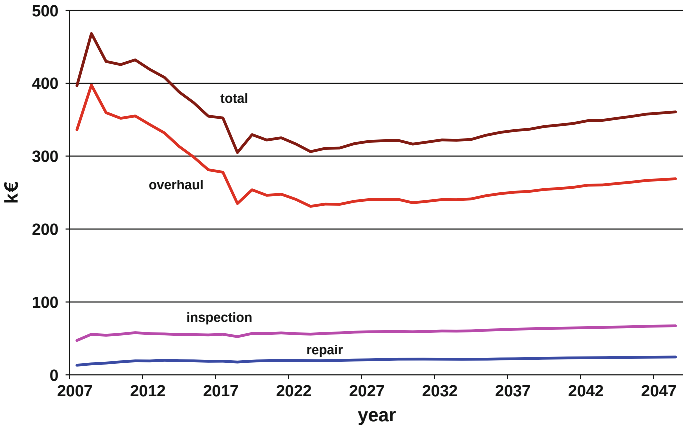


Fig. 3.43 Influence of maintenance actions with different time intervals on the availability of equipment [18]

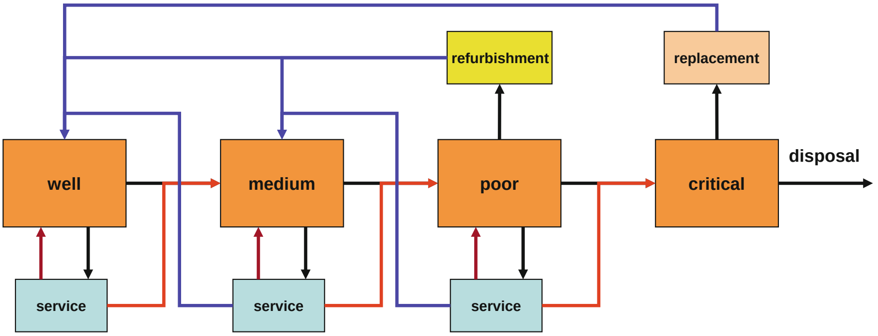


Fig. 3.44 Aging and condition model of equipment (Markov model)

Based on these considerations, an aging model was developed, which realizes the change of the technical condition (technical and artificial aging). As an example, the condition model can be considered according to Fig. 3.44 as various maintenance activities and the particular condition classes are modeled. Taking into account the different transition rates between the condition classes resp. actions, the condition of equipment can be derived as a function of the age by the aid of the Markov model. In total, Fig. 3.44 consists of four condition classes which are described by well–medium–poor–critical. While a maintenance task (service/inspection) is assigned to the first condition classes, a replacement or disposal of the affected equipment is applied to the class “critical.” Basically, the equipment can be transferred to the same, better, or worse condition class due to maintenance activity.

On the contrary, in each case a condition improvement is associated with an exchange of a part of equipment (refurbishment), as a new component is installed.

The parts of the total asset group, which belong to a condition class (in this case: good, medium, poor, critical), have to be evaluated by a condition assessment, which was already presented in Sect. 3.4.1.1. The particular components pass through the different classes and the maintenance activities can slow down or speed up this process what depends on the success of the maintenance measures or of their cycles (Fig. 3.43). An important task in this step is thus to assign all components to different classes and to determine the transition rates between the condition classes. In this case, the aging model must satisfy the following prerequisites:

- The condition of the equipment changes depending on the age, so that a transition to another condition class is guaranteed.
- Each equipment has a maximum resting time in a condition class. This ensures that each device will be replaced after a maximum operation time.
- It must be possible that components can age “artificially” if, for example, a service is no longer possible at a type of equipment, so it makes sense to replace this equipment earlier.
- A constant failure rate is assumed within a single condition class for simplicity.

- The transition rates between the various condition classes are constant during the period under review and take into account a uniform distribution of the components.

Usually, however, an asset group, for example circuit-breakers, consists of various types of equipment (air blast, minimum oil, and SF_6 circuit-breaker) which have a different behavior with respect to the condition and failure rate. Consequently, it is useful to derive a variant aging model for the each deviant equipment type and simulate the various aging processes by different models.

3.4.1.3 Cause–Effect Chains

The effects of aging of equipment and the resulting measures (maintenance and replacement) can be determined by cause–effect chains. Figure 3.45 shows exemplarily the relationships between the areas: Technology–Human Resources–Finance–Customer–Company. Based on the aging model of equipment, the necessary human and financial resources of a system operator can be determined in terms of maintenance and replacement of equipment. At the same time, the condition of the components has an impact on the overall condition of the network, which has an influence on the voltage quality and the failure behavior at system nodes, which has an impact on the consumption behavior of customers. Basically, it is possible to extend Fig. 3.45 by the areas: Community, legislation, regulator, etc., to consider further influences resp. requirements.

On the basis of the developed simulation model, various asset strategies can be simulated and evaluated in detail. Furthermore, important lever actions can be identified by parameter variations and sensitivity analyzes. The asset management wins a better

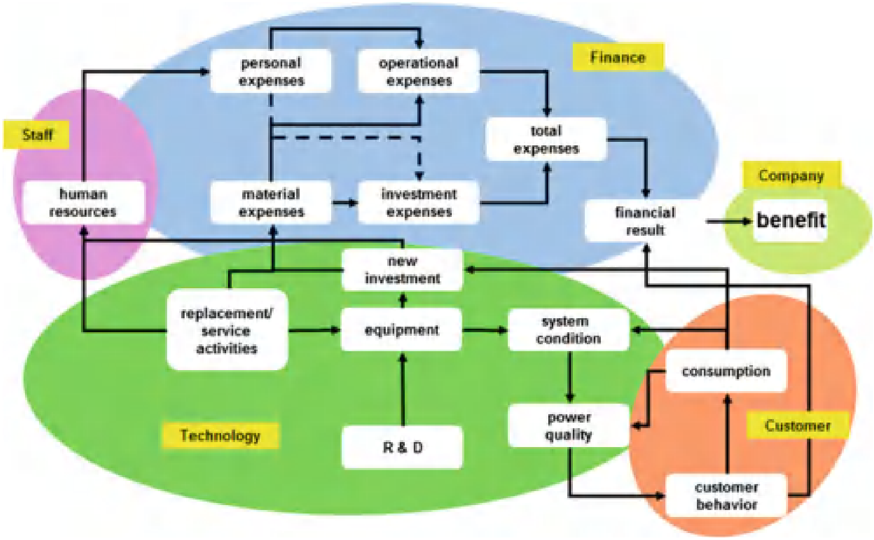


Fig. 3.45 Cause–effect chains of the asset management process

understanding regarding the future behavior of its facilities as well as the potential long-term effects of the proposed action and is thus in a position to formulate and to implement established and sustainable asset strategies.

3.4.2 Input Data

Various input data are used for the application of the dynamic asset simulation, which can be grouped into classes in order to reduce the complexity accordingly. Of course, the selection of different data depends on the questions to be solved, for example, the following information is used:

- General information
  - Type and age of equipment,
  - maximum operation time,
  - condition assessment of the asset group, and
  - simulation time (e.g., 40–50 years).
- Outage data
  - Failure rate and outage time depending on the age of equipment resp. condition as a function of the failure consequence (minor, major),
  - Personnel expenditure in case of an outage,
  - failure consequence (e.g., ENS resp. not fed in, damages to other equipment), and
  - repair costs (personnel and material requirements).
- Maintenance data
  - Personnel and material expenditures of maintenance measures (inspection/outage),
  - maintenance cycles (inspection, overhaul), and
  - availability of equipment in case of maintenance works.
- Financial and other data
  - Specific asset costs for a single equipment,
  - type of the new equipment,
  - inspections costs (personnel and material expenditures),
  - overhaul costs (personnel and material expenditures),
  - accounting of renewal (operation costs of investment),
  - period of amortization resp. the asset depreciation in case of investment,
  - requirements of the regulator,
  - power losses, financial assessment of losses,
  - costs of ENS resp. not fed in,
  - number of new installations (network expansion),
  - replacement rate of equipment (ratio of new related to replaced equipment),

- disposal costs, and
- inflation rate (if necessary).

In case of the selection of the above input data, a simulation of the investment portfolio can be performed, and out of this, the financial expenses can be derived. If the target exists to optimize the calculations on the balance sheet and the consolidated profit and income statement of a company, further details may be required these include the development of equity, debt and the approved system charges, etc.

3.4.3 Application of Dynamic Simulation

Taking into account various expenses and the knowledge, how many resources must be maintained and replaced per year, in principle, it is possible to determine the total costs of investment and operation costs for an asset group and thus for the entire network in compliance with the company-specific accounting practices over the considered period (e.g., 40 years). In addition, it is possible to estimate probable costs of repair and failure on the basis of the failure rates, split into “major” and “minor” failures. A distinction can be made between the following costs over the entire period as a function of the operational requirements:

- CAPEX: Capital Investment Expenditure (investment costs: capitalized renewal and new construction) and
- OPEX: Operational Expenditure (operating costs: costs of losses, maintenance and operational costs, and outage costs), non-investment renewal costs.

The summary of these costs is referred to as Total Expenditure (TOTEX) and shows the total expected financial expenditure for an asset group of a network so that different investment and maintenance strategies can be derived. In addition, other simulation results are possible for the period under consideration:

- Personnel requirements for maintenance and replacement,
- structure and age profile of the components,
- capital assets,
- ENS or not fed in,
- age distribution of asset group,
- quality indicators for the network (failure frequency, outage duration, estimation of ENS, or not fed in for the entire network, etc.),
- personnel costs for renewal and maintenance,
- financial costs for renewal and maintenance,
- amount for depreciation and book value of the equipment,

- allocation of the costs of necessary maintenance measures,
- development of equity and debt, and
- identification of risk (determined from the frequency and the damage in case of supply interruptions).

The reproduction of the assets resp. asset group is the basis of any simulation and thus the entire infrastructure system over the simulation period. This estimation of the necessity of maintenance, renewal, or other measures is possible in each year. Basically, there are different methods to simulate an entire collective of equipment in terms of a dynamic simulation, these include exemplarily:

- Using the age or condition dependent failure rate of the equipment and
- consideration of a statistical failure of equipment.

While in the first approach the condition assessment is assumed by various single pieces of equipment, like this is shown in Sect. 2.1.2.2, the second method uses a statistical failure rate of the equipment group that is derived from the experience of the system user. Different possibilities are illustrated by examples in the following Sects. 3.4.4 and 3.4.5.

The simulation is applied in order to assess the development of other parameters regarding a defined period using the definition of fixed values in case of the parameter selection and finally to compare different strategies by parameter variation. The aim is to select the strategy that satisfies the fixed parameters and achieves the most desired results in the development of strategies and avoids criteria for exclusion. In general, the financial parameter TOTEX will be determined because the available financial resources are fixed in the context of cash flow. But already the allocation of CAPEX and OPEX is variable and has a determining impact on the net result of the infrastructure operator, as their effect is fundamentally different on the operating result.

Other parameters, which are considered in the context of a strategy, are the development of fault occurrence and the substance of the capital asset as a degree of the conversation of value resp. amortization by “life from the substance.” It is therefore necessary in case of a strategy development, for example, to determine for all asset groups of the infrastructure system how the financial funds have to be applied in case of fixed resources and a given substance development that the quality of the task fulfillment of the infrastructure system has not worsened or improved by means of renewal and maintenance.

In this case, particular strategies are perfectly processed by simulations such as the long-term controlled replacement of certain delicate components or even the transition to other technologies such as overhead lines to cable solutions. Also constraints are taken into consideration, such as the equalizing of the use of resources over a defined period instead of strong annual variations.

3.4.4 Simulation: Condition Assessment

Listed below, two examples of an asset simulation are presented, focusing on the area of high voltage (circuit-breakers, Sect. 3.4.4.1) and medium voltage (cable, Sect. 3.4.4.2, [2]).

3.4.4.1 High-Voltage Circuit-Breakers

Input data

Hereafter, different steps and the resulting results are shown, which can be derived based on a 110 kV circuit-breakers collective [14, 15]. In this case, the condition assessment provides a distribution depending on different types of circuit-breakers in accordance with Sect. 3.4.1.1: Air blast, minimum oil, and SF_6 as shown in Fig. 3.46 [3]. According to Fig. 2.30, various technologies have been used in different time periods, so that the SF_6 circuit-breakers correspond to the today's technology and thus represent the younger collective.

The condition assessment on the basis of various criteria provides results that can be represented as a function of age, and they reflect the different periods of the use of various technologies. A condition value of “0” means that this unit is in good condition, while a value of “100” can be described as critical, according to Fig. 3.44. It can be seen on the basis of the condition distribution that different circuit-breakers may be assigned with the same condition but different installation years. In these cases, thereby the actual age of the equipment is deviating from the “artificial” age, which must be taken into account during the classification of the cluster “age and condition model” according to Fig. 3.44. The condition of equipment is defined due to the lower envelope curve as shown in Fig. 3.46, which is considered as the benchmark for the other equipment of the same age. This

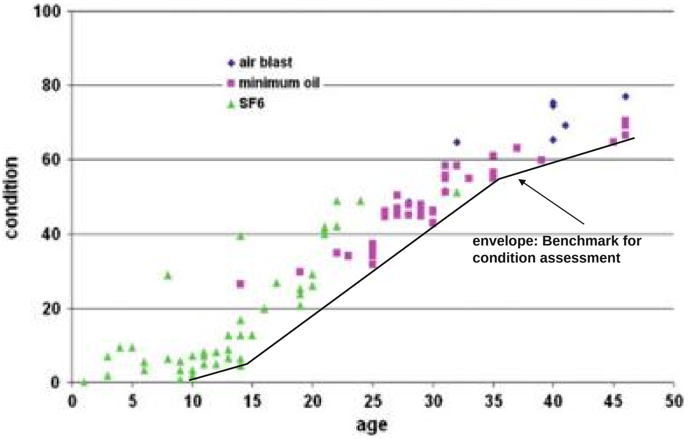


Fig. 3.46 Condition/age diagram of circuit-breakers [3]

means, for example, that the SF_6 circuit-breaker with 8 years of operation (Fig. 3.46) has an "artificial" age of just 24 years taking into account the condition.

Considering the failure data and expenses for maintenance and repair for used circuit-breakers, a simulation over the entire observation period can be carried out, in this case over 40 years. The failure rates (failures per year) of the circuit-breakers are provided due to the statistical data for a "major" failure as follows:

- Air blast: 0.0039,
- Minimum oil: 0.0021, and
- SF_6 0.0024.

According to [19], an average ratio between "major" and "minor" failures of 7.0 for the 123 kV voltage level are assessed. In practice, commonly used values are applied in determining the personnel and material costs, costs of inspections/overhauls as well as for the repair of "major" and "minor" failures, so that it is possible to calculate the operating costs. It is assumed that a circuit-breaker, which has reached the end of its useful life, is replaced by a new SF_6 device. Basically, it can also be useful to replace only a part of the circuit-breaker fleet, since a lower number of breakers may result on the basis of a new network structure, which was determined on the basis of a new network planning or modified switchgear types. Moreover, an extension of new installed capacity of 1 % per year is assumed, based on the existing fleet (1000 circuit-breaker).

Results

Using the input data according to Sect. 3.4.2, a simulation of the circuit-breaker stock and the resultant financial expenses can be performed over the entire observation period. The results of the simulations are exemplarily shown in Figs. 3.47, 3.48, and 3.49.

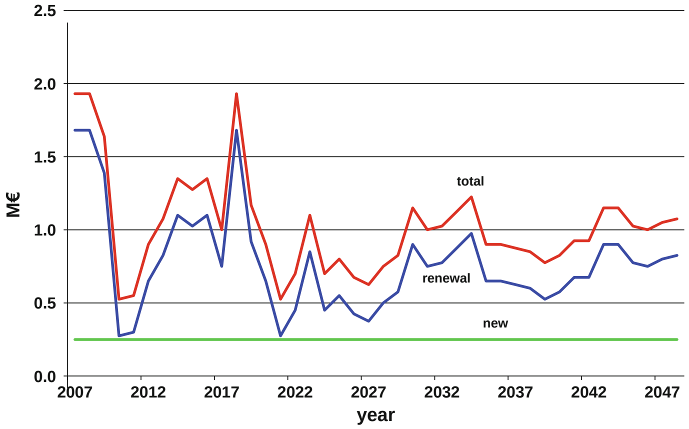


Fig. 3.47 Budget needs per year [15]

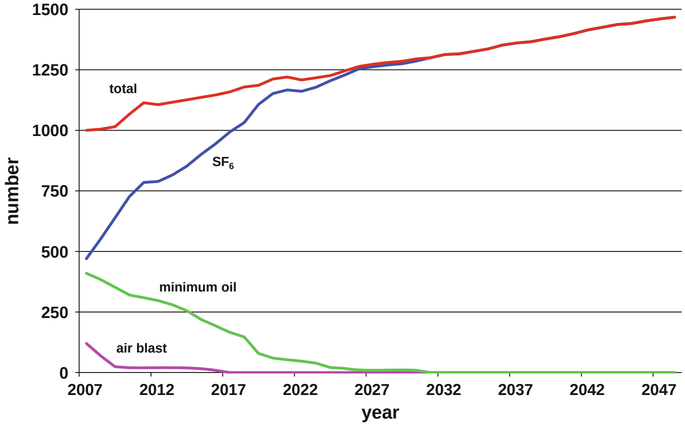


Fig. 3.48 Portfolio of circuit-breakers depending on the extinguished medium [15]

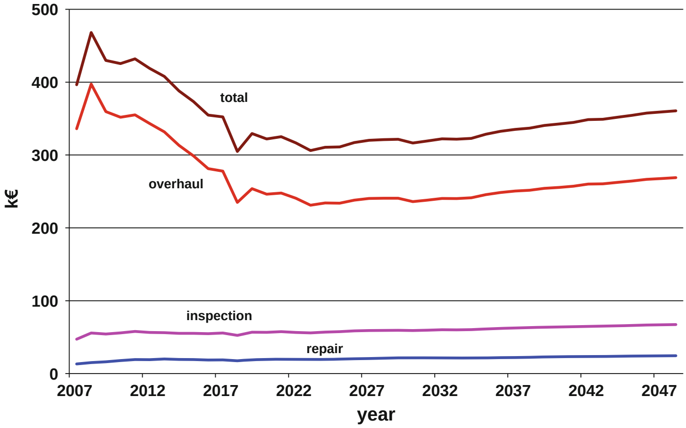


Fig. 3.49 Financial needs for inspection/overhaul and repair costs [15]

Figure 3.47 shows the total required budget (replacement or new demand) under the assumption of a constant replacement value of the circuit-breakers over the observation period. The budget peak at the beginning of the simulation (2007) results from the condition assessment according to Fig. 3.46, since many circuit-breakers are already in the class “critical” at the beginning, so that an exchange is performed in the first simulation year. In addition, the second budget peak results in 2018, the background is that during this year all remaining minimum oil circuit-breakers have to be replaced. Due to a limit on the maximum of two times the average value of financial resources (based on the entire time range), higher peaks have already been avoided in order to achieve optimal utilization of human and financial resources. To achieve a further smoothing of the budget requirements, the maximum financial expense per year can be restricted, so that it is shifted to the later years. This can ensure that the necessary human and financial resources are more evenly utilized.

Figure 3.48 shows the overall circuit-breaker portfolio at the end of a year as a function of the extinguishing medium over the observation period. The last air blast or minimum circuit-breakers will be taken out of service in 2015 or 2029. In this case, it is assumed that the equipment is taken out of service at the end of a year due to the condition and is replaced by a new one at the beginning of next year, which can explain the numerical decrease of the portfolio in a few years. The linear increase is the result of a constant extension of additional new units of 1 % per year.

On the basis of the number of switching devices, both the annual probable repair costs—as a result of failure rates for “minor” and “major” failures—and the annual expenses for inspections and overhauls (maintenance) are calculated. The results are plotted in Fig. 3.49. In the early years, the reduction of overhaul costs is influenced by a decrease of the air blast and minimum oil circuit-breakers and the trend shows the growing portfolio of SF_6 circuit-breakers. It turns out that the repair costs are of minor importance as a result of the low failure rate in this example in relation to the total operating costs. The same is also approximated for the annual inspection costs.

Due to reliability calculations, the contribution of a switching device on the ENS resp. the interruption frequency or interruption time can be determined at all network nodes (Sect. 2.1.2.3), so that the change of these reliability characteristics can be represented as a function of the simulation time using an additional diagram.

3.4.4.2 Medium-Voltage Cable

Input data

This example considers two different variants in case of the subsequent asset simulations for a medium-voltage cable system in order to determine the influence on the investment and operating costs, the described simulation corresponds to the representation according to [2, 13]:

- Variant 1: Maximum operating time of the cable is 70 years, i.e., exchange of all existing cables after this time,
- Variant 2: Maximum operating time of the cable is 80 years, i.e., exchange of all existing cables after this time under consideration of higher repair expenses as a result of an increased failure rate in the age range >70 years compared to variant 1.

This text and the following belongs to the heading “input data” life of 70–80 years is assumed. Out of this, it can be deduced that a significant need for renewal can be expected in the coming years, so that the definition of a strategy is necessary. The peak at the age of 99 years based on the fact that no precise data concerning the year of construction exist, however, in these cases a minimum age of >80 years can be accepted.

This example shows that a large number of the existing cables have exceeded the maximum expected life of 70 years (variant 1), so that these cable connections have immediately to be replaced. This results to a large budget volume in the subsequent simulations in the first year of observation. In addition, it is assumed that only 80 % of the existing cables are replaced by new ones because of changed network structures.

An aging model (Sect. 3.4.1.2) is used for the simulation, which consists of several condition classes. The characteristic values of different classes are shown in Table 3.25 in terms of age and the failure rate. In this illustration, only dielectric failures are taken into account, on the one hand only these failures represent the aging behavior, and secondly outages caused by external influences (e.g., earthworks) are balanced by the causer of the outage; therefore, it does not stress the financial resources of the company.

The failure rates are assumed for a life of >40 years and a similar aging behavior is considered for the two different cable types (lead-covered cable, polymeric cable). Based on the operating experience, the simulation assumes that after 40 years (or 50 years, variant 2) already 10 % of the cable lengths must be replaced and that only 5 % of the cables achieve their maximum life, depending on the variant.

Results

Figure 3.51 shows the total investment for new cables over the entire period of 50 years for the two investigated variants. The investment peak at the beginning of the simulation (2008) is a consequence of the age distribution according to Fig. 3.50. In addition, the second peak 2035–2045 (or 2040 and 2052 depending on the variant) is a result of the high level of investment at the beginning of the 60s and 70s of the last century, what can also be read from Fig. 3.50.

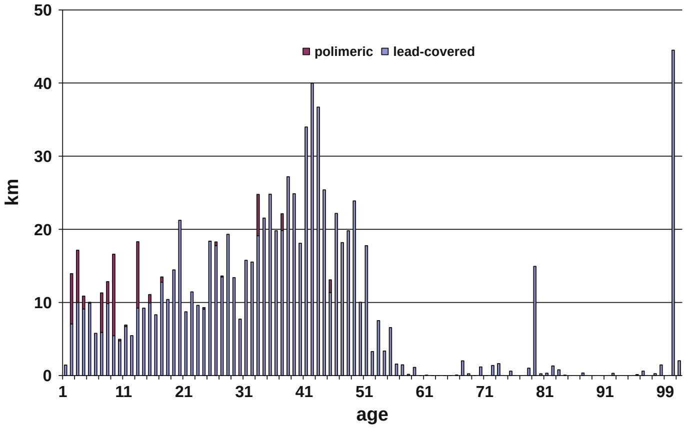


Fig. 3.50 Age distribution of the considered cable network [2]

Table 3.25 Classification of the aging model depending on the failure rate (1.0 p.u., only dielectric failures) of paper-insulated lead-covered cable: 0.0065 1/(a × km); polymeric cable: 0.0020 1/(a × km) [28]

Class	Age	Failure rate (p.u)
1	1–5	1.0
2	6–25	1.0
3	26–40	1.0
4	41–55	2.0
5	56–70	4.0
6	70–80	6.0

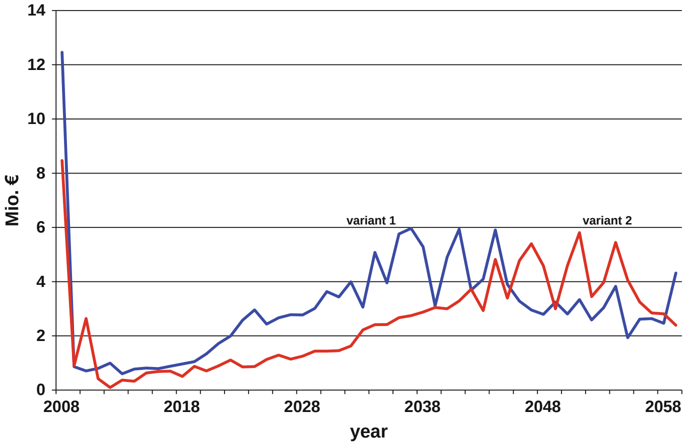


Fig. 3.51 Annual renewal expenses [2]

Based on the total cable distances and the failure rates, the annual probable repair costs plus the annual costs of cable inspections (exclusively cable joint box, cable sealing terminal) and the cable losses can be determined. It is assumed that the cable-related losses (kW/m) are constant in case of a constant power load. The result represents the total operating costs over the period under consideration (Fig. 3.52). In the late years, the reduction of operating costs is a consequence of the replacement of the lead-covered cables by polymeric cables with the same current carrying capacity, because an inspection of the cable joints is not necessary. In addition, lower failures and a reduced replacement demand may result due to the better quality.

Hereafter, the operational costs are examined in detail in terms of the different components for the variant 1 and the following cost items are considered:

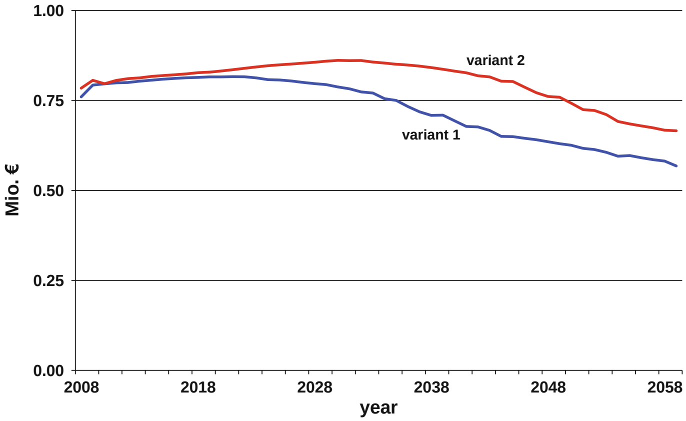


Fig. 3.52 Annual operational costs [2]

- Power losses of cables due to the load (an economic assessment is considered by 3.8 ct/kWh),
- repair costs due the consequence of outages,
- inspection costs of cable joints (lead-covered cables), and
- costs of ENS (assumption: 5 €/kWh).

The determined operating costs are summarized for the period under consideration in Fig. 3.53, but the costs for ENS will be omitted on the list due to the modest figure (the maximum is approximately 28 k€, year: 2028), although the not supplied kWh is evaluated by 5 €. Here, the value of 5 €/kWh should correspond to the economic damage in case of interruption of supply. It turns out that the assessed costs of cable losses have the

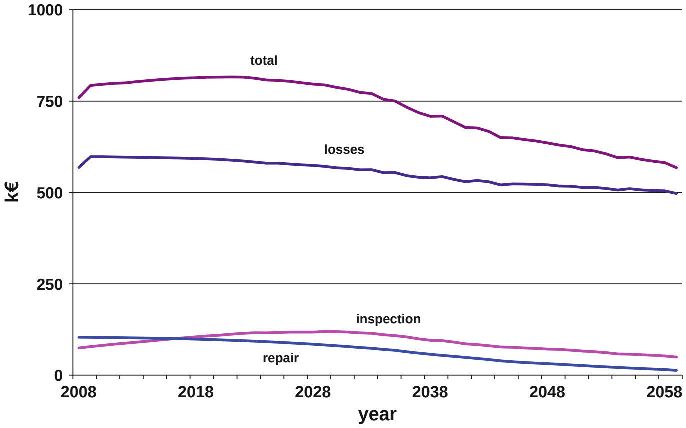


Fig. 3.53 Total operational costs (variant 1) [2]

Table 3.26 Accumulated cash flows of investment and operational costs

Type of costs	Variant 1	Variant 2
Renewal (Mio. €)	159.49	127.76
Operation (Mio. €)	37.72	41.67

Variant 1: maximum operating life 70 years
Variant 2: maximum operating life 80 years

greatest impact on the operating costs with a value between 0.6 and 0.5 million € per year, while the remaining types of costs are not significant. The maximum value of operating costs occurs in the year 2021 with a value of 815.7 k€ and is later reduced.

Assessment

Based on the two study strategies (variant 1 and 2), the consequences on the annual capital and operating costs for the cable network can be determined and summed up. The results are listed in Table 3.26.

It turns out that the total renewal costs are lower by 31.7 million € in case of a longer useful life of cables (variant 2), despite a higher failure rate (between 70 and 80 years), with a simultaneous increase in operational costs of 4 million € compared to variant 1. A significant impact on the payments in this case has the failure behavior of the cables in the time range between 70 and 80 years, since the difference in operating costs is primarily a consequence of the repair costs, while the costs of ENS is not important. In addition, the value could be investigated regarding a strategy decision in a second step by which the failure rate can increase in order to obtain cost parity of the two variants according to Table 3.25 in the time range >70 operational years.

Moreover, in principle it should be considered that strategies are shifted to later years that are characterized at the beginning of the simulation by a lower investment and thus perhaps higher operating costs. Therefore, these strategies always have the advantage against strategies, which are characterized by larger, more CAPEX at the beginning and OPEX in current years. This is a consequence due to the interest rate of the equity in case of the present value calculation, which may be in the range of 7–9 %/a.

3.4.5 Simulation: Statistical Failure Rate

In contrast to the asset simulation in Sect. 3.4.4, as the future aging behavior is derived from a condition assessment of an asset group, it is in principle possible to estimate the renewal or replacement rate of an entire asset group with the help of the operating experience, so that either the number of units to be replaced per year, based on the population (density function, Fig. 3.54), or the cumulative failure probability (distribution function, Fig. 3.55) can be specified. If, for example, a normal distribution is assumed according to Sect. 3.5.2.1, the corresponding distributions can be calculated if according

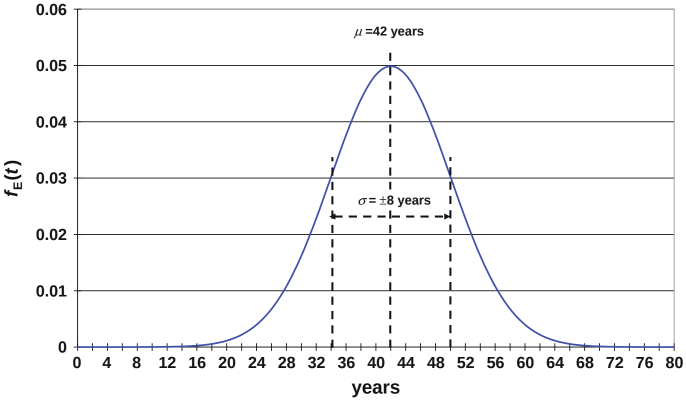


Fig. 3.54 Exchange (replacement) rate $f_E(t)$ of high-voltage power transformers [43]

to [6] or Sect. 2.1.6, Table 2.16, an average life is considered for high-voltage transformers (≥110 kV) of 42 years with a standard deviation of 8 years.

According to Figs. 3.54 or 3.55, in total 50 % of the originally installed transformers are replaced after 42 years and, due to the standard deviation of 8 years, about 68.2 % of the components were replaced in the time window of 34–50 years.

The conversion between the statistical variables $f_E(t)$, Fig. 3.54, and $F_E(t)$, Fig. 3.55, is determined using Eq. (3.27), see Sect. 3.6.2.7:

$$F_E(t) = \int_0^t f_E(t) \cdot dt \text{ resp:} \quad f_E(t) = \frac{dF_E(t)}{dt} \tag{3:27}$$

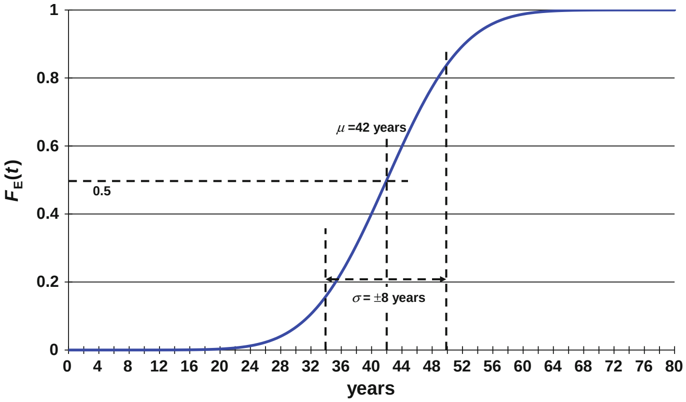


Fig. 3.55 Cumulated replacement probability $F_E(t)$ of high-voltage power transformers [43]

If in contrast to the replacement rate $f_E(t)$, based on the entire collective at the time $t = 0$, the replacement rate $\lambda_E(t)$ is selected, which refers to the components which are still in operation, $\lambda_E(t)$ is calculated to:

$$F(t) + R(t) = 1 \tag{3:28}$$

$$k_E(t) = \frac{f_E(t)}{R(t)} = \frac{f_E(t)}{1 - F(t)} \tag{3:29}$$

where

$R(t)$ number of assets which are still in operation
$F(t)$ number of assets which are already replaced

While according to the Figs. 3.54 and 3.55, a normal distribution with a symmetrical behavior for the replacement of equipment is assumed, it is more realistic in many cases to use a Weibull distribution (Sect. 3.6.3.3), since in these cases the replacement rate in the time ranges can be adapted in different ways before and after the maximum value. In addition, a replacement rate can be derived (corresponding to Fig. 3.54) from the existing collective by the calculation of the function $f_E(t)$ based on the artificial/real age according to Fig. 3.46.

Figures 3.56 and 3.57 show both, the density and the distribution function under the assumption that in total 50 % of the original components have already been replaced in case of equipment age of 42 years. It is shown that depending on the parameter according to Eq. (3.75, Sect. 3.6.3.3), the waveform of the failure rate can be adjusted, so that the aging behavior is reproduced. For example, in case of a value of $\beta = 10$, the shape of the replacement rate is up to the maximum value more flat against the shape after 43 years of operation. In addition, all equipment must be replaced after 54 years.

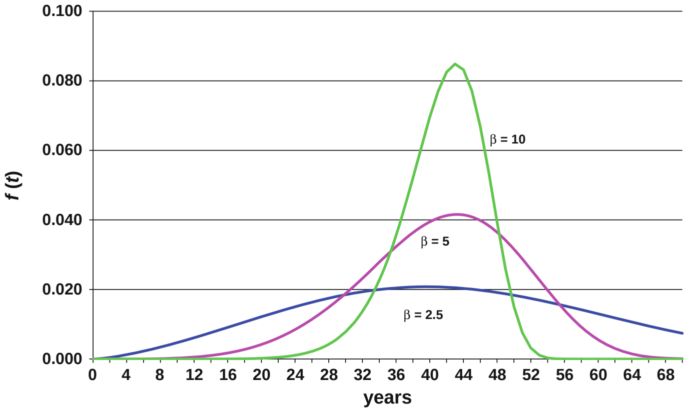


Fig. 3.56 Replacement and renewal rate $f(t)$ with the aid of Weibull distribution, parameter β

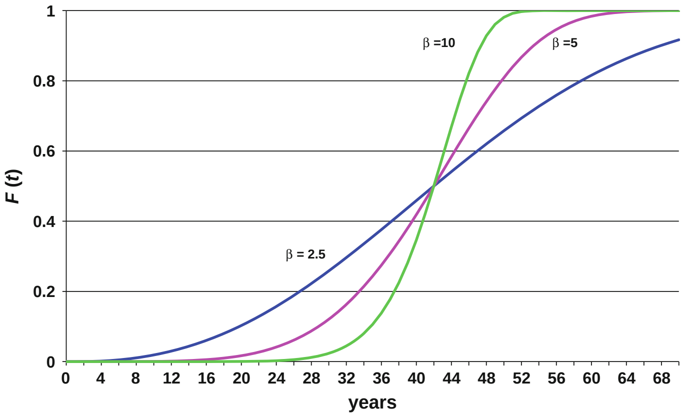


Fig. 3.57 Cumulated replacement rate $F_E(t)$ with the aid of the Weibull distribution, parameter β

The basic procedure of the simulation can be divided according to Fig. 3.58 into several steps:

- The division of the existing collective of equipment is based on the current age of equipment, since all distributions (failure rate, replacement rate) refer to this age.
- Depending on the fault behavior [$\lambda_{mf}(t)$ resp. $\lambda_{MF}(t)$ minor (mf), major (MF)], the collective of equipment can be divided into different classes, for example, different failure costs can be assigned to (Fig. 3.42).
- Using the annual replacement rate $\lambda_E(t)$, the pieces of equipment were calculated which are replaced in each year. Herewith, it can be taken into account that not all components are replaced by new ones, if a reduction of the components in the network takes place due to a target network planning ($n_E < 1$).

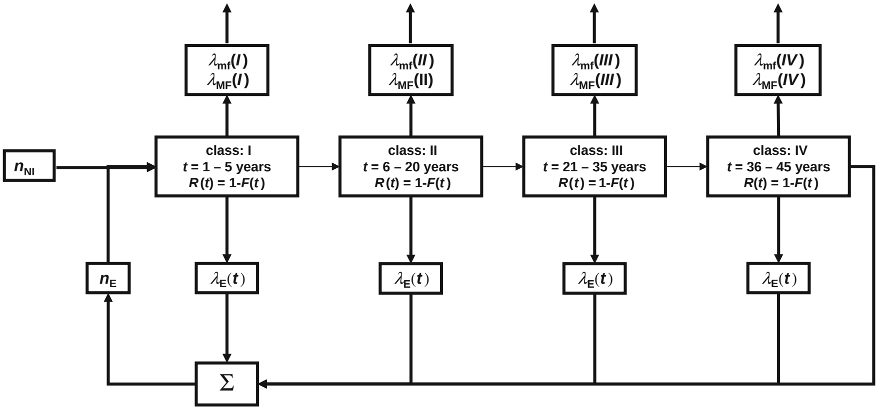


Fig. 3.58 Simulation with statistical values (work steps)

- New components can be additionally taken into account due to new investments depending on the year ($n_{NI} > 1$).
- After a maximum operating time, all remaining components have to be replaced, in this example, after 45 years.

3.4.6 Conclusion Asset Simulation

Using an asset simulation, the renewal and maintenance needs can be determined in different years under definable boundary conditions (failure rates, costs of maintenance, etc.). The impact on the financial needs and the supply reliability can be derived and optimized in case of changed failure rates by the variation of parameters, e.g., extended maintenance cycles. In these cases, however, the outage behavior of equipment has to be estimated, if the maintenance cycles are changed.

In addition to knowledge of the financial requirements concerning the current maintenance and renewal strategy, the main advantage of a dynamic asset simulation is the determination of the impact that a different strategy will have on the results, such as the shift of the renewal with the help of a singular and complex overhaul or extension of the maintenance interval. This will also be of particular interest in a discussion with the appropriate government authorities or regulators regarding the investment strategy and thus the necessary financial expenses that can be derived out of this.

The exchange behavior of the collective of equipment is assumed in these cases due to the operating experience, which is reflected in the corresponding exchange rates (Figs. 3.46 and 3.48). This simulation thus takes into account the technical behavior of equipment, which is derived from the past. On the contrary, even the renewal behavior could be based on the requirements of a regulator (Sect. 1.3.2), so that it may be economically useful, to replace the components deviating from the current technical requirements by new ones.

3.5 Optimization of Maintenance

With the help of the area of work operations research (OR), it is possible to carry out a process optimization under various boundary conditions. In the past, various problems have been solved, including the problem of the traveling salesman which is the most famous [27]. Below, the knapsack problem is presented and in addition, the application of game theory is an example for an optimal maintenance [36–38].

3.5.1 Game Theory

The aim is to solve a multi-objective problem with the help of game theory. It should be checked whether a model is suitable to determine optimal maintenance strategies for the components of a given network on the game-theoretic basis. For this purpose, firstly the relevant reliability parameters must be determined using a calculation program. Subsequently, the effects of different maintenance strategies are considered and evaluated at the selected network components [37].

3.5.1.1 Basis of the Calculation

The calculations are carried out using a 110 kV grid, which represents a section of a real transmission network. The entire sub-network consists of two- and three-winding power transformers, disconnectors, circuit-breakers, transmission lines, and loads. Basically, the network considered has three feed-ins from the 380 kV voltage level and one feed-in from the 220 kV grid. This is a small section of a 110 kV group, since the transmitted power is only about 133 MW in this sub-network. This power has a significant impact on the ENS, which in turn has a significant influence on the optimization process in the further course.

The considered network section itself supplies various downstream 20 kV medium-voltage networks. Only three different asset groups are taken into account for the subsequent calculation, namely:

- 9 power transformers (PT),
- 22 circuit-breakers (CB), and
- 44 disconnectors (DIS).

As the failure rates of the equipment can be used with the help of the fault statistics of the FNN, which takes into account not age-dependent outages, an average equipment age of 20 years is assumed for the calculation of the ENS at different network nodes, which should correspond to the average age of the components in the network. However, the components are assumed randomly distributed in the time range between 1 and 40 years for the simulation, thus resulting in a different age of the particular components in the network. This has an effect on the failure rate of the single equipment, which is taken into account for the reliability calculation.

The age structure of the used equipment can be found in Fig. 3.59, the average age of all components is found to 20.4 years.

Procedure of the game theory

It is not possible in many optimization problems to describe all objective functions by a variable, for example, by a monetary value, but they are in principle independent from each other. The multi-criteria approach tried to use the game-theoretic methods to find a solution for the planning of maintenance tasks. The solution found represents a so-called Pareto optimum, the result is that the needs of all players will largely be satisfied and thus

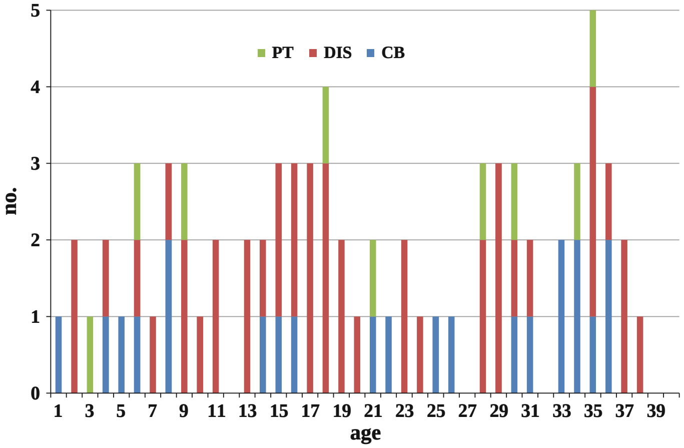


Fig. 3.59 Age structure of the used equipment. PT power transformer, DIS disconnector, CB circuit-breaker

represents a best compromise between the competing goals of the participants. In the presence of a Pareto optimum, no participant may be better without worsening the situation of another participant.

The goal of the maintenance planning of equipment in networks is to get the operating condition of network components as long as possible by the coordinated use of the maintenance activities. Herewith different planning criteria of economy, reliability, and preservation of asset compete. When planning, requirements of various departments of the company are provided and proposals are formulated and a maintenance strategy (IH) can be defined. An assessment and modeling of the quality of each strategy results from the above-mentioned criteria and these criteria are simultaneously participating in the game as players.

Initially, defined result functions of the players are calculated for each maintenance strategy, and then, the proposals will be transformed and evaluated to a utility function. By using game theory methods, a strategy combination is selected that represents an optimal compromise (Pareto optimum) between each planning criteria or players. The realization of the Pareto optimal solution is the new created maintenance scenario.

A considerable computational effort can be saved by the utilization of the game theory and the existing effective solution algorithm. With the use of this application method, it is not necessary to calculate all possible strategy combinations. In total, $3^{75} = 6.08 \times 10^{35}$ strategy combinations are possible in case of 3 maintenance strategies and 75 pieces of equipment. When using a combinatorial approach, all combinations have to be calculated. With the game-theoretic algorithm used in this study, only 11,400 strategy combinations must be examined, if only two rounds are considered. Thus, the method reduces the computational effort to be made to allow selection of the best compromise from the set of Pareto optimal solutions.

In a game-theoretic model, there are competing planning criteria which also represent the participating players. It must be the goal of finding efficient solution algorithms for such multi-objective tasks. While fixed and immutable boundary conditions are applied in the model in case of classical approaches, they can be optimized within the planning process in this multi-criteria approach.

Maintenance strategies

In the present model, there are three possible maintenance or servicing strategies that can be applied to the analyzed components such as power transformers, circuit-breakers, and disconnecting switches. A selected maintenance strategy is realized in each case for the entire period for the equipment. The individual strategies have different effects on the failure rate $\lambda(t)$ of equipment, and thus on the resulting energy deficit of the network. They also affect the new investments and maintenance costs.

For further consideration, three different maintenance strategies are assumed, which differ in their frequency of maintenance activities resp. their maintenance cycles. The assumptions made are valid for each of equipment and are therefore independent on the other components of the network. Furthermore, they remain constant in each year of the selected period under consideration. These strategies are as follows:

- Status quo (current strategy): In case of the strategy "status quo," maintenance activities will continue for each year at the current level. Thus, maintenance costs and the deficit energy of the network stay on the current values (strategy A).
- Reduced maintenance: The strategy "reduced maintenance" means that the service interval is increased for the equipment compared to the strategy "status quo." This decreases subsequently the annual maintenance costs, with increasing the failure rate of equipment compared to the strategy "status quo." Herewith, the expected deficit energy will increase caused by this equipment (strategy B).
- Improved maintenance: When using this strategy, the maintenance cycles are reduced for equipment compared to the strategy "status quo." As a consequence, the maintenance costs increase, while the failure rate is reduced compared to the strategy "status quo." Moreover, the resulting deficit energy is accordingly reduced (strategy C).

The maintenance cycles of the different maintenance strategies are listed in Table 3.27.

Failure rate

In general, the age-dependent failure behavior can be simulated with the aid of a bathtub curve, in which three various time ranges differ: Firstly, early failures occur which, however, do not represent a sequence of an age behavior but occurs to failures during commissioning or installation. A constant range of the failure rate follows at a lower level

Table 3.27 Annual maintenance costs and cycles per year depending on the strategies

Equipment	Strategy A		Strategy B		Strategy C	
	Annual costs/€	Cycle/a	Annual costs/€	Cycle/a	Annual costs/€	Cycle/a
Power transformer	1000	10	833	12	1250	8
Circuit-breaker	680	5	567	6	850	4
Disconnector	200	10	167	12	250	8

and, finally, following an increasing failure rate due to aging. As the following discussion relates to the impact of a maintenance strategy, it is useful to represent exclusively the later stages of the bathtub curve with the aging behavior, so that the failure rate can be described by an exponential equation, Eq. (3.27).

$$k_i(t) = k_{i;0} \cdot e^{t=T} \qquad (3:30)$$

where

$\lambda_{i,0}$ failure rate at time $t = 0$
T time constant depending on the maintenance strategy

Under these conditions, the age-dependent profile of the failure rate results exemplarily according to Fig. 3.60 for the circuit-breaker model.

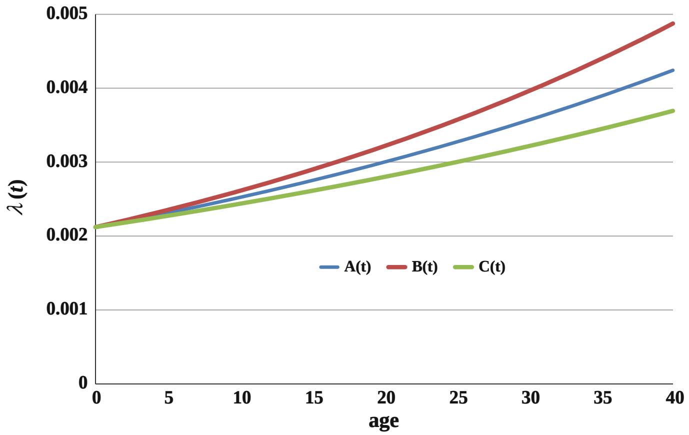


Fig. 3.60 Failure rates depending on the maintenance strategies A, B, and C (exemplary, circuit-breaker)

Renewal and investment

It is essential for long-term asset simulations that criteria are created, which define the conditions to replace the components. This can be exemplary when

- the equipment does not have an acceptable failure rate, or
- a maximum life is exceeded, e.g., 50 years.

In addition to the methods mentioned above, in this example, a renewal is additionally performed, if the book value of the fixed assets of all units is leaving a bandwidth of 25 % of the originally scheduled assets. The reason is that the system operator is forced to make investments in order to keep the availability of the equipment on a high level. The choice of the replaced equipment occurs in the order of the equipment that causes the highest value of ENS in the network in case of a failure until the invested capital reaches again at least 100 %. Here, the value of 100 % refers to the value of fixed assets at the beginning of the simulation (not replacement value of the equipment). The amortization period of all components is assumed to be 40 years in the following study.

3.5.1.2 Design Criteria

In total, three criteria are adopted for the proposed optimization of maintenance, which are also the players at the same time. These criteria are presented below.

Maintenance costs (service costs)

The maintenance costs and cycles for the considered groups of equipment are listed in Table 3.27, from which the annual costs can be determined, taking into account the different maintenance strategies according to Sect. 3.5.1.1.
The total annual maintenance costs consist of the costs of all components of the network.

Investment costs

Investment costs per year arise, if the residual value of the asset portfolio falls below a critical value according to Sect. 3.5.1.1. The order of the equipment is determined by the ENS of all the components. The following values are used as investment costs for the various components:

- Power Transformer: 675 k€,
- Circuit-breaker: 34 k€, and
- disconnector: 19 k€.

These values can be considered as exemplarily.

Energy not supplied

The amount of ENS at the network nodes is performed using reliability calculations. Herewith, the ENS at all network nodes is determined based on the failure rate of certain equipment. For simplification, the calculation is carried out with an average failure rate according to the FNN statistics [17]. The result of this calculation is that each piece of equipment can be assigned to the deficit energy for the entire network, as a consequence of a fault at this unit. It is assumed for simplicity that the failure rate for the reliability calculation remains constant, since otherwise a separate calculation has to be made for each change of strategy or age.

3.5.1.3 Example

Based on the 110 kV sub-network, it is shown how the optimum with regard to the maintenance strategy can be found and in total three players are used, namely:

- Service costs,
- deficit energy, and
- investment costs.

The aim of the study is to find the optimal maintenance strategy for each of the 75 existing pieces of equipment, which are referred to as A, B, and C according to Sect. 3.5.1.1. The optimization of the maintenance strategy is considered over a period of 40 years, this corresponds to the age distribution according to Fig. 3.59 as the start value.

The Pareto optimum is found by means of various steps:

1. Derivation of the baseline scenario,
2. Transformation and standardization,
3. Global utilization function, and
4. Rules for the derivation of the optimal

The individual steps are described in the following.

Derivation of the baseline scenario

For the baseline scenario, the maintenance strategy A is used for each equipment and the behavior is simulated with respect to three players over a simulation period of 40 years. The exchange of components is based on the boundary condition that the invested capital is permitted to fluctuate within a bandwidth of 25 %, based on the fixed assets at the beginning of the simulation. Due to the target, three objective functions are determined by the players. Since the results of the objective functions are directly not comparable, standardization is necessary.

Transformation and standardization

A utilization function is created for each player by the particular benefit of a strategy and can vary between 0 and 1. The conversion of concrete value $V_p(IH)$ of an objective function is shown in Fig. 3.61; this is the amount of maintenance and investment costs and ENS into a standardized benefit function $B_p(IH)$. For each player, it is possible to determine a particular benefit function of the maintenance strategy. The curve shown can be determined using Eq. 3.31.

$$B_P(IH) = \frac{1}{1 + e^{c_P \cdot V_P(IH)}} \tag{3:31}$$

where

$B_P(IH)$	benefit of the strategy for each player
$V_P(IH)$	value of the objective function depending on the strategy
c_P	standardization factor

It is possible to change the slope of the curve and hence to influence the weighting of the various players by the standardization factor c_P. The determination of the benefit function used cannot be changed during the game.

Different target directions can be set by altering the choice of the sign of the standardization factor (improvement or degradation) compared to the baseline scenario. In addition, as a result of the baseline scenario, a bandwidth W is determined that results from Eq. 3.32 on the minimum and maximum utilization values.

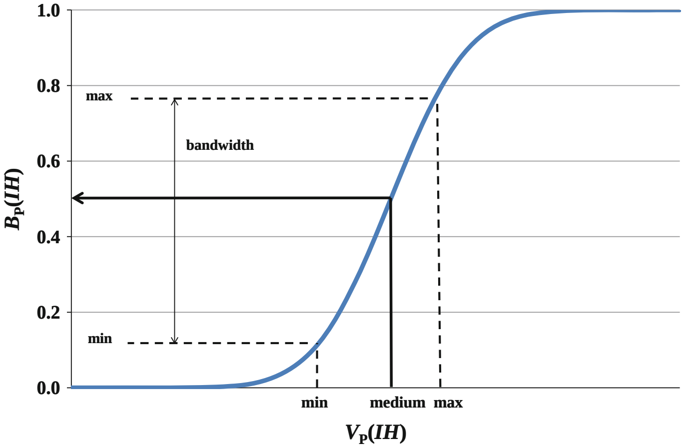


Fig. 3.61 Standardized benefit function

$$W = B_{P;\max}(\text{Basis}) - B_{P;\min}(\text{Basis}) \qquad (3{:}32)$$

In the baseline scenario, the results of the target function are averaged for all years within the simulation period and the result is assigned to the benefit value $B_P(A) = 0.5$.

Global utilization function

It is ensured by taking into account a global utilization function that the global benefit of various combinations is improved in respect of the previous simulation, while other combinations are rejected. The global benefit of a combination is determined by the sum of the individual benefit functions and is used to select the dominant player. All possible combinations of single benefits are within a quadrant according to Fig. 3.62.

Starting from a baseline scenario (point A, Fig. 3.62), improvements are realized as the benefit of the two players is always improved. The Pareto optimum is achieved when the improvement of a player can only be achieved by the degradation of the second player.

3.5.1.4 Result

The optimal maintenance strategies A, B, and C are derived for all pieces of equipment in accordance to Sect. 3.5.1.1, where various strategies are possible for different an asset groups, this is due to the various ages and the ENS, which is caused by a failure. The last value depends on the network load and topology. Figure 3.63 shows the results for three groups of equipment (PT, CB, and DIS). The different maintenance strategies for the asset groups are the result of equipment age and the location in the network or their impact on the availability of different network nodes. In addition, a maintenance plan is developed for each unit and maintenance strategies as well as the replacement times can be determined.

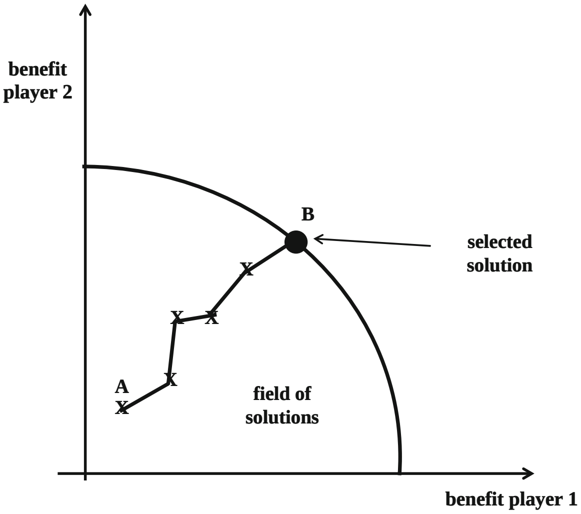


Fig. 3.62 Selection of the Pareto amount in case of two players

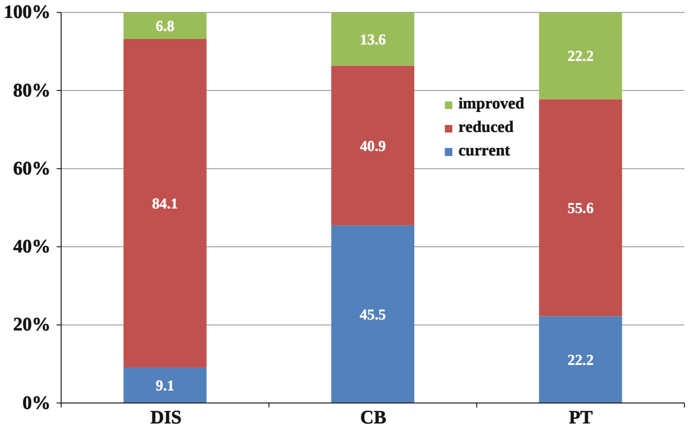


Fig. 3.63 Optimal maintenance strategies of asset groups. (A) Current maintenance, (B) reduced maintenance, (C) improved maintenance

According to Fig. 3.63, the majority of the recommended maintenance strategies for asset groups are as follows:

- Disconnector: less maintenance (84.1 %)
- Circuit-breaker: service according to “status quo” (45.3 %) by the majority, another part should be maintained reduced (40.9 %)
- Power transformer: reduced maintenance by the majority (55.6 %), the rest is distributed among each of the other two strategies.

Figure 3.63 shows that disconnectors are to be maintained reduced by the majority, a further analysis indicates that the strategy is depending on the location, Fig. 3.64. Some

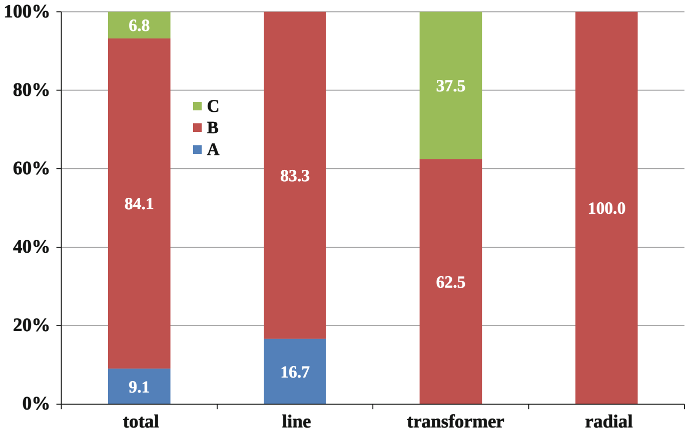


Fig. 3.64 Strategy of disconnectors depending on the location (legend Fig. 3.63)

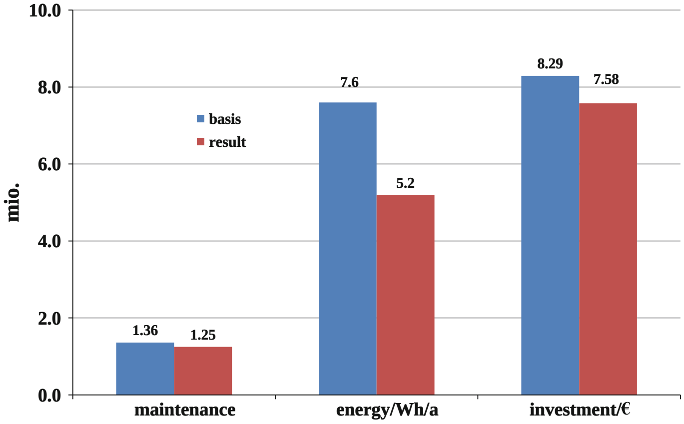


Fig. 3.65 Comparison of the scenarios

disconnectors in line fields (with a remote substation) should be serviced according to the current strategy (16.7 %), while some switches in transformer fields should be serviced improved (37.5 %). In radial feeders (without remote station), all disconnectors should be serviced reduced because the availability is primarily influenced by the overhead line.

In the baseline scenario, the maintenance strategy A is performed for all pieces of equipment and thereby information can be identified over the entire simulation period regarding the maintenance costs [€], the ENS [Wh/a] and the investment costs [€]. Figure 3.65 presents the changes of the final scenario relative to the baseline scenario for the three players.

It turns out that through the optimization process, the ENS is significantly reduced (by 31.6 %), while the other two variables are each reduced by 8.1 and 8.6 %.

3.5.2 Knapsack Problem

A well-known optimization method of operations research represents the knapsack problem, which is derived from the activity of a walker: He faces the task of packing his backpack optimally for a hike in which the target is to maximize the sum of the specific useful values of the packed items, with the constraint not to pack more weight than he is able to carry. In practice, it is also useful to consider several constraints, such as working hours, personnel, and financial resources.

3.5.2.1 Basis of the Calculation

This general method can be applied for use in the area of electrical power supply so that a maintenance plan can be derived for the considered components. In this case two options are adopted, namely intensive maintenance or replacement of the equipment [36]. This means that various maintenance activities represent the different items and the weighting constraint represents the annual budget. In this case, the maximum benefit is that the energy loss is minimized at various network nodes. To solve this particular task, a modification of the simple knapsack problem is used, namely the multiple-choice knapsack problem. The procedure is that n different categories represent various pieces of equipment of the network and the choice i of possible maintenance actions can be applied for each device and exactly one of which must be carried out for the year to be considered. A maintenance action is thus characterized by the costs applied and the energy loss when it is performed at an asset next year. This means that the energy loss must be minimized, with the following constraints:

- Equipment is subjected to either a maintenance action or not.
- Only one measure of the possible maintenance action will be considered.
- The maximum available budget must not be exceeded.

The optimization is carried out with a similar subnetwork, as illustrated in Sect. 3.5.1.1 with a slightly changed amount of components (28 circuit-breakers, 46 disconnectors, and 8 power transformers). In addition, three different maintenance strategies are used with the following values according to Table 3.28.

Annual budget

During the simulation, a total annual budget for all maintenance activities is fixed, i.e., for maintenance and replacement. The maximum value of the budget corresponds to the largest single measure, in this case consisting of the replacement of a power transformer, i.e., B_{max} = 675 k€ or provisions have to be applied for annual major investment measures. In addition, a minimum budget is valid which is determined by the fact that only inspections have to be exclusively carried out for the components.

Energy not supplied

As the ENS is to be minimized at load nodes, reliability calculations are performed in the 110 kV network. The result of this investigation is to determine the contribution of equipment to all network nodes with respect to the ENS. The outage frequencies (1/a) and the outage duration (h) are taken from the network statistics which provides the average values for all equipment groups [17]. Since only average statistic data are available, it is assumed that the considered equipment collective is equal to the average age. If the age of the equipment deviates, it is accordingly converted into a changed value of the ENS.

Table 3.28 Annual maintenance costs depending on the maintenance measure

Equipment	Inspection	Reduced service	Service
Power transformer	675	3713	6750
Circuit-breaker	68	289	510
Disconnector	38	162	285

The reliability calculations perform the following values of ENS at the load node of the 110 kV network, each per equipment and year:

- Circuit-breaker: 0.246 MWh/a,
- Disconnector: 0.101 MWh/a, and
- Power transformer: 0.897 MWh/a.

3.5.2.2 Optimization Algorithm

Basically, it is possible to consider various optimization algorithms, which represent different circumstances. But all objective functions have in common to minimize the ENS for the next year under the constraint that the annual budget is not exceeded. Three simple different algorithms are calculated and compared to the results of the exact solution (ES), namely:

- Minimum maintenance (MM),
- Absolute benefit (AB),
- Relative benefit (RB), and
- Exact solution (ES).

Different algorithms are described in the following sections.

Minimum maintenance (MM)

Only minimal maintenance actions (inspections), and no renewal investments are carried out; this means that the components are not exchanged after 50 years. This variant is used to compare the results to all other options.

Absolute benefit (AB)

The ENS is calculated, which is caused by this equipment, for the existing network components, taking into account three maintenance options and the renewals. In total, 328 maintenance measures are possible, which may exclude each other since a single maintenance measure can only be applied to a single component. This ensures that a maintenance action is provided for each piece of equipment and each device is assigned to the action “inspection” at the beginning of the simulation.

To compare the measure to the particular components, the difference of the ENS of the previous year is assessed as the benefit of the maintenance measure. The calculated values of the total ENS are sorted in descending order. The sorted list is processed regarding each element and the appropriate maintenance procedure is listed, which can be funded by the remaining annual budget.

Relative benefit (RB)

The calculation of the ENS is performed, but the energy difference is related to the costs caused by the maintenance measure. The determined relative benefit is sorted in descending order and successively taken into account if the annual budget is not exceeded, and a maintenance activity at this component has not yet been carried out.

Exact solution (ES)

The ENS is minimized due to the given annual budget. In contrast to the algorithms described above, all equipment and service combinations are tested and the results lead to the lowest value of the ENS under the boundary conditions.

3.5.2.3 Example

Two different scenario simulations are performed for the given network, which differ in terms of the available annual budget. Here, the different optimization algorithms are compared and evaluated, the simulation time in each case is 20 years. If the specified budget is not fully needed in the year, this can be transferred to the next year.

Scenario 1

In this scenario, the annual budget for maintenance measures is 300 k€, whereby reserve assets for the replacement of transformers is possible. In Table 3.29, the results of the simulations are shown for different algorithms.

Scenario 2

In contrast to the previous scenario, a lower annual budget of 70 k€ is fixed in this case, which is oriented to the expenditure for “more maintenance,” while the replacement of a transformer can only be done with considerable reduction of maintenance at other components. Under the above conditions, the results are summarized in Table 3.30.

Table 3.29 Results of the simulation 1 (300 k€ annual budget)

Value	MM	AB	RB	ES
ENS (1st year/MWh)	23.6	19.9	19.9	19.5
ENS (20th year/MWh)	55.4	15.0	23.5	14.5
Sum ENS (MWh)	758.6	321.0	406.1	311.6
Average age (1 year)	25.5	19.3	19.3	19.3
Average age (20 years)	44.5	17.8	8.5	17.3
Maintenance costs (k€)	181.0	1236.1	1097.2	1265.7
Investment costs (k€)	–	4208.0	4895.0	4223.0
Total costs (k€)	181.0	5444.1	5992.2	5488.7
Not used budget (k€)	5819.0	555.9	7.8	511.3

ENS energy not supplied

Table 3.30 Results of the simulation 2 (70 k€ annual budget)

Value	MM	AB	RB	ES
ENS (1st year/MWh)	23.6	21.9	21.6	21.3
ENS (20th year/MWh)	55.4	29.9	30.7	24.2
Sum ENS (MWh)	758.6	500.6	500.8	444.5
Average age (1 year)	25.5	24.5	23.9	24.5
Average age (20 years)	44.5	24.2	23.3	28.5
Maintenance costs (k€)	181.0	345.7	320.8	729.0
Investment costs (k€)	–	1053.0	1076.0	671.0
Total costs (k€)	181.0	1398.7	1396.8	1400.0
Not used budget (k€)	1219.0	1.3	3.2	0.0

ENS energy not supplied

Table 3.31 Number of changed equipment during the total simulation period (scenario 1 and 2)

Equipment	Scenario 1			Scenario 2		
	AB	RB	EX	AB	RB	EX
Circuit-breaker	22	73	23	17	16	8
Disconnector	40	127	39	25	28	21
Power transformer	4	0	4	0	0	0

Assessment

A comparison of different versions shows that the optimization using the absolute benefit (AB) is similar to the exact solution (ES) what can be seen from the comparison of the ENS. An analysis based on the relative benefit (RB) does not make sense, which, for example, can be seen from the number of changed components over the simulation period of 20 years according to Table 3.31 (scenario 1). The minimum maintenance (MM) always leads to the worst values with respect to the network condition (age of equipment and ENS).

The simulation shows that according to scenario 1, the annual budget can be reduced by about 25 k€ without having an impact on the network behavior, while the annual budget of the second scenario is too small, as this amount leads to an increase of the ENS and the age of equipment.

3.6 Statistic

The knowledge of the failure behavior of the equipment used is essential to establish maintenances action or reliability calculations. The task is often to derive the future characteristics of a population due to the variety of devices from a sample, which describes the amount of data. Basis of the mathematical statistics is the application of the probabilistic theory [1, 30, 40, 46, 48]. Below, details are considered on the basic fundamentals of statistics, which are described in the indicated references.

3.6.1 Probability

The future behavior of equipment can be characterized with the help of the probability, which is derived from the observation of the frequency of events from the past. The probability calculation makes use of the descriptive statistics.

3.6.1.1 Simple Probability

Simple probability is described as the incident of a particular event related to the total population of all possible events. This may be independent, mutually exclusive, or complementary events, with the following definitions:

• Independent	The damage events of equipment A has no effect on the damage behavior of the equipment B
• Mutually exclusive	The damage events cannot occur at the same time
• Complementary	There is only the choice between two events, i.e., the equipment is either on or off, so that the sum of the probabilities for the two events is always $P = 1$

3.6.1.2 Conditional Probability

In case of the conditional probability, the occurrence of an event depends on the behavior between the time T and the current time t. This means, that the failure of equipment, such as the complete loss and thus the required replacement, depends on the status, that this device has not been replaced up to this point. Thus, the probability of the occurrence of the event A in the time domain $T + t$ depends on the probability of the event B up to the time T.

3.6.2 Characteristics of Probability Distributions

Different values are used to identify statistical relationships of a distribution.

3.6.2.1 Expected Value – Mean Value

The expected value $E(x)$ of a density distribution is also referred to as an arithmetic mean value μ and identifies the center of a distribution (however, it does not represent the expected value, but this is only reached for an infinite number of data). The mean value is calculated from the number of particular values x_i multiplied by the probability value according to Eq. (3.33) for the discrete case.

$$E(x) = \sum_{i=1}^{n} x_i \cdot P_i \text{ resp:} \quad E(x) = \frac{x_1 + x_2 + \cdots + x_n}{n} = I \tag{3:33}$$

If a function $f(x)$ is available for each of the outputs, then the summation can be transferred into an integral. The expected value is obtained in the case of a continuous distribution (Sect. 3.6.2):

$$E(x) = \int_{-\infty}^{+\infty} x \cdot f(x)\, dx \tag{3:34}$$

The mean value of a data set is largely driven by statistical outliers, and for this reason, it may be advisable to eliminate these extreme values during the general consideration (Sect. 3.6.2.4).

Example

Metal oxide arresters (MO arresters) consist of individual disks, the permissible continuous operating voltage can vary from a rated value due to the production. In case of a specified voltage of U_c = 6 kV, a distribution results according to Table 3.32.

Table 3.32 Distribution of the measurement results of a sample

Voltage (kV)	Portion (%)
2.94	3.55
2.96	12.34
2.98	20.71
3.00	39.05
3.02	16.54
3.04	5.92
3.06	1.78

The mean value $E(x)$ follows from Eq. (3.33):

$$E(x) = (2:94 \cdot 0:0355 + 2:96 \cdot 0:1234 + 2:98 \cdot 0:2071 + 30:00 \cdot 0:3905 + 30:02 \cdot 0:1654 + 30:04 \cdot 0:0592 + 30:06 \cdot 0:0178)\,\text{kV} = 2:9922\,\text{kV}$$

The mean value of the entire test series is therefore given as $E(x)$ = 2.9922 kV.

3.6.2.2 Median Value

If the values n of a sample are sorted, the median value is in the middle of the total sample. So that the median value depends on the measurement results and on the number n:

$$n(\text{odd}) \quad x_M = \frac{n+1}{2} \tag{3:35}$$

$$n(\text{even}) \quad x_M = \frac{n}{2} \tag{3:36}$$

Only the median value of an odd number of measurement points is unique according to Eq. (3.36).

3.6.2.3 Variance (Statistical Spread) and Standard Deviation

The variance $V(x)$ is a measure of the deviation of each value based on the expected value and represents the mean value of the square deviations from the mean value, so that it becomes

$$V(x) = \frac{1}{n}\sum_{i=1}^{n}(x_i - E(x))^2 \tag{3:37}$$

The term "statistical spread" is also widely used for the term variance. If according to Table 3.32, the particular numerical values are recorded with a probability, then the variance results from Eq. (3.38) to:

$$V(x) = \sum_{i=1}^{n}(x_i - E(x))^2 \cdot P_i \tag{3:38}$$

Equation (3.35) can be written with the aid of the displacement law [1]:

$$V(x) = \sum_{i=1}^{n}\left(x_i^2 \cdot P_i\right) - E^2(x) \tag{3:39}$$

In practice, the term standard deviation σ is commonly used:

$$r = +\sqrt{V(x)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - E(x))^2} \tag{3:40}$$

The standard deviation shows, how the different measured variables spread around the mean value, which is exemplarily presented in Fig. 3.70.

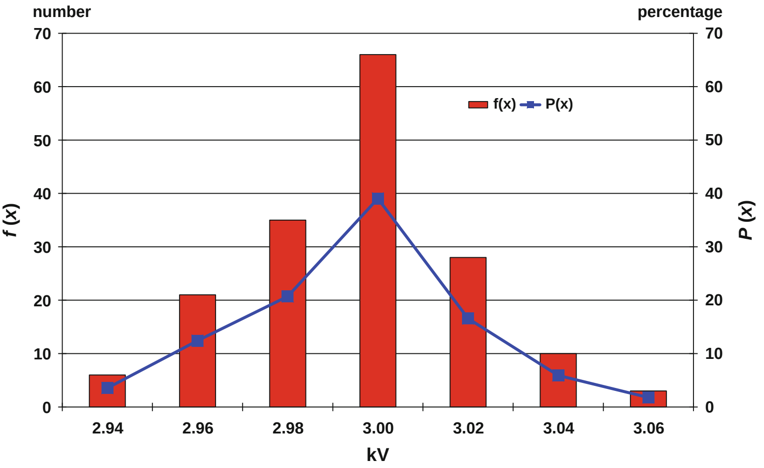


Fig. 3.66 Density function f(x) and the probability function P(x) of the MO disks having a reference value of U_c = 3 kV

Example

For the example of Fig. 3.66, it follows for the variance or standard deviation:

$$\begin{aligned} V(x) &= (2:94^2 \cdot 0:0355 + 2:96^2 \cdot 0:1234 + 2:98^2 \cdot 0:2071 + 30:00^2 \cdot 0:3905 \\ &\quad + 30:02^2 \cdot 0:1654 + 30:04^2 \cdot 0:0592 + 30:06^2 \cdot 0:0178)\,\mathrm{kV}^2 - 2:9922^2\mathrm{kV}^2 \\ &= 0:01069\,\mathrm{kV}^2 \\ r &= 0:1034\,\mathrm{kV} \end{aligned}$$

For this example, the standard deviation is given by σ = 0.1034 kV.

3.6.2.4 Spread

The spread of a data set is determined by the relationship

$$Sp = \max(x_i) - \min(x_i) \qquad (3:41)$$

However, the value depends to a great extent from statistical outliers. On the contrary, the quartile range is much more robust, for example, as it only takes the area of the middle 50 % of the data set into account, so that applies:

$$Q_{50} = x_{0:75} - x_{0:25} \qquad (3:42)$$

3.6.2.5 Scaling

It is useful for a better comparison of different frequency distributions to standardize these distributions. This can be done, e.g., by a centering or standardization. In case of centering, the zero point of the distribution is set in the center μ, so that the new mean value of the amount of data is zero-centered.

In case of a standardization of a distribution, the values are additionally based on the standard deviation (Eq. 3.43).

$$\tilde{x}_i = \frac{x_i - l}{\sqrt{V(x)}} = \frac{x_i - l}{r} \tag{3:43}$$

Therefore, these data according to Eq. (3.43) have no dimension, since the mean value is equal to zero and the variance is 1.

3.6.2.6 Density Function

The density function $f(x)$ generally represents the discrete distribution, for example, the failure rate in dependence on a variable, for example life years. On the contrary, the (cumulative) distribution function $F(x)$ is the summation of the probabilities based on the density function, Sect. 3.6.2.7.

Example

Figure 3.66 shows the distribution of measurements according to Sect. 3.6.2.1, as the voltage values are applied due to Table 3.32.

According to Fig. 3.66, the density function $f(x)$ is applied on the left ordinate and on the right, the probability function $P(x)$ of a discrete random variable x_i (Sect. 3.6.4). The sum of all probabilities is given by:

$$\sum_{i=1}^{n} P(x_i) = 1 \tag{3:44}$$

The bar graph as shown in Fig. 3.66 is also referred to as a histogram.

3.6.2.7 Distribution Function

A further possibility to present the result of Fig. 3.66 is the distribution function $F(x)$ due to Fig. 3.67 and the message thereof is the probability that a MO disk is less than a certain voltage value. Here, the distribution function represents the integral of the density function $f(x)$.

The relationship of the functions $f(x)$ and $F(x)$ is therefore given by:

$$f(x) = \frac{F(x)}{dx} \quad \text{resp:} \quad F(x) = \int_{x_1}^{x_2} f(x)dx \tag{3:45}$$

With the help of Eq. (3.45, on the right), for example, the probability of entering the area between x_1 and x_2 can be determined.

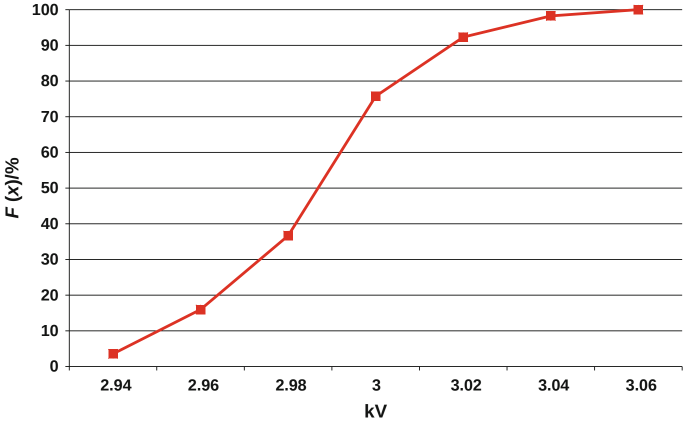


Fig. 3.67 Distribution function F(x)

In the area of asset management, it is often important to estimate the probability of correct performance of equipment depending on age, for example, if the density function is present for an entire collective according to Fig. 3.68. The distribution f(t) decreases after a maximum value because the number of failures becomes smaller again, based on the original total collective (most components had already failed). Due to the area F (t) according to Fig. 3.68, the proportion of components is identified, which had failed. On the contrary, the value R(t) represents the number of units which are still in operation, so that the sum applies to:

$$R(t) + F(t) = 1 \tag{3:46}$$

In this case, the variables F(t) and R(t) are calculated by the integral of the density functions f(t), Eq. (3.45).

$$F(t) = \int_0^t f(t)\,dt \text{ resp:} \quad R(t) = 1 - \int_0^t f(t)\,dt = \int_t^\infty f(t)\,dt \tag{3:47}$$

$$f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt} \tag{3:48}$$

3.6.2.8 Hazard (Failure) Rate of Equipment

The failure rate $\lambda(t)$ is often used to describe the failure performance of a collective, based on the remaining collective. The value describes the number of failures, based on the number of equipment still in operation, which can fail. If the value

$$N_a = N_i + N_0 \tag{3:49}$$

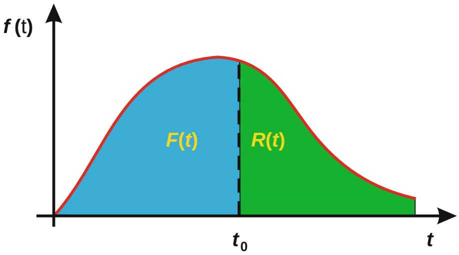


Fig. 3.68 Density function of equipment collective

describes the original number of pieces of equipment,

- $N_i(t)$ equipment in operation
- $N_o(t)$ equipment out of operationthen the following relationships are valid:

$$R(t) = \frac{N_i(t)}{N_a} = 1 - \frac{N_o(t)}{N_a} \text{ resp: } \quad F(t) = \frac{N_o(t)}{N_a} \tag{3:50}$$

The quantities R(t) resp. F(t) are derived according to Fig. 3.68 by the number of already failed components related to the components still in operation. After derivation with the help of the Eqs. (3.48) and (3.50), it becomes

$$\frac{dR(t)}{dt} = -\frac{dF(t)}{dt} = -\frac{1}{N_a} \cdot \frac{dN_o(t)}{dt} \tag{3:51}$$

With Eq. (3.45) follows:

$$f(t) = +\frac{1}{N_a} \cdot \frac{dN_o(t)}{dt} \tag{3:52}$$

Based on Fig. 3.68, the failure rate $\lambda(t)$ can be determined by the total number N_a of equipment related to the number N_i of equipment, which are still in operation according to Eq. (3.52). The result is as follows:

$$k(t) = \frac{1}{N_i(t)} \cdot \frac{dN_o(t)}{dt} \tag{3:53}$$

According to Eq. (3.53), the failure rate is calculated by the change of the number of failed equipment $N_o(t)$ based on the equipment in operation. Finally, the result is as follows:

$$k(t) = \frac{N_a}{N_i(t)} \cdot \frac{1}{N_a} \frac{dN_o(t)}{dt} = \frac{f(t)}{R(t)} \tag{3:54}$$

By substituting, the derivation of Eq. (3.48) becomes

$$k(t) = \frac{1}{R(t)} \cdot \frac{dR(t)}{dt} \tag{3:55}$$

The outage probability $\lambda(t)$ is determined by the result of the last equation, if the density function is known. Taking into account Eq. (3.48), it can also be written:

$$k(t) = \frac{f(t)}{\int_t^\infty f(t)\,dt} = \frac{f(t)}{1 - F(t)} \tag{3:56}$$

This means that the failure rate $\lambda(t)$ is obtained according to Fig. 3.68 by the density function $f(t)$, divided by the area of $t \to \infty$.

In contrast to the presentation according to Eq. (3.55), a conditional failure rate of equipment may be determined, which indicates the probability that equipment can fail during a time period $(T + t)$. Here, according to Eq. (3.57), the failed components during the time range are based on the devices which are still in operation, depending on the density function $f(t)$.

$$k(t) = \frac{\int_T^{T+t} f(t)}{\int_T^\infty f(t)\,dt} \tag{3:57}$$

3.6.2.9 Correlation

Using the correlation, it is possible to show the dependency of different values, which are characterized by a scatter diagram. The equations for calculating the correlation coefficient r in case of linear equations are given in Sect. 3.6.4, Eq. (3.113), here a value of $r = 1$ means that the values x and y are linearly dependent on each other.

3.6.2.10 Confidence Interval, Random Sample

With the aid of a confidence interval, it is possible, to determine an estimated parameter, such as the mean $\bar{X}$ of a random sample, based on a predetermined probability. This means that the mean value $\bar{X}$ of a random sample is not determined, but a confidence interval that includes the mean value. If, in this case the probability of error is described by α, the confidence interval is obtained to $(1 - \alpha)$. Figure 3.69 shows the normal distribution. Here, it is assumed that in case of a normal distributed population, the sample is also normally distributed.

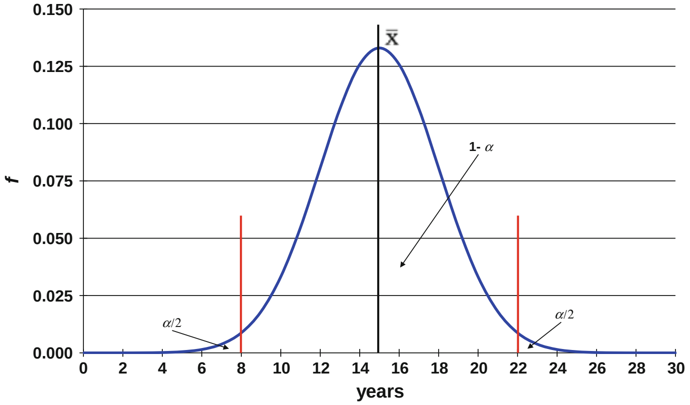


Fig. 3.69 Example for the definition of the confidence interval

If it is assumed that the standard deviation σ is known, the standardized random variable becomes (Sect. 3.6.2.5):

$$Z = \frac{\bar{X} - I}{r\sqrt{n}} \tag{3:58}$$

where

$\bar{X}$ value of the random sample
μ mean value of the expected normal distribution
σ standard deviation
n number of elements of the random sample

The random variable depends on the random sample size; however, but it turns into the standardized normal distribution for $n \to \infty$. The confidence interval becomes under considerations of the boundary conditions u_{uG} and u_{oG} [29]:

$$u_{uG} \leq \frac{\bar{X} - I}{r\sqrt{n}} \leq u_{oG} \tag{3:59}$$

This means that the desired random variable should be between these two limits. The probability, that the desired value $\bar{X}$ is within the required limits, leads to the relationship (Eq. 3.60), with the help of the statistical security S, if the expression $\pm u_s$ is set for both limiting values u_{uG} and u_{oG}:

$$P\left(-u_S \leq \frac{\bar{X} - I}{r\sqrt{n}} \leq +u_S\right) = S \tag{3:60}$$

Table 3.33 Quantile of the standard normal distribution

Interval (%)	u_S
90	1.282
95	1.645
99	2.327
99.9	3.090
99.99	3.719

In Eq. (3.60), the expression $-u_S$ represents the $+u_S$ quantile of the standard normal distribution. The desired mean value µ can be determined by solving the Eq. (3.60).

$$P\left(\overline{X} - u_S \cdot \frac{r}{\sqrt{n}} \le I \le \overline{X} + u_S \cdot \frac{r}{\sqrt{n}}\right) = S = 1 - a \tag{3:61}$$

The statistical security factor S according to Eq. (3.61) describes the percentage which is inside the confidence interval, so that the value $\alpha/2$ describes the value according to Fig. 3.62 that is outside the observed distribution of the symmetric standard normal distribution.

If, for example, various confidence intervals are assumed in percent, then the values u_S can be determined in case of a normal distribution according to Table 3.33, as the integral has the value 1 below the distribution curve according to Fig. 3.69.

The desired confidence level arises from Eq. (3.62) to determine the mean value μ of a normal distribution starting from the estimated value $\overline{X}$ depending on the confidence interval and the size n of the control sample:

$$I = \overline{X} \pm u_S \cdot \frac{r}{\sqrt{n}} \tag{3:62}$$

Example

Due to the example in Sect. 3.5.2.1, the following confidence interval arises under these conditions ($\overline{X} = 2{:}9955\,\mathrm{kV};\ r = 0{:}02653\,\mathrm{kV}$), if a confidence interval of 95 % and a total sample size of n = 10,000 investigations are required.

$$I = 2{:}9955\,\mathrm{kV} \pm 1{:}645 \cdot \frac{0{:}02653}{\sqrt{10{;}000}} = 2{:}9955\,\mathrm{kV} \pm 0{:}0004\,\mathrm{kV}$$

3.6.3 Equicontinuous Distribution

In case of a continuous probability, the distribution function f(t) is defined over an infinite number of points, so that the interval $-\infty < t < +\infty$ may also be available. In practice, different statistical distributions are used, which are selected depending on the equipment behavior.

3.6.3.1 Normal Distribution

The normal probability distribution (Gaussian distribution) is a frequently used distribution for statistical problems. The identifying feature of a normal distribution is that the mean and median values are identical. The density function is therefore symmetric around the mean value and the variance is determined by the standard deviation. The density function f(t) of a normal distribution is generally determined according to Eq. (3.63):

$$f(t) = \frac{1}{r\sqrt{2 \cdot p}} \cdot \exp\left[-\frac{(t-l)^2}{2 \cdot r^2}\right] \text{ for } -\infty \backslash t \backslash +\infty \qquad (3{:}63)$$

where

σ standard deviation
μ mean value

After standardization (Sect. 3.6.2.5), the normal distribution $N(\mu; \sigma^2)$ with $\mu = 0$ and $\sigma^2 = 1$ is transferred into the standard normal distribution $N(0; 1)$, so that the density function becomes:

$$f(t) = \frac{1}{\sqrt{2 \cdot p}} \cdot \exp\left[-\frac{t^2}{2}\right] \qquad (3{:}64)$$

The general Eq. (3.64) describes the Gaussian bell-shaped curve. Herewith, the factor $1{=}\sqrt{2 \cdot p}$ is a constant, so that the area below the density function f(t) gives a value of one.

The typical density function of a normal distribution is shown in Fig. 3.70 as a function of different standard deviations σ, with the maximum at $t = \mu$ and the inflection points $\mu \pm \sigma$. In this example, an average life of the equipment is expected to $\mu = 15$ years with different standard deviations of $\sigma = 1, 2$, and 3 years. In this case, the size of the standard deviation is an indication of the spread around the mean value.

A change of the mean value causes a shift of the distribution in the direction of the x-axis, while another standard deviation causes a flattening of the overall curve.

The distribution function F(x) is generally determined by integration of the density function of the normal distribution, Eq. (3.64):

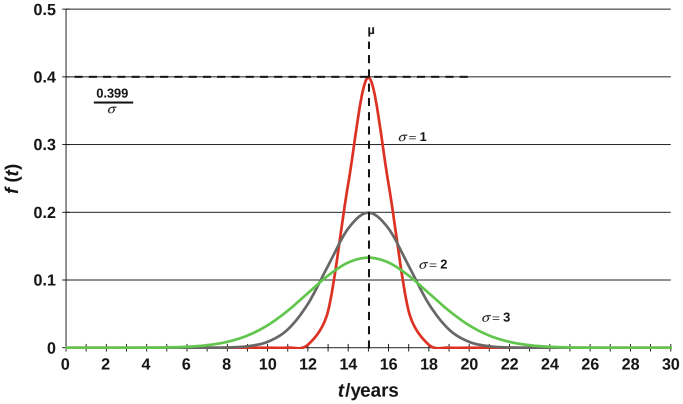


Fig. 3.70 Density function f(t) of the normal distribution

$$F(t) = \frac{1}{r\sqrt{2 \cdot p}} \int_{-\infty}^{\infty} e^{-\frac{(t-l)^2}{2r^2}} dt \qquad (3{:}65)$$

Figure 3.71 shows the distribution function of the failure probability F(t) which is given by integration of f(t) according to Eq. (3.65), corresponding to three different standard deviations.

The most important point of the distribution function is that the failure probability becomes F(t) = 0.5 in case of the mean value μ, this means that, for example, 50 % of all installed components are faulted, which is a consequence of the symmetry of the normal distribution. The probability can be specified as a function of the standard deviation σ that, for example, measurements are within a range around the estimated mean value $\bar{X}$ according to Table 3.34.

This means that about $\Delta F(\pm 1\sigma) = 0.6826$ of all events occur in the range of ±1 σ according to Fig. 3.71. In practice, the range $\pm 3\sigma$ is often used, so that in this case $\Delta F (\pm 3\sigma) = 0.9972$ of the events are included.

The failure rate $\lambda(t)$ is determined by Eq. (3.56) and is shown in Fig. 3.72 for a normal distribution as a function of the standard deviation.

The following relationships result for two characteristic parameters (mean value and variance) to describe a distribution:

$$\text{mean value:} \quad l = \frac{1}{r\sqrt{2 \cdot p}} \int_{-\infty}^{\infty} x \cdot e^{-\frac{(x-l)^2}{2r^2}} dx \qquad (3{:}66)$$

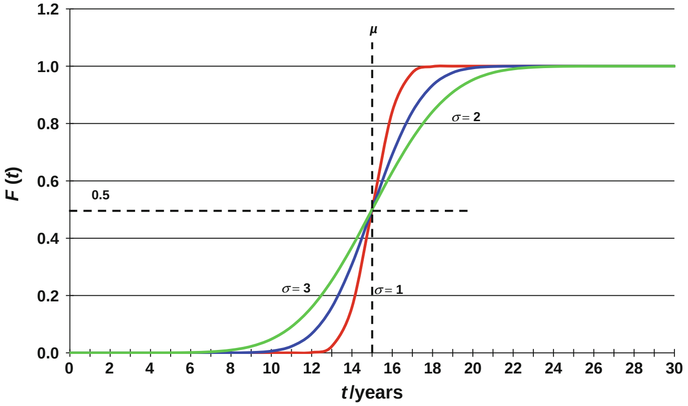


Fig. 3.71 Distribution function F(t) of the normal distribution

Table 3.34 Confidence interval depending on the standard deviation σ

Interval	Range in %
$\pm 1\sigma$	68.26
$\pm 2\sigma$	95.45
$\pm 3\sigma$	99.74
$\pm 4\sigma$	99.99

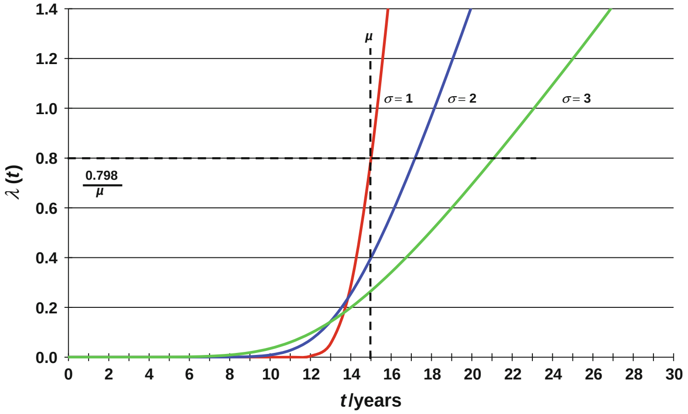


Fig. 3.72 Failure rate λ(t) of the normal distribution

$$\text{variance:} \quad r^2 = \frac{1}{r\sqrt{2 \cdot p}} \int_{-\infty}^{\infty} (x - l)^2 \cdot e^{-\frac{(x-l)^2}{2r^2}} dx \qquad (3:67)$$

Example

In case of 10,000 medium-voltage surge arresters, which belong to a system operator, an expected life of 30 years is expected, with a standard deviation of 6 years. This raises the question, for example, what number of failed surge arresters can be expected in the first 18 years of service life. In addition, the number of surge arresters has to be determined which will fail between the 27 and 36 years of operation.

According to the above-mentioned values, the following can be derived for the normal distribution:

$$\text{Mean value: } l = 30 \text{ years} \quad \text{standard deviation } r = 6 \text{ years}$$

With the help of the density function according to Fig. 3.66, the areas of Q1 and Q2 can be determined by the integral according to Eq. (3.65), resp. a failure probability can be taken of $F(18) = 0.02275$ for the period until 18 years according to Fig. 3.73

$$F(0 - 18) = \frac{1}{r\sqrt{2 \cdot p}} \int_{0}^{18} e^{-\frac{(t-l)^2}{2r^2}} dt \qquad (3:68)$$

The number n_1 of surge arresters, which fail up to the age of 18, Eq. (3.68), is valid:

$$n_1 = F(18) \cdot 10;000 \approx 228$$

Also applies for the period from 27 to 36 years.

$$n_2 = [F(36) \cdot F(27)] \cdot 10;000 \approx 5328$$

In addition, it is possible to determine directly the corresponding values by the distribution function (Fig. 3.74).

3.6.3.2 Exponential Distribution

In case of a reliability calculation regarding the determination of the availability of networks, the exponential distribution is often applied, which can be derived from a constant failure rate λ to describe the failure behavior of the equipment. Taking into account the failure rate, according to Eq. (3.50), the survival probability becomes

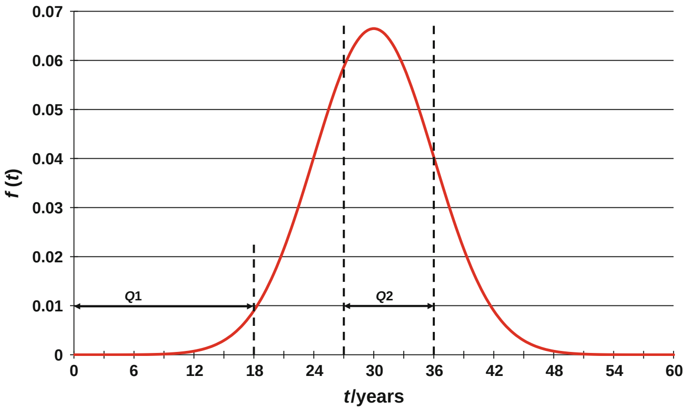


Fig. 3.73 Density function to determine the failure probability of surge arresters

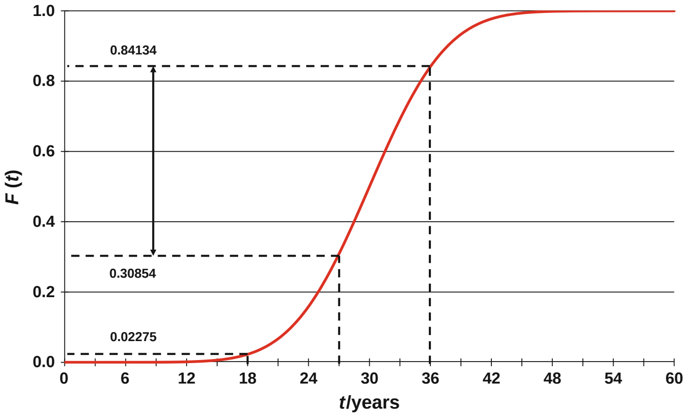


Fig. 3.74 Distribution function to determine the failure probability of surge arresters

$$R(t) = e^{-kt} \tag{3:69}$$

so that the density function results after derivation:

$$f(t) = \begin{cases} = \dfrac{-dR(t)}{dt} = k \cdot e^{-kt} & t \geq 0;\ k\ [\ 0 \\ = 0 & t \backslash 0 \end{cases} \tag{3:70}$$

and for the distribution function according to Eq. (3.48):

$$F(t) = \int_0^t k \cdot e^{-kt} dt = 1 - e^{-kt} \tag{3:71}$$

The failure rate $\lambda(t)$ becomes taking into account Eq. (3.56)

$$k(t) = \frac{f(t)}{1 - F(t)} = k \tag{3:72}$$

This means that the failure rate $\lambda(t)$ is considered to be constant over the entire time range. For this reason, the exponential distribution is only used when the failure rate is available regardless of the age of the equipment as an average value, in contrast to the description of the failure behavior according to Sect. 2.1.5.2.

For the characteristic parameters (mean value and variance), the following relationships are valid:

$$\text{Mean value} \quad l = \frac{1}{k} \tag{3:73}$$

$$\text{variance} \quad r^2 = \frac{1}{k^2} \tag{3:74}$$

Figures 3.75 and 3.76 show the profile of the density function f(t), failure rate $\lambda(t)$, and the distribution function F(t) of an exponential distribution.

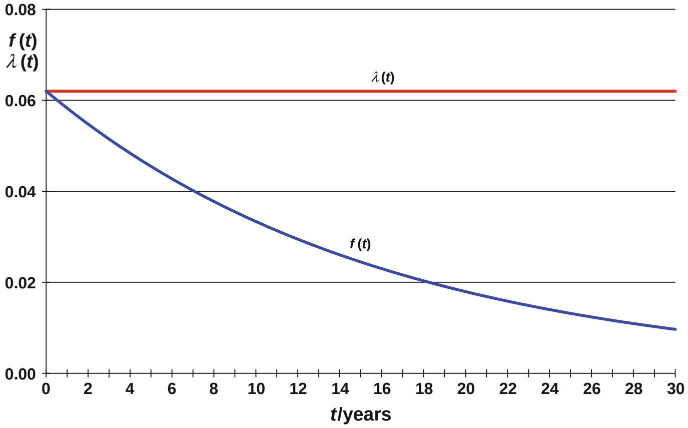


Fig. 3.75 Profile of the density function f(t) and failure rate $\lambda(t)$ of an exponential distribution

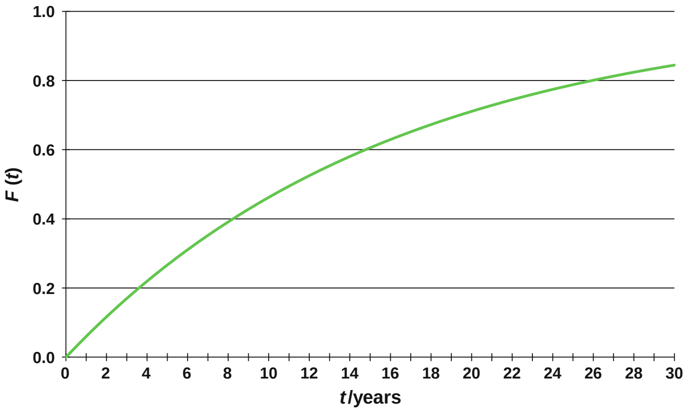


Fig. 3.76 Profile of the distribution function F(t) of an exponential distribution

3.6.3.3 Weibull Distribution

The Weibull distribution has an essential property, which distinguishes it from the other distributions: Different distributions can be simulated by the selection of the parameters. For this reason, the Weibull distribution plays an important role in the statistics. For example, in case of the description of the failure behavior of equipment, when the failure rate in the first time period runs differently than in the second period (Sect. 3.4.5, Fig. 3.56). The density function is modeled according to Eq. (3.75).

$$f(t) = \begin{cases} = \frac{b \cdot t^{b-1}}{a^b} \cdot \exp\left[-\left(\frac{t}{a}\right)^b\right] & t \geq 0 \\ = 0 & t \setminus 0 \end{cases} \tag{3:75}$$

The following relationships result for the other parameters, the distribution function F(t), the survival probability R(t), and failure rate λ(t):

$$F(t) = \int_0^\infty f(t)dt = 1 - \exp\left[-\left(\frac{t}{a}\right)^b\right] \tag{3:76}$$

$$R(t) = \int_t^\infty f(t)dt = \exp\left[-\left(\frac{t}{a}\right)^b\right] \tag{3:77}$$

$$k(t) = \frac{f(t)}{R(t)} = \frac{b \cdot t^{b-1}}{a^{b}} \tag{3:78}$$

The expected value of the Weibull distribution is obtained from the integral Eq. (3.76).

$$E(t) = \int_{0}^{\infty} t \cdot \frac{b \cdot t^{b-1}}{a^{b}} \cdot \exp\left[-\left(\frac{t}{a}\right)^{b}\right] dt = a \cdot C\left(\frac{1}{b} + 1\right) \tag{3:79}$$

With the gamma function,

$$C(c) = \int_{0}^{\infty} t^{c-1} e^{-t} dt \tag{3:80}$$

The standard deviation resp. the variance σ^2 results to

$$r^{2} = a^{2}\left[C\left(1 + \frac{2}{b}\right) - C^{2}\left(\frac{1}{b} + 1\right)\right] \tag{3:81}$$

Due to the different values for β, various distributions, density functions, and failure rates can be modeled as shown in Figs. 3.77, 3.78, and 3.79:

- ß < 1: decreasing failure rate as a feature for failures during start-up or installation, e.g., $\beta = 0.5$, Fig. 3.79
- ß = 1: constant failure rate (exponential distribution); failures occur randomly and show no age dependence, Fig. 3.79

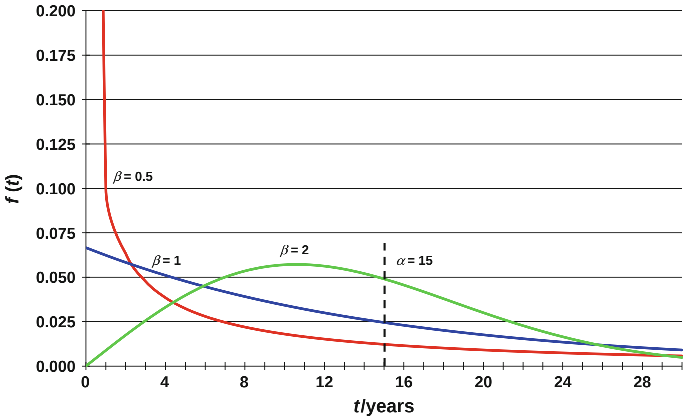


Fig. 3.77 Density function f(t) of the Weibull distribution

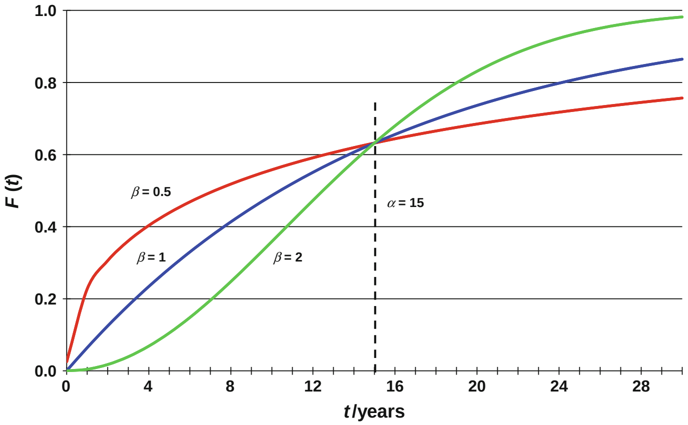


Fig. 3.78 Distribution function F(t) of the outage probability (Weibull distribution)

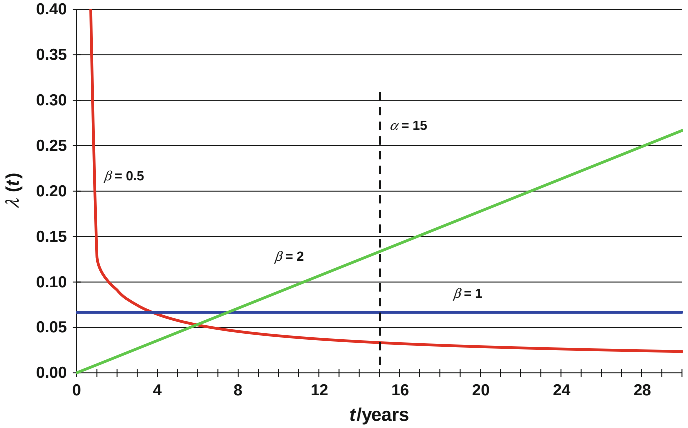


Fig. 3.79 Failure rate $\lambda(t)$ of the Weibull distribution

- ß > 1: increasing failure rate as a feature of age-related failures, such as $\beta = 2$, the failure rate is linearly time dependent, Fig. 3.79.

There are two particular cases, as described above, which can be distinguished on the basis of the value β:

- $\beta = 1$:
  The density function is according to Eq. (3.75):

$$f(t) = \frac{1}{a} \exp\left[-\frac{t}{a}\right] \tag{3:82}$$

The failure rate $\lambda(t)$ becomes

$$k(t) = 1{=}a \tag{3:83}$$

The expression according to Eq. (3.83) represents an exponential distribution, as the failure rate is time-independent and therefore constant with the standard deviation $\sigma = 1/\alpha$, so that in this case ($\beta = 1$), the Weibull distribution is transferred into an exponential distribution. This is also reflected in the comparison of Figs. 3.75 and 3.79.

- $\beta = 2$:
  Here, the density function f(t) follows from Eq. (3.75):

$$f(t) = \frac{2 \cdot t}{a^2} \exp\left[-\frac{t^2}{a^2}\right] \tag{3:84}$$

The failure rate $\lambda(t)$ becomes

$$k(t) = \frac{2 \cdot t}{a^2} \tag{3:85}$$

In this case, the Weibull distribution corresponds to the Rayleigh distribution, Sect. 3.6.3.4. The conditional failure rate $\lambda(t)$ is determined according to Sect. 3.6.2.8 in accordance with Eq. (3.57) to

$$k(t) = \frac{\int_T^{T+t} f(t)dt}{\int_T^{\infty} f(t)dt} = 1 - \exp\left[-\frac{(T+t)^b - T^b}{a^b}\right] \tag{3:86}$$

Similarly, the probability becomes that equipment is in operation during a period:

$$R(t) = 1 - F(t) = 1 - \frac{\int_T^{T+t} f(t)dt}{\int_T^{\infty} f(t)dt} = \frac{\int_{T+1}^{\infty} f(t)dt}{\int_T^{\infty} f(t)dt} \tag{3:87}$$

Example

The failure probability F of 10,000 medium surge arresters has to be determined, a value of α = 15 years is assumed for the Weibull distribution. The parameter ß is 0.5, 1, and 2 (according to Fig. 3.69). The number of arresters has to be determined that fail between the 12th and 18th year of operation. According to Eq. (3.76), it yields:

$$F(18) = 1 - \exp\left[-\left(\frac{18}{15}\right)^{b}\right] \text{ resp: } \quad F(12) = 1 - \exp\left[-\left(\frac{12}{15}\right)^{b}\right]$$

Depending on the parameter ß, the result becomes

$$\begin{array}{lll} b = 0{:}5: & F(18) = 0{:}66656 & F(12) = 0{:}5912 \\ b = 1: & F(18) = 0{:}6988 & F(12) = 0{:}5507 \\ b = 2: & F(18) = 0{:}7631 & F(12) = 0{:}4727 \end{array}$$

The number of failed arresters is determined to n_{out} = F(18 − F(12) · 10,000, thus resulting in the following numbers:

$$\begin{array}{ll} b = 0{:}5: & n_{out} \approx 745 \\ b = 1: & n_{out} \approx 1481 \\ b = 2: & n_{out} \approx 2904 \end{array}$$

If, in contrast to the example above, the probability is determined that an arrester, which has already been in operation for 12 years, is still in service after 18 years, the following Eq. (3.55) applies:

$$k(t) = \frac{\int_{T}^{T+t} f(t)dt}{\int_{T}^{\infty} f(t)dt} = 1 - \exp\left[-\frac{(T+t)^{b} - T^{b}}{a^{b}}\right] = 1 - \exp\left[-\frac{18^{b} - 12^{b}}{15^{b}}\right]$$

The following values are calculated for the failure rate that a considered surge arrester must be replaced in this period depending on the parameter ß:

$$\begin{array}{ll} b = 0{:}5 & k = 0{:}1821 \\ b = 1 & k = 0{:}3297 \\ b = 2 & k = 0{:}5507{:} \end{array}$$

This means that under the assumption of a linear aging, these surge arresters will fail and must be replaced with a probability of 55.07 % in the considered time range between 12 and 18 years, based on the stock after 12 years of operation.

3.6.3.4 Further Distribution Functions

In addition to the above-mentioned distributions, further functions are used in the reliability calculation. In this case, the different density functions are as shown below:

Gamma distribution

$$f(t) = \frac{t^{b-1}}{a^{b} \cdot C(b)} \exp\left(-\left(\frac{t}{a}\right)\right) \tag{3:88}$$

with $\Gamma(\beta)$ according to Eq. (3.80)

Raleigh distribution

$$f(t) = \frac{2 \cdot t}{a^{2}} \exp\left(-\frac{t^{2}}{a^{2}}\right) \tag{3:89}$$

Logarithmic distribution

$$f(t) = \frac{1}{t \cdot r\sqrt{2 \cdot p}} \exp\left(-\frac{(\ln t - l)^{2}}{2 \cdot r^{2}}\right) \tag{3:90}$$

Rectangular distribution or Equal distribution

$$f(t) = \frac{1}{b - a} \quad \text{for } a \leq t \leq b \tag{3:91}$$

3.6.4 Discrete Random Variable

A random variable x is called discrete if the occurrent values represent a finite number. The density function of discrete random variables is described by the following relations:

$$f(t) = \begin{cases} p_{j} & \text{for } t = t_{j} \\ 0 & \text{for all others } t \end{cases} \tag{3:92}$$

3.6.4.1 Poisson Distribution

Using the Poisson distribution, the probable occurrence (x) for rare events will be described for a period, and in this case, the average expected failure rate λ is constant. A discrete random variable x has a Poisson distribution when x can adopt the discrete values 0, 1, …, x with the density function f(x):

$$f(x) = \frac{k^x \cdot e^{-k}}{x!} \quad \text{for } x = 0;\ 1;\ 2;\ldots \tag{3:93}$$

And the distribution function F(t):

$$F(x) = e^{-k} \cdot \sum \frac{k^x}{x!} \tag{3:94}$$

For the characteristic parameters (mean value and variance), the following relationships are valid:

$$\text{Mean value} \quad l = k \tag{3:95}$$

$$\text{variance} \quad r^2 = k \tag{3:96}$$

Therefore Eq. (3.93) can be written when the mean value μ is used:

$$f(x) = \frac{l^x \cdot e^{-l}}{x!} \tag{3:97}$$

Example

In case of HV overhead lines, an average failure rate is assumed of 1 failure per 100 km and year. The probability of 0, 1, 2, etc. failures on the overhead line with a length of 40 km has to be determined for a period of 10 years. Thus, the failure rate λ applies:

$$k = \frac{1\,\text{failure} \cdot 40\,\text{km}}{\text{year} \cdot 100\,\text{km}} = 0{:}4\,\text{failure/year}$$

For a period of 10 years, the expected value becomes E(x) = 0.4 · 10 failures = 4 failures = μ.

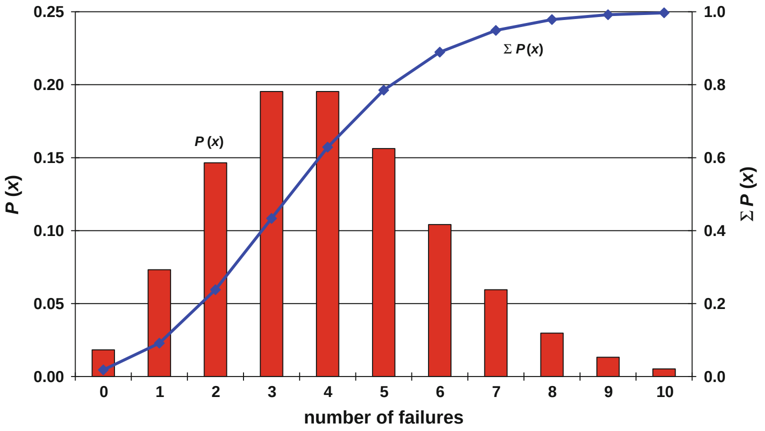


Fig. 3.80 Example of a Poisson distribution

The failure probability f(x) is according to Eq. (3.93).

$$f(x) = \frac{4^x \cdot e^{-4}}{x!} \quad \text{for } x = 0;\ 1;\ 2; \ldots \text{failures}$$

Figure 3.80 shows the density function [f(x)], and the distribution function [$F(x) = \Sigma f(x)$]. The result is that three failures are to be expected with a probability f(3) equal to 19.5 % on the overhead line, while the probability drops to 3 % in case of eight failures.

3.6.4.2 Binominal Distribution

The binomial distribution describes independent results of a series, whereby only two variants are possible, so that in general the binomial distribution can be described by the following expression, where in each case, the options "p = true" and "q = not true" can occur:

$$(p + q)^n \tag{3:98}$$

Here, however, some requirements are necessary:

- There are a prescribed number of experiments, i.e., n is known.
- For each experiment, there are only two possible events that may occur, which means the item is either in service or out of service, so that $p + q = 1$.
- The values q and p are constant.
- All experiments are independent; this means that if an element is faulty, this has no effect on the next.

The binominal expression, Eq. (3.98), can be written as a series expansion:

$$(p+q)^n = p^n + n \cdot p^{n-1} q + \frac{n \cdot (n-1)}{2!} \cdot p^{n-2} q^2 + \cdots + \frac{n \cdot (n-1) \cdots (n-r+1)}{r!} \cdot p^{n-r} q^r + \cdots + q^n \tag{3:99}$$

The density function f(x) becomes, according to Eq. (3.100), in case of the probability that exactly x opportunities occur in n experiments:

$$f(x) = \frac{n!}{x! \cdot (n-x)!} \cdot p^x \cdot q^{n-x} = \binom{n}{x} \cdot p^x \cdot q^{n-x} \tag{3:100}$$

where

p probability that one event occurs
q probability that one event does not occur
x number of events (=0, 1, 2, …)
n number of data resp. measurements

The corresponding distribution function is given by:

$$F(x) = \sum f(x) \tag{3:101}$$

The characteristic parameters (mean value and variance) are calculated according to Eq. (3.102)–(3.103).

$$\text{mean value} \quad l = n \cdot p \tag{3:102}$$

$$\text{variance} \quad r^2 = n \cdot p \cdot (1-p) \tag{3:103}$$

Example

The probability of a faulty surge arrester is p = 0.1. The probability f(x) is to be determined that in case of 30 arresters exactly x arresters are defective.

$$f(x) = \frac{n!}{x! \cdot (n-r)!} \cdot p^r q^{n-r} = \frac{30!}{x! \cdot (n-x)!} \cdot 0{:}1^x \cdot 0{:}9^{30-x}$$

Table 3.35 Example of a binominal distribution

Number of faults x	f(x)	Sum F(x)
0	0.04239	0.04239
1	0.14304	0.18370
2	0.22766	0.41135
3	0.23609	0.64744
4	0.17707	0.82451
5	0.10230	0.92681
6	0.04736	0.97417
7	0.01804	0.99222

Table 3.35 shows the probability f(x) that a predetermined number of arresters are defective if a binomial distribution is assumed. Additionally, the cumulative frequency F(x) is given.

The calculation shows the probability of 23.6 % that three arresters of the entire collective are defective. Furthermore, the probability is less than one percent that more than seven arresters are defective.

3.6.5 Best Fit Calculation

In many areas of asset management, various data are accumulated, must be recorded, and assessed to derive therefrom, for example, an averaged behavior or to extrapolate future developments. The result is that best fit calculations are essential to control optimally the used resources. A best fit calculation is the representation of a relationship such as between a measured variable and the dependent parameters by a continuous function. This function is determined that the sum of the deviation between the measured values and the parameters becomes a minimum.

3.6.5.1 Measurement Errors

Basically, measurement errors occur when taking a test series, which may have different causes, so that several sources of error are possible:

- deviations as a result of a false meter reading,
- systematic errors, the cause may be, for example, an incorrectly calibrated instrument, and
- statistical or random errors, which are a consequence of boundary conditions change, or can depend on other contingencies.

Only the statistical errors are considered in further consideration, so that the connection between two parameters is determined as a result of deviations according to Sect. 3.6.5.2.

3.6.5.2 Regression Function

In practice, it frequently happens that two variables (y, x) have a mutual dependence, for example, the failure rate of equipment depends also on the life, so that a correlation of these variables can be derived. According to Sect. 2.1.5.1, the failure rate of equipment can be modeled as a function of the age by different mathematical function curves. For example, the following regression functions are possible:

$$y = a + b \cdot x \quad (\text{Linear dependency}) \tag{3:104}$$

$$y = a + b \cdot x + c \cdot x^2 \quad (\text{Quadratic dependency}) \tag{3:105}$$

$$y = a + b \cdot e^{c \cdot x} \quad (\text{Exponential function}) \tag{3:106}$$

The Eqs. (3.104)–(3.106) imply that the random variables y are dependent on the average from the values x and thus represent the expected value E(x), with the variance σ^2. The determination of the smoothing function by which a relationship between the variables (x, y) according to Fig. 3.81 (regression curve, Eq. 3.104) can be best prepared, is carried out according to the method of the sum of least squares, so that it generally applies:

$$\min = d_1^2 + d_2^2 + \cdots + d_n^2 \tag{3:107}$$

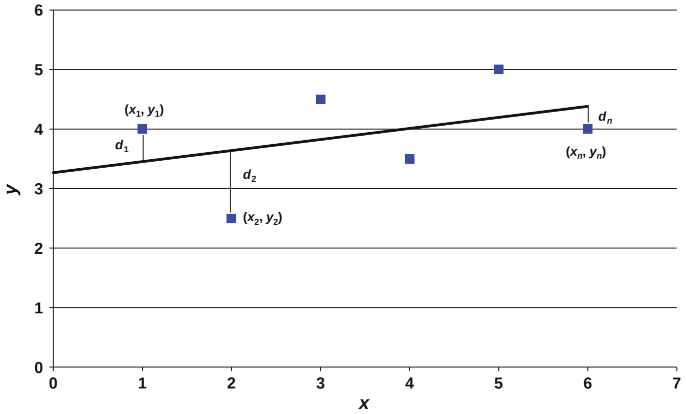


Fig. 3.81 Determination of the smoothing function (regression curve)

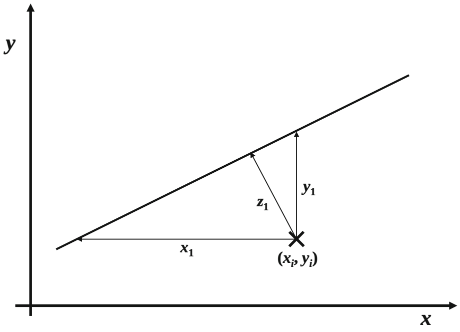


Fig. 3.82 Possibilities of determined least square method

The definition according to Eq. (3.104) and Fig. 3.81 is only valid if y represents the dependent and x the independent variable, this means that the value y may be subjected to an incident and is therefore faulty. In the other case, the horizontal distances between the points (x_i, y_i) and the regression curve are to be minimized. In addition, it is also possible to take the vertical distance between the regression curve and the measurement points as a target (z_i), but this option is rarely used. Moreover, the sum of the distances of a scatter plot to the regression curve can be minimized. In this case, the determined regression curve represents the major axis of the scatter plot. Figure 3.82 shows the different ways in determining a regression curve using the least square method.

For the calculation of the least square method, the measured values y will be determined by the calculated values y according to the Eq. (3.108).

$$\sum_{i=1}^{n} [y_i - (a + b \cdot x_i)]^2 = \min \qquad (3:108)$$

The regression coefficient (a, b) for a regression curve (Eq. 3.104) can be estimated as follows [16, 41], taking into account the average values according to Eq. (3.110):

$$b = \frac{\sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad \text{and} \quad a = \bar{y} - b \cdot \bar{x} \qquad (3:109)$$

with

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad \text{and} \quad \bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \qquad (3:110)$$

The coefficients may also be determined according to the following equations:

$$a = \frac{\sum_{i=1}^{n}(y_i)\cdot\left(\sum_{i=1}^{n}x_i^2\right) - \left(\sum_{i=1}^{n}x_i\right)\cdot\left(\sum_{i=1}^{n}x_i\cdot y_i\right)}{n\cdot\sum_{i=1}^{n}x_i^2 - \left(\sum_{i=1}^{n}x\right)^2} \tag{3:111}$$

$$b = \frac{n\cdot\sum_{i=1}^{n}(y_i\cdot x_i) - \left(\sum_{i=1}^{n}x_i\right)\cdot\left(\sum_{i=1}^{n}y_i\right)}{n\cdot\sum_{i=1}^{n}x_i^2 - \left(\sum_{i=1}^{n}x_i\right)^2} \tag{3:112}$$

The regression curve can be derived by the relationship between the values of x and y as shown using the determined coefficients a and b. In general, the correlation coefficient r is used to assess the accuracy that a fitted curve reproduces the data set. It is calculated according to Eq. (3.113):

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})\cdot(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\cdot\sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{3:113}$$

Values $r = 1$ mean that all data points are mapped exactly by the regression curve (all values are on the line), while in case of at $r = 0$, there is no relationship between x_i and y_i. As previously described, two different regression curves can be derived to determine a dependency due to which value is dependent or independent (Eq. 3.114).

$$y = a + b\cdot x \quad \text{and} \quad x = c + d\cdot y \tag{3:114}$$

In these cases, the correlation coefficient according to Eq. (3.113) can be derived by the relationship:

$$r = \sqrt{b\cdot d} \tag{3:115}$$

In addition to the presentation in accordance with the Eqs. (3.104)–(3.106), it is also possible that a dependent variable z may dependent on two independent variables x and y, so that the following relationship is valid:

$$z = a + b\cdot x + c\cdot y \tag{3:116}$$

In this case, the coefficients of the following equations can be determined by Eq. (3.116) that all values are added and multiplied according to:

$$\sum_{i=1}^{n} z_i = n\cdot a + b\cdot\sum_{i=1}^{n} x_i + c\cdot\sum_{i=1}^{n} y_i \tag{3:117}$$

$$\sum_{i=1}^{n} x_i \cdot z_i = a \cdot \sum_{i=1}^{n} x_i + b \cdot \sum_{i=1}^{n} x_i^2 + c \cdot \sum_{i=1}^{n} x_i \cdot y_i \tag{3:118}$$

$$\sum_{i=1}^{n} y_i \cdot z_i = a \cdot \sum_{i=1}^{n} y_i + b \cdot \sum_{i=1}^{n} x_i \cdot y_i + c \cdot \sum_{i=1}^{n} y^2 \tag{3:119}$$

Example

Figure 3.83 shows an example of the condition assessment of high-voltage circuit-breakers, depending on the equipment age, and in total, three different basic designs are considered (SF$_6$, minimum oil and air blast), Sect. 3.4.4.1, Fig. 3.46. The calculations of the linear regression curve for all types lead to the following relations, including the correlation coefficient r:

SF$_6$: $y = 1{:}9095 \cdot x - 8{:}7859$ $r = 0{:}8247$

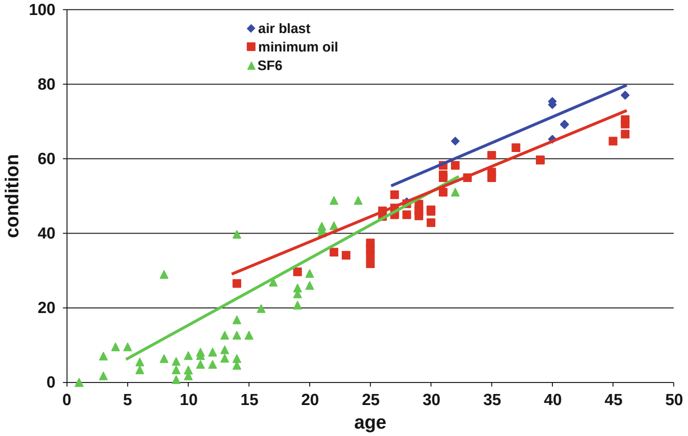


Fig. 3.83 Regression curves for different types of equipment

Table 3.36 Characteristic values of regression polynomial, Fig. 3.83

Regression curve	Correlation coefficient r	Σ squared distance q
$y = f(x)$	0.9555	4702.06
$y = f(x^2)$	0.9560	4648.51
$y = f(x^3)$	0.9638	4110.74

minimum oil: $y = 1{:}4333 \cdot x + 5{:}1810 \quad r = 0{:}9316$
air blast: $y = 0{:}4711 \cdot x + 10{:}3180 \quad r = 0{:}9017$
with: y condition
x age of equipment

The individual correlation coefficient r illustrates that the relationship between the condition and age is very pronounced in case of the minimum oil circuit-breakers, contrary to the illustration of SF_6 circuit-breakers. The respective regression curves are included additionally in Fig. 3.83.

While according to Fig. 3.83, only straight lines are calculated as regression curves, it is fundamentally necessary to consider whether other features may provide a better approximation between the values x and y. Table 3.36 shows the correlation coefficient r for each entire collective equipment and the sum of the squared distance q for the considered curves.

Table 3.36 shows that for the simulation of the entire collective equipment, a third-order polynomial is the best approach, which has a correlation coefficient r close to the value 1.0 and shows the smallest sum of the squared distance.

3.7 Conclusion

The control functions allow the asset manager to perform his manifold tasks. These features generally include economic considerations, such as the present value calculation to compare the costs of different investment opportunities with each other, as well as the determination of the LCC. Here, the LCC include all expenses incurred during the life of the equipment, ranging from the project costs over the operating costs to disposal.

A condition assessment and the evaluation of the measurement results are essential for an assessment of assets; here, various diagnostic and monitoring procedures are to be used depending on the type of equipment. The fault data of equipment or network nodes are the prerequisite to change to a risk-based maintenance strategy. In this context, the identification of risk is in the foreground, independently thereof, whether this risk is acceptable or appropriate measures are necessary to reduce a risk in each case. While in the past, reliability figures were used determining the risk, which describe the expected value, e.g., of an outage, it is useful to determine the “value-at-risk” (VaR), which is known from the financial world. In this case, it is considered that both the outage of the assets and the outage costs are randomly distributed. The result represents the probability that an outage value is exceeded within one year. Special indicators have to be defined by the company to support a final decision that should be fixed by consultation with the involved groups of the supply process. Here, the indicators can be assigned to different areas, such as finance/economics, reliability, customers, employees/safety, network availability, and the environment.

In recent years, “asset simulations” are increasingly used with respect to a long-term view of the operating equipment. In this context, key figures of the investment portfolio and out of this, the derived variables (cost of maintenance and replacement or economic indicators, such as cash flow) are determined over a period of, e.g., 40 years. With this approach, it is generally possible to identify investment peaks in advance to take appropriate measures so that an optimal use of resources is possible with respect to personnel and finance.

It is possible to perform an optimization of the maintenance or renewal of several groups of equipment with the aid of the scientific area “operations research.” Here, suitable methods are used, such as the knapsack problem or the Pareto optimum is determined by means of game theory, and different criteria are considered as players. The advantage of the use of game theory is that the possible combinations can be suitably reduced so that a computational treatment of the optimization problem is possible.

Finally, the key figures and the statistical distributions are presented, which are essential for the installation of a database to assess the malfunctioning of equipment in a suitable manner.

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Integration into the Business Organization

4

With the liberalization of energy markets, power companies in particular were confronted with different forms of organization. The original integrated handling of all fields of sales, trading, generation, and infrastructure system was no longer possible for larger companies due to the new framework, as the "unbundling act" prevented this previous integration. As part of the necessary corporate reorganization, the internal processes have been generally studied in order to achieve a higher efficiency as the utilities are suddenly exposed to competition in the liberalized world. Competition has also been established between different companies in the remaining monopoly of network operators because of the introduction of efficiency benchmarks of the regulator.

This constraint was the motivation to think about the core business and the working depth in many utilities. In this situation, the implementation of an asset management function has been a necessary step regarding the accountability and transparency in the grid area. Moreover, with the introduction of this function and the discussion about the intensity of labor, there are various models and ways of organization that are explicitly described in the following. The essential functions are divided into three parts (see Sect. 1.5) and covered by the roles of the

- Asset owner,
- Asset manager,
- Service provider.

In the course of this discussion, the question as to whether an activity is—according to the asset owner function—not part of the core business arises. If that is the case, it must not be provided within the company, but can be provided cheaper and without increased risk by service providers on the market. For this reason, among others, this chapter also deals with the circumstances related to the transfer of work to third parties (Sect. 4.3).

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But also the political landscape has changed by the regulation and the European legislation (the so-called internal market packages and local political constraints), which certainly has an impact on strategies and on the network operating of infrastructure systems. The established subject of concession contracts for the infrastructure in Germany—with which the local authorities grant the network operators the use of public roads and land—alone is a major challenge for the stable and above all cost-effective operation of this infrastructure. This topic will also be examined more closely in the following. The role of the technical asset management has taken a high priority for strategy and development costs as well as the sustainable, stable, and secure network operation since the mid-1990s.

4.1 Functional Allocation in the Area of Asset Management

The essential tasks around the entire asset management, as already described in Sect. 1.5, are summarized as follows. Once again, it has to be pointed out that the term "asset management" describes the entire process of providing the infrastructure systems. Whereas the "asset manager" is exclusively responsible for the tasks described below. The tasks lead to roles that are established as internal or external functional units in an organization:

- Asset owner: He assumes the principal role to the asset manager, approves the overall operating and investment programs, and is responsible for long-term maintenance of value of networks and facilities. This specifically includes the planning of the strategic objectives of the activities (e.g., network development, preservation of substance, specifying the supply reliability, temporal development of the total budget). It is essential that the asset owner is responsible for both the refinancing of costs and the discussion with regulators and higher approval authorities.
- Asset manager: He controls—in the function of a customer—the technical services that have to be conducted for the operation and maintenance of networks or assets. In detail, the following essential tasks are included:
  - development of strategies (network planning, construction, optimization, maintenance),
  - specification of standards (equipment, technology, documentation),
  - instruction of system operation and service (business agreements with service providers).

Basically, the task of the asset manager is to split the more global technical and financial requirements of the asset owner into the different technical levels and implement measures and projects by commissioning appropriate services.

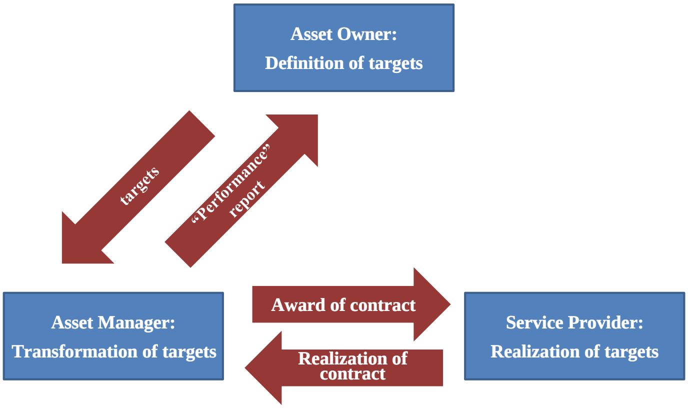


Fig. 4.1 Task allocation in asset management process [4]

- Service provider: He is responsible for the execution of services regarding the construction and operation of the infrastructure system on behalf of the asset manager. These include, for example, the following activities:
  - commissioning or decommissioning of equipment,
  - monitoring of ongoing operations and ensuring the operational safety (hazard control),
  - diagnosis and testing,
  - responding to failure,
  - inspection and maintenance for condition assessment,
  - status of the equipment,
  - design and construction of infrastructure facilities,
  - provision of basic services (e.g., documentation, comments),
  - strategy regarding network activities.

The advantage of this clear assignment is that different tasks are clearly separated, with defined interfaces concerning responsibilities and decisions [5]. Figure 4.1 shows the simplified and superior relationships between the groups involved in the process.

Based on these fundamental distinctive functions, a role model can be defined for every organization which reflects different forms of organization and processing depths of utilities. These models will be discussed in the following chapters.

4.2 The Role Model of the Management of Infrastructures

With the described allocation of tasks (Sects. 1.4 and 4.1) as a basic understanding, various options for the organizational structure of the company can be represented depending on the intensity of labor within a company [1, 2, 5].

Regardless of the methods of the corporate organization described in the following chapter, there are defined rules and “unwritten” objectives within the role model that correspond to the nature of the roles. The overall objective of a company, especially in the infrastructure sector, is to maintain a stable business base, i.e., a reliable infrastructure system, a law- and standard-compliant operation, and finally an adequate profit due to the requirements of the capital market. Therefore, the prior objective of the asset owner’s role is the refinancing of the assets and an appropriate return on investment. This goal is to be controlled by the pricing policy, but is usually limited by the approval of the price by regulators. Further options are efficiency gains and cost reductions, but in order to ensure that the second objective of a stable business base is not at risk, they need a solid foundation.

The role of the service provider aims primarily on the activity of the staff and—if this business is located outside the company—on achieving a reasonable profit from its activities. The service provider also has the potential for optimization to reduce operating risk and expand the infrastructure system from the operational point of view in an “easy way”, which in the rule means generous redundancy of assets, control options, and spare parts. He should always make use of the latest and maintenance-friendly technology to reduce his activities and possibly to maximize the profit.

Between these two roles, the asset manager is asked to identify and to specify the most economical concepts and to define stable and workable standards over the life of the considered assets. Thus, the asset manager may be superficially in an uncomfortable position, as he has to deal with arguments of both the asset owners as well as the service provider in order to neutralize their conflicting objectives. He can only maintain his position if he has appropriate skills and control possibilities.

Compared to the service provider, the asset manager must have the authority to issue guidelines and he must be able to implement them in a professional manner. He also must have clear structures of commissioning and competences in project management and maintenance strategies, including the necessary budget responsibility, i.e., he must control the money provided by the asset owners. In this function, it may be possible that requests and suggestions from the service provider will not be implemented because the asset manager is not able to represent either the technical need or the economic needs for the requested measures. However, the risks or difficulties arising from non-compliance with these suggestions may still be consistent with the overall strategy. The identification of these dependencies can only be carried out on the basis of the asset manager’s own expertise, including a more strategic point of view which is supplemented by the use of data, metrics, and temporal experience in the assessed segment.

Basically, technical asset management is a matter of risk management as there must be a balance between financial expenditures and the possible risk reduction. This objective is achieved if a risk level, accepted by the asset owner, will be met with minimal funds at all points of the system.

Compared to the asset owners, the asset manager must represent the minimum necessary costs (OPEX and CAPEX) in the right proportion, as he is confronted at this interface with the profit maximization demands of the asset owners. Therefore, the task is to provide a

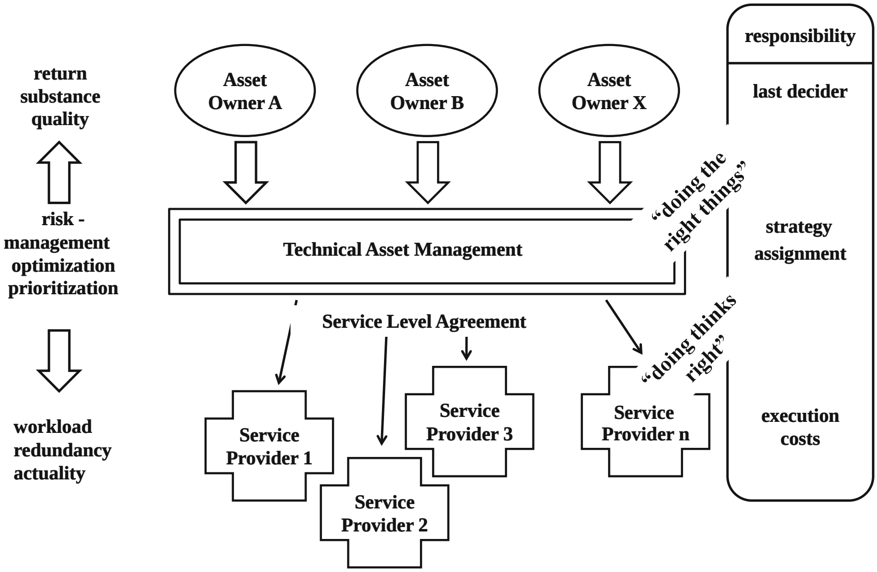


Fig. 4.2 Role model and interaction of asset owners, managers, and service providers

high level of transparency on the impact of measures or total financial constraints of the asset owners to indicate the long-term consequences in line with risk management. The asset owner is responsible for the final decision, so he must be set in a position by the asset manager to meet his strategies and objectives based on knowledge of the consequent development, such as medium-term asset erosion, high future outage costs, reduction of the power supply. To fulfill this task, the asset manager has access to data and figures, which he receives by special software systems (see Chap. 5). These systems are used for risk management, simulation of the future as well as action prioritization and utilize recognized procedures, so that traceable and reproducible results with respect to the effect of the actions are provided. If, in extreme cases, the requirements of the asset owners regarding safety measures cannot be implemented, the asset manager will not assume responsibility. In Fig. 4.2, the role model and the position of the asset manager are illustrated.

Considering this role model, the question arises as to whether tasks of a company belong to the center of interest with respect to the business case and which activities may be outsourced to a competitive market on more favorable conditions (compared to internal costs). Latter would influence the corporate structure, so the consequences of such contemplation lead in total to four different possible models that differ with respect to the intensity of labor.

In case of this perspective, the role of the service provider (as the area that is most likely to be outsourced) can be divided into the classical working department (pure assembler and construction activities) and the so-called network manager who occupies a higher level in the management experience and operational responsibility. The four models are as follows:

- Service provider model (Sect. 4.3.2)
- Network manager model (Sect. 4.3.3)
- Asset manager model (Sect. 4.3.4)
- Asset owner model (Sect. 4.3.5)

Basically, two different ways exist to reduce the infrastructure costs, namely

- for existing structures, the costs of investment and maintenance are be optimized, so that the resources achieve the highest efficiency with respect to a constant reliability or
- to buy sub-tasks from third parties that can provide these services cheaper as a result of other cost structures, business organizations, or economies of scale.

In any case, the conclusion is that various activities may not be defined as core functions in their own organizations and therefore being bought from third parties on the open market. This means that different activities are passed to subcontractors, taking into account the client's requirements of selection and inspection. This process should lead to a reduction of costs, but may be expected to increase risks. For a final decision, a balance between a potential risk (which may result from the outsourcing of activities) and the simplification of internal processes and thus a reduction of the costs must be provided.

It should also be noted that the selection and allocation process, the controlling of tasks, and quality control are associated with costs. Hence, it is opposed to the pure cost reduction, a fact that is to be included in the economic analysis. Another aspect is the situation of the infrastructure company in the regulatory environment. If the infrastructure system belongs to a regulated monopoly, such as the electricity and gas networks, the service costs of a third party are to be considered with regard to acceptance by the regulator. Often, third-party charges are greatly used as possible reductions by regulators in case of the approval of the system surcharge, so that a possible economic advantage from outsourcing is excluded.

The basic approach in case of the evaluation, which services can be passed on to third parties, is shown in Sect. 4.3. Surveys of utilities have found that the following reasons were crucial in awarding services to third parties, according to their importance order [2]:

- achieving a cost advantage,
- focus on the priorities of a company ("core business"),
- achievement of competitive advantage,
- use of know-how, which is not currently available within the company,
- improvement of service quality,
- increase of revenue,
- achieving of changing requirements,
- increase "shareholder value",
- increase performance,
- achieving internal flexibility due to the changed tasks.

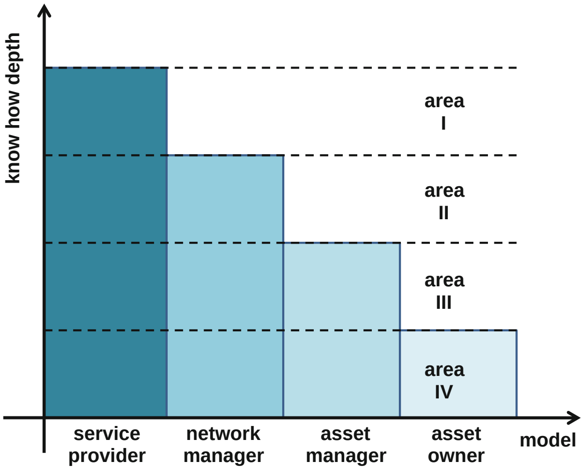
The different intensity regarding the tasks can easily be deduced from Fig. 4.3. Depending on the different models, the intensity of the tasks is reduced starting from the model of the service provider to the asset owner.

According to [3], the following tasks can be assigned to different areas I to IV, according to Fig. 4.2:

- Area I: Service activities; maintenance that does not require extensive specialist knowledge or operational experience and easy-to-reproduce expertise (e.g., mowing the lawn in a substation, painting of overhead line towers, meter reading);
- Area II: Operational processing of network operations and projects; require the operational experience and knowledge of the interrelationships of activities within an infrastructure company. This includes company specialized skills with appropriate training duration;
- Area III: Derivation and implementation of maintenance strategy and maintenance planning; commissioning of basic services, project management, provision of resources, standardization (benchmarks, processes, technology); infrastructure development and network planning; operational business organization of budgets, variant considerations with cost calculations, etc.; high level of specialist expertise for the evaluation of services from customer point of view and for the permanent improvement of the policies and conditions within the system;
- Area IV: Contract management, commitment of long-term development, control, consideration of the impact of regulatory models, refinancing by system surcharges, observation of total costs of the infrastructure business.

A key task is to measure the generated service ("performance") to ensure the quality of services, taking into account a defined reliability, regardless of whether it is outsourced to a third party or not. Therefore, it is necessary to define relevant indicators, which should

Fig. 4.3 Know-how depending on the business models [3]



be fixed by an agreement [service level agreement (SLA)], as is shown in Table 3.20, Sect. 3.3.3.

Basically, it can also be the philosophy of a company to perform all essential activities themselves, because a high quality at all levels is solely ensured in this way. In these cases, the service provider or the network manager model is applied.

4.3 Corporate Organization

As a consequence of different functions within a utility, a company organization can be derived depending on the intensity of labor, employee competences, and resources which are already available in the company. The focus of the business organization is mainly on responsibilities in the operation of infrastructures. Each organization must have distinct interfaces between internal processes and internal and external service providers, to ensure operation of the infrastructure system which is permitted by law, starting from inspection of facilities up to, for example, operational safety and environment protection. This includes an extensive and detailed documentation of organizational charts, of procedures related to process descriptions, work instructions, service contracts, SLA, etc. It is helpful and advisable for a company that the organization is certified by external advisory companies to provide an independent confirmation of the productive and standard-compliant organization or to get hints for the improvement and continuous development of the corporate organization. There are various options for certification, such as the so-called TSM Certification which was developed specifically for infrastructure companies from the respective associations (DVGW, FNN) and monitors the technical security management (TSM). In addition, the certification of integrated environmental management organization—in accordance with DIN 14001 and the widespread quality management certification according to DIN/ISO 9001—is mentioned here.

Many other partial verifications starting from work security up to IT security are possible and can be usefully executed, depending on the company organization. The presentation of this, partly formal confirmation of the business organization, is not part of the further description.

4.3.1 Decision Criteria

In the following, the services that can be outsourced to third parties will be presented. Here, it is necessary to perform an effectiveness/risk assessment as various activities and services of a company can be assigned to different classes [2]. These are as follows:

- Distinctive competence (1): In case of asset managers, this includes developing and commissioning of strategies or the development and enforcement of standards, whereas the knowledge of the network regarding the maintenance of assets belongs to the network manager.

- Essential competence (2): This skill is essential for the organization of the company, e.g., the ability to start the plant after an outage, to perform switching operations and security-related activities, but also involves the securing of actions by budget allocation and material supply.
- Spillover competence (3): In addition, it is possible to offer own services on the free market to come to a better utilization of resources. Leasing of assets, that will be otherwise not used, or not needed expertise, which is available in conjunction with the normal activity, are to be mentioned here. These activities can be marketed as a service, so that additional external revenue is obtained here.
- Protective competence (4): This competence is similar to (2), but also connected with activities that are associated with a high risk if their implementation is not guaranteed. As an example, the understanding of the power protection of an electrical utility can be considered.
- Parasitic competence (5): This is a competence that stresses the organizational resources in principle without being essential to the core activity or contributive to corporate success. In general, this is true for simple activities, such as the painting of overhead line towers.

To evaluate, which of the above skills can be outsourced, the assignment in a diagram is useful according to Fig. 4.4. A distinction will be made between the effectiveness of keeping a competence within the company and the risk of acquiring it from a third party. Once this evaluation has been made, a statement as to whether an activity can be outsourced or not is possible.

Based on the different quadrants A to D, a classification can be defined. In this context, "effectiveness" is understood as the result of the performance which can be achieved for the own company:

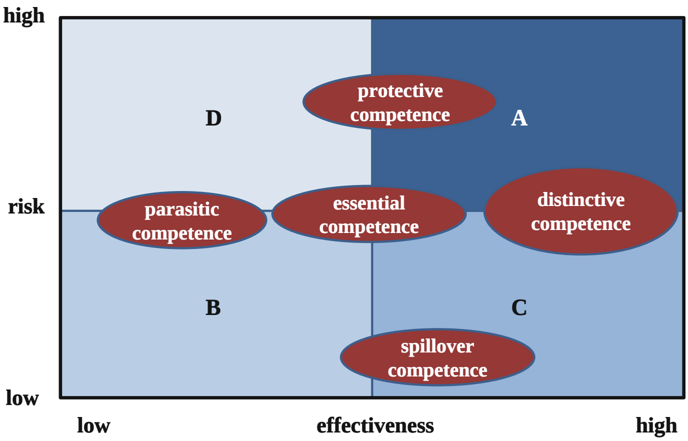


Fig. 4.4 Effectiveness/risk model for the assessment of services [2]

- A: As the efficiency is very high, this activity should remain within the company. This assumes that this effectiveness can also be preserved in the future. The risk should be controlled in this case.
- B: In this case, the effectiveness and the risk are low so that these activities should be outsourced.
- C: It is assumed that the effectiveness is high and the risk is low. According to these conditions, a shift is useful if the efficiency can be again improved by a third party.
- D: Under these boundary conditions, the asset manager has the task to increase the effectiveness significantly or to reduce the risk considerably. The shift to an outside company is particularly appropriate if the risk is reduced and the efficiency of service by other companies is higher.

Besides the assessment of the operational risk and the quality and effectiveness of the services, costs have to be considered as well, so that a decision can be derived depending on the economic assessment which activities can be outsourced. In particular cases, it should be noted that under certain circumstances, service contracts with outside companies should be run over a longer time range, so that a special diligence in the selection is required.

On the basis of this risk/effectiveness model, a nomination and assignment of all relevant processes and activities has to be developed and positioned within the model. This leads to different positions within the diagram (Fig. 4.4) depending on the business model. E.g., in the service provider model, the execution of a service is an essential competence so be located more in the A sector. However, in case of the asset owner model, a classification of this competence as parasitic (sector B) makes sense. The result is a sequence of necessary steps within the company organization.:

- selection of the model to be aimed at
- listing of required activities and processes for the infrastructure system,
- evaluating and positioning of the activities in the effectiveness/risk matrix,
- decision regarding internal and external activities.

As a basis for the first step, a decision regarding the length of the value-added chain is required. There are many boundary parameters to be observed, from the consideration of synergies with other business units up to the company philosophies. This is the reason that there is no universal recommendation or a guideline for the selection of one of the four models described below. This decision must be made on the basis of the existing boundary parameters and the individual company.

4.3.2 Service Provider Model

In this model, all activities are carried out by the company itself, if the appropriate resources are available. Only activities that do not count to the core business even with the largest definition of the value-added chain will be outsourced. This will only happen if the balance between the benefits and the financial expenses is favorable to an outsourcing. Otherwise, more resources are developed and the activities are implemented internally. On the upside, this model leads to a large portfolio of resources and a lot of know-how within the company. On the downside, there will be high inflexibility of personnel management and workload and thus correspondingly high costs, especially when the volume of activities is decreasing. The risk is minimized, however, that an activity cannot be executed due to lack of competence and capacity, as a relationship to third parties or to the service market does not exist. Such an organization provides special advantages, if the service capacities are very limited on the market (seller's market → high costs), and e.g., due to full employment, an increase of the capacity is not possible.

The intensity of labor of this model corresponds to the processing in a "traditional" utility (range I to IV according to Fig. 4.3) with coverage of the entire value chain of an infrastructure company.

4.3.3 Network Manager Model

In this model, the critical work processes stay inside and the company will be responsible both for the implementation of investment projects and for operations with associated responsibilities (facility responsibilities, emergency services, network management, etc.). Service activities will only be outsourced for two reasons: Firstly, if this leads to a better result due to external specialists with extraordinary knowledge and because the implementation of this knowledge within the company does not make sense. Secondly, if operational services can be provided by free service providers, which do not require in-house expertise or deeper knowledge of the infrastructure system. The concentration of the internal service supply depends on the management skills of the processes in planning and operation.

Therefore, it is ensured that planning, engineering, and operational know-how remain within the company, whereupon the cost benefits of a service market are used for simple and exchangeable activities. The network manager model is a first level of optimization with respect to workload and staffing levels, while minimizing potential risks in construction and operation. However, support tasks such as internal services and non-technical activities are particularly outsourced (region II to IV according to Fig. 4.3).

4.3.4 Asset Manager Model

All activities related to the technical asset management tasks remain within the company, such as developing strategies, project planning, identification of projects and activities, setting of technical standards. In contrast, already operational activities and maintenance activities are outsourced. The information concerning activities in the system and the feedback regarding the condition of the assets depend exclusively on the contract by so-called SLA and the reporting described therein. Compared to the network manager model, this characteristic is to be handled more stringent with respect to the configuration of the interface between asset managers and service providers, as this is a relationship between two companies. Thus, the control is indeed no longer given to the service provider within the company which inherently leads to an increase of risks. Otherwise, there is the possibility of using multiple suppliers for critical volume of work, thus to be able to control the risk of a project cluster with insufficient capacity easier. The responsibility is clearly defined by clear contractual external commission on the warranty.

The asset manager carries all risks of the operating failure, the investment, and financial expenses (region III–IV according to Fig. 4.3). He is also responsible for the acquisition of sufficient staff resources on the market to ensure the safe operation. This is possible and economically feasible only in an appropriately developed services market. For this reason, there is the choice of such an organization in a strong buyer's market.

4.3.5 Asset Owner Model

In this model, most of the tasks will be outsourced, whereas the described asset owner's functions remain within the company. The company owns the assets (economic ownership), and it controls the system based on superior quality and financial data and is therefore responsible for the financing. The asset owner is thus the buyer for external service providers to which the commissioning of the activities of the technical asset management comes first. In this role, the asset owner has the ultimate decision-making responsibility as in other models. Due to the external allocation, he also has the duty of selection and thus the responsibility for the traceable qualification of the asset manager. The subsequent use of service providers is no longer carried out by the asset owners, but in the prescribed order by the assigned asset manager. This model is especially referred to geographically dispersed assets resp. more non-continuous divisions, so that a selection of different asset managers comes into question for the commissioning. Also, a newly established infrastructure company can choose this option reasonable, since the development of a qualified asset manager, who is responsible for all further steps, is not applied and the experience on the service market can be used.

The consequence of this model is that the company's operational risk is organized by contractual arrangements and the legal liability must already be ensured in the selection of the service provider with the appointment of the asset manager, which requires a high level of carefulness in the selection and assignment (region IV, as shown in Fig. 4.2).

4.4 Influence of the Infrastructure Systems on the Organization

The organization of investment management and the specification of the described role model require a non-negligible amount of highly qualified personnel and systems. The infrastructure system itself, which has to be managed, has a corresponding impact on scope and type of the organization. This approach ranges from very small systems, in which the establishment of a strong organization is not economical and thus makes no sense, up to a system with geographically dispersed non-contiguous assets that require a more complex form of strategy development and implementation. In this case, the ownership and the influences of external "stakeholders" to the system infrastructure are a non-negligible value.

4.4.1 Economies of Scale of Systems

One of the main factors for the establishment of an asset management organization is the total size of the system itself. This encompasses the geographic characteristic as well as the quantity frameworks of the assets in the system. In this context, the merging of several similar infrastructure systems, e.g., with different asset owners—which have concluded the management task to the same asset management organization—is to be understood. (see also Fig. 4.2). So there are three main cases:

- very small single system (case 1),
- medium to large coherent system (case 2)
- large, but a distributed system with multiple asset owners (case 3).

In this view, four factors need to be discussed:

- existence and provision of expert knowledge,
- development and implementation of support systems,
- the development of strategies including the coordination with the asset owners, and
- ensuring the operational management with one or more service providers.

Under the consideration that an economic efficiency of resources with high basic costs and low scalable marginal costs is given only if the quantity structure or the number of an object reaches a critical value, three cases, which are described above, can be characterized with respect to the four factors.

4.4.1.1 Expert Knowledge

As different systems and procedures (that need to be considered regarding the provider as well as in terms of legal and normative conformity) exist in an infrastructure system, an expert knowledge is required in all relevant areas for asset management.

In case 1, an economic efficiency with the help of own experts cannot be reached, case 2 will develop its own resources above a certain level, and case 3 is predestined for the creation of central own expertise. Every increase in the system's complexity above a certain threshold will raise the efficiency in cases 2 and 3 as principally the existing expertise applies to any quantity structure and is independent of the structure and connections of an infrastructure system.

4.4.1.2 Support Systems

Systems for control, documentation, and strategies are usually associated with high development and operating costs and therefore require a critical size. Growth of assets leads to partially volatile expansion costs (storage, performance, etc.), but these costs are not comparable to the costs of a new implementation. Such support systems are also possible for the first case, but here, very simple and possibly intrinsically programmed solutions which are based on standard software should be applied. These solutions are often individual-related and affected by adaptation needs due to release changes of the standard software. This leads to specific high costs and low continuity.

Case 2 is ideal for the development of such a system landscape, as a connected asset with economic size and thus low specific system cost can be introduced.

Case 3 includes the feature that different asset owners should have access to "their" relevant data of the system landscape, but not to all data, especially not to data of other asset owners. For this reason, a system must always be multi-client-enabled in order to harmonize the use requirements of different users. Case 3 includes the chance of a very high efficiency, but also the requirement of avoiding strong individual solution requirements. In addition, an acceptable settlement model of system costs is required for the various asset owners.

4.4.1.3 Development of Strategy

On the one hand, main strategies in asset management are based on the asset characteristics (circuit-breakers, steel pipes, telecommunications converter, etc.). On the other hand, they also depend on the quantity structure (target network planning, different technologies, statistical key figures). This still needs to be distinguished into a basic strategy, development, and application of regulations, as well as a development strategy with the definition of procedures and processes for defined business transactions. A development strategy in case 1 will not be fundamental, but tailored to the specific assets of the small system due to the special situation. The basic strategy is related to open access regulations of, e.g., associations and organizations. The loss of any savings due to a particular interpretation of the regulations will be accepted due to economic reasons.

Cases 2 and 3, however, are developing their own basic strategy to make use of the individual advantages of interpretation of standards and regulations in their organization. Here, in case 3, the coordination with several asset owners is required, which in certain cases will affect the scope of the regulations and also, for example, the use of technology. Therefore, in this case, it has always to be checked whether the increase in size accompanied by new asset owners will lead to an ineffectual swelling of the rules (instead of positive economies of scale) and therefore makes the whole system less efficient.

4.4.1.4 Commissioning of the Operational Management

The asset manager is also responsible for securing the resources for the construction and operation of the infrastructure system. He uses either internal or external service providers which should be ordered and controlled by a uniform processes. Case 1 is problematic because usually, individuals take over the role of the service provider as well as the one of the asset manager with all its responsibilities. Hence, in case of outage (illness, resignation, retirement) of these people, a high operating risk occurs in these infrastructure systems.

In case 2, the securing of resources is easily possible, usually a responsible service provider organization may be available for each individual division, which provides the appropriate capacity and the performance guarantees.

Case 3 is to be regarded specifically due to the lack of connection between geographic units and, sometimes, structures. For the construction of assets, this factor is not of a great importance, planning and project is being implemented project-based and follows the laws of scalability. For each project, a corresponding project engineer is required with expenditure of time. The operation, however, is highly dependent on a working organization. The economies of scale are larger, if the ratio of working time to traveling time is better, so that widely separated asset areas do not lead to positive influences. Even more subjects are to be considered in this context, such as organization of the on-call service, control of widespread of operation, etc. Case 3 is therefore more likely to lead to the commission of various service provider organizations for similar divisions in different areas, and the optimization problem is the overall control and the replacement of, e.g., spare parts, emergency materials across borders. Therefore, it has to be considered at every stage of the system growth, if really economies of scale can be created during operation of if there are suitable areas which point out a correspondingly high effect by closing the gap.

Finally, it can be stated that the system size has a strong influence on the efficiency of asset management of infrastructure systems. In this regard, case 1 predestined for collaborations with larger partners and the allocation of many functions of expert knowledge up to the development strategy by third parties. The constitution of own resources and systems cannot be implemented economically. Case 2 is actually the ideal case in all factors, as it can easily generate economies of scale in all factors without high complexity and coordination. Also, the leverage of optimization processes is correspondingly large. The third case is also influenced by the opportunity to raise economies of scale, but the particular case always has to be considered concerning the extent of these possibilities. In addition, there is always the risk of increasing complexity and inefficiency in this case.

4.4.2 Effect of System Homogeneity of Infrastructure

The system homogeneity, already discussed to some extent under Case 3 in the previous section (Sect. 4.4.1), is of outstanding importance due to the general observation in many particular issues, both technical and related to the structure of the owner. The coordination of the asset manager with the particular asset owner, who has the final decision in respect to his facilities and equipment, must take place at a defined level. This is essential for the capacity of the asset management and the lifting of synergies. The role definition must be clearly defined as a fragmentation of relationship, defined by contracts, leads to unmanageable responsibility. Here, a risk of decision errors exists due to non-unique assignment of responsibilities. This is contrary to a secure management of all relevant infrastructure systems, so that, in this context, there are three steps to be defined of a parent organization which generates gradually an increase of synergies:

- Step 1: uniform strategy development of distributed systems,
- Step 2: in addition, use of uniform support systems,
- Step 3: combination to a system (real or virtual).

The trend in today’s political environment, especially in Germany, is to ignore largely these considerations or to use them to argue for a competition in infrastructure systems. The fact that smaller systems want to grow specifically in the discussion of concession contracts, of course, creates in particular the incentive to integrate neighboring systems and thus to optimize locally. However, since this leads to the fact that these areas need to be extracted from existing larger units, there is a risk of synergy destruction in general and the emergence of a corporate landscape which is partially represented by the case 1 discussed in Sect. 4.4.1. That is, from the viewpoint of the asset manager, the situation is developing toward smaller systems, thus in reverse order compared to the points mentioned above. The separated systems may fall out of the strategy application and also of the support systems. This is so to speak the “worst case” for the synergies in the asset management. Besides, further disadvantages occur, such as new interfaces in the structure as well as data transfers, which will be necessary for the collaboration at the system boundaries.

4.5 Conclusion

Business model, management, construction, and operation of an infrastructure system are modeled by a three-part role model with asset owners, asset managers, and service providers. These roles are connected to each other via external service contracts, which describe the ordered services and the quality of the so-called SLA. The responsibilities are assigned according to the distribution of tasks, with the asset manager, who is in a so-called sandwich position between the return on investment requirements of the asset owners and the desire for the investment of the service provider. The asset manager is able to lead and oversee this role by

- the data and systems which are used by him,
- his experience, and
- the indispensable authority over decisions on technical and procedural standards, commissioning of projects, and budget planning, including control.

There is no universal answer to the question as to whether these roles are filled internally or externally in a corporate organization. This decision is dependent on exogenous factors, such as market volumes, competition, personnel availability, on the one hand and endogenous factors such as corporate philosophy regarding the basic structure of the systems and equipment on the other hand. Hence, the judgment must be made individually, based on an analysis of the relevant interpretative competences.

Four possible models of business organization with different labor intensities are described and may be used as a basis for the implementation of an asset management model for infrastructure systems. Boundary conditions for the organization are the quantity structures to be managed, which leads to economies of scale in case of the provision of software systems and expertise from a given volume. However, the homogeneity and geographic distribution of the systems and the structures of the asset owners play a significant role in the organization and definition of asset management.

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System Landscape in the Area of Asset Management

5

5.1 Asset Management Data

As described several times, any kind of data are the basis for the implementation of asset management tasks. A multitude of data must be collected, stored, and processed in different programs and data files. Ideally, the programs and databases are linked to each other, whereas this constellation is referred to as “data system landscape.” The single basic elements of this system landscape are described in the following sections in detail.

A corresponding data model is used in each program, in which objects are mapped and assigned with properties/attributes. These objects generally represent equipment groups, individual equipment, up to items of equipment. Networking of the programs is the main requirement for a redundancy-free data acquisition and processing, so that the used data models lead always to consistent results in case of mutual evaluations. In particular, this means that the attributes may be recorded and changed in only one single defined data file of the system landscape. All other programs have to access this data field in this file, if there is a need to process this information.

The amount of data models has an extreme economic importance. Each defined necessary data point of these models represent a financial expenditure in acquisition, data administration and also with any further development of the systems themselves, and particularly in maintaining the correct processing in the networking world. Partly, also data from third parties must be included in this system environment such as weather data or geographical information of the survey authorities. These efforts are also connected with a corresponding expense. For this reason, an uncontrolled procuring or acquisition of existing or producible data, the so-called data mining, is not the right way to build the necessary database. In fact, the asset management must define the necessary data points and develop efficient data models for its goals and strategies and configure the appropriate data models in a cost-benefit assessment. This is not a trivial task due to the long-life cycle

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of equipment and the associated data. If in a management case the importance of making acquisition of a specific attribute is identified, it may take several years to configure and collect a substantial database in case of certain data. Some data, such as certain measurement data at the time of commissioning of a plant or a piece of equipment, can only be collected at the time of the event and not afterward. This clarifies that the data of an infrastructure system constitute a financial and operationally necessary value in itself. For the asset management, the modeling and the amount of data models represent a sensitive balance between intended, necessary information acquisition and efficient operation.

The structure of the data itself can be, regardless of place of acquisition and storage, divided into the following categories:

- Portfolio documentation,
- Order and movement data, and
- Process and control data.

In addition, there are a variety of other information and data, which cannot be described extensively in their entirety and therefore are not considered in this context.

Tables 5.1, 5.2, and 5.3 give an overview of the most important data with its possibilities, in which program systems this information may be collected and provided. It is apparent in these tables that the "enterprise resource planning system" (ERP) and the "geographic information system" (GIS) lend themselves to the system documentation. In fact, it depends on the company's philosophy and especially of the IT strategy which option is chosen. Overall, these two systems represent the core of data storage, to which most of the features of the other programs will have access.

The portfolio documentation is characterized that the data and documents are subject to little fluctuation and are fixed over the lifetime of equipment, not depending to customer connections and work organization. It is developed with the expansion of the infrastructure, with the use of new materials, change of technology, or on expansion of the number suppliers and represents in some ways the history and evolution of the infrastructure company.

The dynamic data of technical equipment are subject to short-term adjustments and are maintained by the normal operation. Here, the information converges generated with work orders and obtained from the workmanship. They represent the operational documentation and are thus also the proof concerning the operation of the infrastructure system due to the law and standards. In addition, the dynamic data are the basis for the process and control data.

The asset management is gaining its basic data for the development and adaption its strategies as well as the assignment of the executive operating units from the process and control information and in particular of their development over cycles and fiscal years. In this case, all strategies of the maintenance are analyzed starting from removal and development of single equipment up to the entire infrastructure system. It is a question of

Table 5.1 Portfolio documentation

Data	Program system
Technical asset, object description – CAD plan – Technical data, design limit, power, etc. – Construction year, manufacturer, classification – Used standards – Approval documents	GIS/ERP
Manufacturer documentation – Operations manuals – Promise of guarantee – Contracting documentation	paper GIS/ERP
Structure of the system/asset – Asset hierarchy – Cross-linking, connection of assets	GIS/ERP, network planning, network control
Resources of materials – Spare parts, materials of emergency – Auxiliary materials, plant equipment	ERP, mobile operation control
Organization information – Field of activity, responsibility – Cost center – Accounting hierarchy – Risk management, crisis management	ERP
External contacts, clients, supplier, etc. – Addresses – Contracts – Constraints, commitments	ERP, mobile operation control

control mechanism, whether the associated targets concerning the strategies are to be achieved or whether corrections are needed in the planning or in the operational implementation.

5.2 Enterprise Resource Planning (ERP Systems)

The term “resource” can be translated from the French with funds or backup, so the naming is related to a system for the organizing of all necessary resources of the company (materials, money, and personnel volumes).

Enterprise resource planning systems have been particularly implemented and further developed in the 1980 and 1990s in big companies. They include the claim by their very nature, to handle all IT-supported business processes within one system and to manage all functions of the above-described data system landscape by the networking of software systems. In reality, however, there are many special topics that are served by special programs with data which are not stored in ERP, so that this claim has so far remained as a

Table 5.2 Order and dynamic data

Data	Program system
Condition information – Reports: inspection, overhaul – Ranking, renewal, lifetime – Systematic failure information	GIS/ERP, mobile operation control
Operational procedure – Individual order, process – Working plans – Workflow	Mobile operation control
Work resources – Employees (operation, stand by) – Planning, project, and construction – Contracting, external services	ERP
Time information – Proof execution, deadline – Start and finish date – Cycle duration, cycles	GIS/ERP, mobile operation control
Status, availability – Approval order – Work permit – Work progress of a contract	Network control, mobile operation control
Construction and operation costs – Plan-actual – Obligation – Material, service, internal activity	ERP

theory. However, ERP systems are used today in many companies as backbone of the information processing for business management. They are engaged in all work processes and provide many administrative working bases for the respective business areas such as finance, human resources, procurement, manufacturing, operation and the asset management. The following discussion is concentrated on the functions and modules necessary for the asset management, and optionally, it mentions adjacent interface modules to other areas. An extensive description of ERP systems can be found at the appropriate economic literature, for example [4].

The main advantage of ERP systems can be realized through the automation and standardization of work processes and operations. According to [6], the main arguments for the use of standardization are as follows:

- Better coordination and avoid duplication of activities; organizational conflict potential is reduced by defined cooperation and precise definition of procedures.
- Increase of productivity; an economic use takes place by the planning of activities and resources; single steps do not need to be questioned or decided individually.

Table 5.3 Process and control data

Data	Program system
Process data – Measurement, load, wear, etc. – Aging behavior, condition development	GIS/ERP, network planning, network control
Outage and damage data – Mean time between failure (MTBF) – Mean time to repair (MTTR) – Specific rate of outages and damages – Outage costs versus total budget	Asset strategy, network planning, network control
Resource indicators – Employee load (external/internal) – Specific order data – Specific construction and operation costs – Asset availability	Asset strategy, network planning, network control
History – Installation/removal – Equipment-related lifetime – Object-related maintenance costs	GIS/ERP, asset strategy

- Relief of executives; once established, control of processes leads to largely automatic implementation and enables the concentration on improvements and the setting of management priorities.
- Increase of the stability of the organizational system; the corporate function does not longer depend on individuals but is granted by the consistency of the standards through fixed process steps defined by the standards.

But standardization makes only sense in case of appropriate economies of scale; the processes has to be carried out in sufficient frequency in order both to justify the development of a standard and to equalize also potential disadvantages in single cases compared with the huge number of standardized applications. Because of this effect, the infrastructure sector has a strong tendency to build cooperations and use shared services in order to realize these benefits at reasonable costs even for smaller companies.

An ERP system can be divided into different categories of tasks according to [4], these are as follows:

- Administration, data management for business transactions,
- Scheduling, automation of routine tasks,
- Information by development of key indicators, and
- Analysis and evaluations by reports in defined time cycles.

The application areas, which are supported by these task categories, have a very wide spread, as described above. The following areas of application are the main important for the asset management:

- Financial planning,
- Budget control, controlling,
- Maintenance control,
- Project planning/control,
- Materials management,
- Human resources, and
- Asset portfolio documentation.

Certainly, the latter area, as already mentioned, can also fully be covered by a corresponding allocation of this function in GIS, particularly because at least the part of the system portfolio documentation, which includes the geographical data of the assets, is mapped in this system. But in this context, the version of the data landscape is described with the system documentation in the ERP. The ERP system is usually built up due to many tasks in different modules that rely on common processes and overall support functions. A very good overview of developments, solution providers, and institutions is exemplified in [9].

5.2.1 Asset Documentation (AD)

As already shown, a comprehensive but targeted documentation of assets of an infrastructure system is the indispensable base for the implementation of asset management. All analyses, studies, statistics, indicators, and thus the derivation of maintenance and renewal measures use the basic data model structure that must be stored in the ERP system. The asset documentation represents so to speak the catalog of the infrastructure system, where the above-mentioned various types of data (portfolio, dynamic, and process data) are stored and can be accessed.

In general, the infrastructure system is represented hierarchically in the system documentation, though two main object types can be distinguished:

- Technical location
  This is a so-called stationary object, such as a substation or a gas pipeline. A technical location is usually a summary of a plurality of movable objects or formed by these. A technical location itself cannot be changed with respect to the integration into the infrastructure system, but is variable in size and number of lower level objects. It is assigned to a specific cross-function with its own character as a definition of a location in the infrastructure but does not consist of any technical data or manufacturer information.

- Equipment
  The equipment is a separable, movable, and technical object that can be assembled and dismounted in a technical location. It is usually a closed technical object, which consists the technical data and characteristics (year of construction, charge, manufacturer information, performance data, equipment history, etc.).

Due to the hierarchical representation, generally, it is also guaranteed that the technical objects with high importance can easily be selected and the appropriate analyzes can be carried out at a very early mapping level of a database. In addition, the number of parent objects is usually small (of the order of a few dozen to less than one hundred records), so that also relevant findings from the documentation can be obtained without intelligent search strategies and database queries. A simple alphabetical search is usually sufficient by property name or even simply scrolling through the records at this level. Slightly similar assets may have to be recognized in huge numbers in the deeper levels of the database hierarchy. Thus, for example, in medium and large electrical distribution networks, the number of substations in a volume of several thousand is not uncommon; a multiple of records are imaginable if deeper levels are considered. In order to obtain the necessary functionality of system documentation, corresponding standard data models have to be developed with the necessary asset management attributes for each resource. Only with these standard data models, intelligent query strategies can be implemented via the system documentation. In particular, special functions are needed to ensure the ability of asset management in strategic planning and reporting. Examples of results performed by of these analyses are as follows:

- Failure statistic,
- Quantity structure (e.g., technology or age related),
- Value analysis,
- Weak point analysis (systematic error),
- Maintenance cycles,
- Condition-based renewal strategy,
- etc.

Interfaces between systems on the one hand, of course, are necessary to ensure the relationships shown in Fig. 5.1 and to meet at the corresponding results. It is assumed that modern ERP systems are interoperable within their module structure, and accordingly, no further coupling effort exists after a corresponding total ERP implementation. For example, the coupling to reporting systems or GIS is often afflicted by IT technical problems and must be checked at each adjustment or new software release and if necessary must be redesigned to guarantee further function. This is usually associated with great efforts, so the highest possible concentration in one system means an advantage. Nevertheless, the necessary system couplings should be performed as lean as possible and should be designed at least as a simple data export. To ensure this, the data in the models

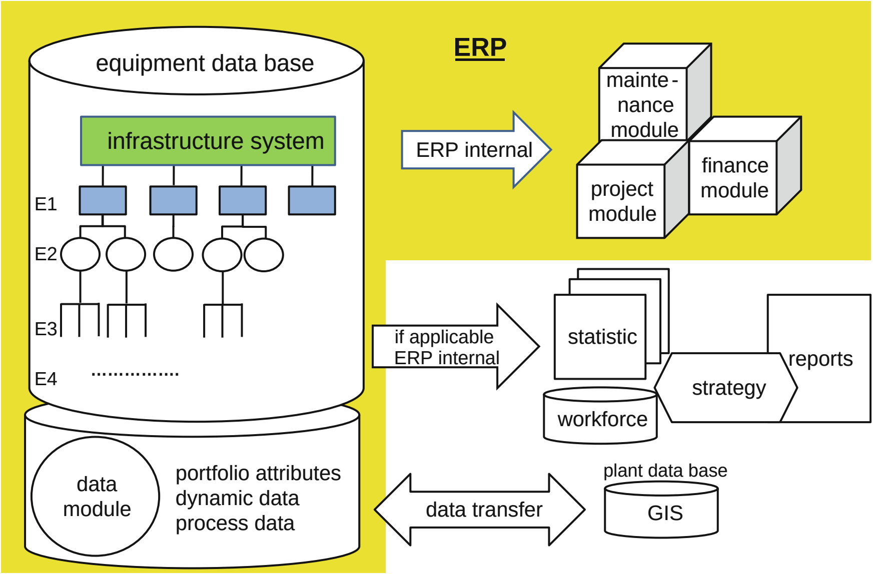

Fig. 5.1 Asset documentation, content, data transfer, and objectives

have a simple structure and should be performed without crosslinks, or multiple relationships. The increase of the data model complexity leads to a many-fold increase in the handling and evaluation efforts as well as interface problems. The relevant other systems outside of the ERP system, which depend on the database of the asset data, are also indispensable for the operation and strategic development of the infrastructure system. These systems are in particular:

- Network calculation tools for planning,
- Asset-based simulation and strategy tool,
- Project prioritization tool,
- Mobile control tools ("mobile workforce"), and
- Network management system SCADA.

They need a defined volume of data for their own functions that must be described for this reason in a data model. Here, the granularity of the data in the model is of great importance especially the number and type of attributes, the detected and evaluated dynamic data, and process data. Each data point represents efforts in both the collection and for the administration and evaluation. Due to the strongly increasing number of technical objects from one high hierarchy level of the infrastructure systems to the following lower level—which can easily reach the volume of several tens of thousands—there must be an accurate test of the need, benefits, and costs of the existence of each data field within the data model. This evaluation includes also the limitation of individual and accurately mapped technical objects. The asset database has to be concentrated on the valuable objects and needs to summarize the last suitable levels, if the granularity is too high in the infrastructure system.

So, for example, not every cable joint box is so far shown as a technical object in a power distribution network. The exact data acquisition of the asset database of the ERP is then in this example finished on the secondary station level resp. on the low voltage level as the lowest object level. Unless they have a geographical significance, deeper levels must indeed be mapped in the GIS, but without extensive asset data attributes such as manufacturer and year.

The asset database is to be separated from the network structure plan layout. The latter serves the safe operation and not the mechanisms of the asset management. The network structure plan layout (e.g., circuit diagrams of assets and network operation plans), therefore, is rather an integral part of the equipment and systems themselves.

5.2.2 Finance Module

The financial sector was basically the root function of the ERP. Every company is obliged to carry out sufficient accounting due to lawfully commercial specifications and to provide a financial years related profit and loss account (P/L). This area was for the implementation of software tools due to the increasing complexity and the always increasing requirement of data acquisition and processing. Companies such as SAP and Oracle have developed intensively in the 1990s these systems and in combination with the efficiency and cost degression in computer hardware, the software was distributed worldwide. The nature of the asset management, as both technically and commercially oriented area, led to the extension of the originally pure financial planning and accounting functions to the technical control level. The financial module links the two worlds together and makes the relevant information available. The influences of the operating department of an infrastructure company on the profit and loss account can be linked in this way. In the other direction, the financial implementation of the operational business can be controlled. The essential functions of the financial module are as follows:

- Assets accounting,
- Cost center, and
- Budgeting.

The asset accounting represents the financial picture of the technical infrastructure system. Here, the individual assets are activated and depreciated over the financial period of use. Thus, summarizing all these financial values of the assets, reduced by depreciations, the so-called book value of the infrastructure system is generated. It should be noted that the assets accounting is not a technically correct image in opposite to the technical asset database. In particular, the asset value and age structure of the assets may differ from the book value. This depends on the different treatment of real renewal activities and their activation in the accounting. For example, a gas pipeline is activated during the initial installation on the date of commissioning and then depreciated over a defined amortization period up to the residual value of €1. During the lifetime of this pipeline, it may be renewed in sections or even slightly misplaced and it comes to real renewal and life extension. As this part of renovation does not represent a completed asset or a main part of it, it is not activated and the original values remain fixed in the assets accounting (date of commissioning, residual value).

The cost center is the main area for the universal cost collection and cost allocation. All activities of personnel costs over operating and office equipment to non-capital project costs are collected via contract invoices or internal pricing agreements and are allocated to the cost centers. Via these all costs are integrated into the profit and loss statement. The cost center structure is partly also a reflection of the business organization and represents the supreme financial control level since all of the operating costs are visible here. A selection of the costs, the management, and the controlling take place via appropriate cost elements, so that the asset management receives analysis options on the development of costs and related on the asset segments partial cost of the asset stocks and the operation activities of the asset.

Budgeting represents the allowance of a financial framework for self dependent commercial action according to [13]. With a background cash-flow-controlling in the financial department, the necessary capital for the operational year will be provided, due to the procedure of the planning process described in 3.1.1, to the measures and project depending on the strategies, which are developed by the asset management. These funds are the base of the ability of the asset management to perform the further commissioning of services and projects in the context of the role model. Thus, the budget has also the direct link to the other ERP modules, such as project and maintenance module. The stored orders in these modules compensate the allocated money in the budget to the assigned cost center, ensuring that a consistent and closed system is created. The budget represents the most important level for the controlling of asset management by the shortcut reference at the order level.

Both the maintenance and the project report can be analyzed (the basis are the orders) on costs and time delivery depending on a defined granularity regarding order types, measures, and projects. Here, the budget control by enabling or disabling of orders is given and thus the foundation of one of the main functions of asset management. Figure 5.2 shows the interaction of the different functions as an overview. It is clear that both levels assigned to the tasks can securely processed by an information flow in both directions and a consistent data set is generated from the operating cash outflow up to the P/L statement.

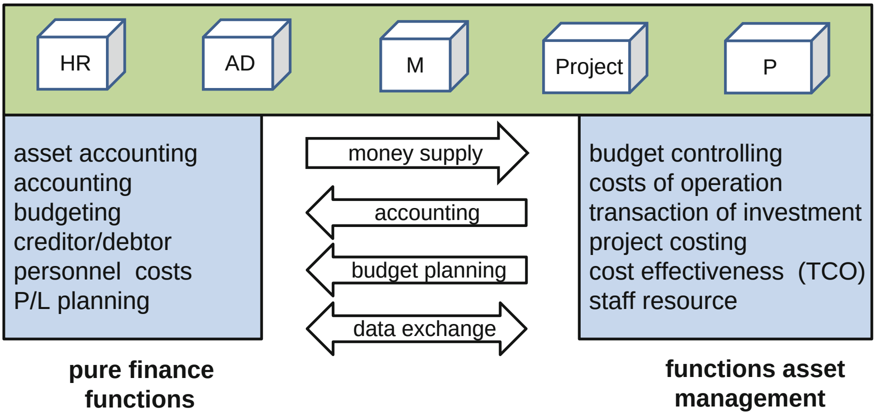

Fig. 5.2 Interaction of finance functions and asset management. HR human resources (Sect. 5.2.3), AD asset documentation (Sect. 5.2.1), M maintenance, TCO total costs of ownership (Sect. 3.1.3.1), P/L profit and loss account, and P procurement

5.2.3 Operation and Maintenance Module

The operation and maintenance of infrastructure systems is characterized by many similar and periodic activities such as inspections, periodic maintenance, and switching operations, which can only be controlled and analyzed by an appropriate IT support in case of many processes. The order system is the foundation of this module, in which the individual activities are generated in a suitable viewing depth by the system in order to act as the base for the execution of the activity and for the feedback of hours, materials, and external costs. This easily generates thousands of orders whose generation must take place automatically due to effectivity reasons. For this purpose, the maintenance module considers the various policy positions, such as time-based or priority-based maintenance. Corresponding orders can be generated for the entire fiscal year by defined timing cycles of the asset management for all equipment with time-based activities. The database is represented by the condition of equipment in case of the priority-based strategy, for example, from inspection reports and the determined importance by the asset management, with which a next maintenance date is calculated which automatically generates an order for this activity (see Sects. 2.1.1.6 and 2.1.2).

The brainpower of the maintenance module is precisely the considered strategies, defined by the asset management, which leads to an automated calculation of the timing cycles per equipment segment and type. Based on this, the automatic order generation for the entire infrastructure system is a comprehensive tool to improve efficiency in this process. Thus, only the unplanned activities such as outages or external measures must be processed as manually generating orders. The orders in their entirety form represent work list for the service area concerning the entire fiscal year, which is also the basis for a follow-up of order execution and the related finance costs on the budget side. A plan/actual comparison is possible for the asset manager on the one hand, and the confirmation of the execution takes place concerning operating and maintenance measures by the order feedback and documentation of this module on the other hand. The higher requirements of detailing of the controlling authorities is the background and furthermore the regulator requires the confirmation of the recognized rules of technology in accordance with § 49 of the German Energy Act (Sect. 2.2.2), which is of great importance.

The maintenance orders contained in the module can be processed in various ways, the use of a digital system for dispatching and feeding back of the operations on digital devices by the service engineers, the so-called mobile workforce is becoming common place.

The maintenance module has contact with various modules inside the ERP system. The maintenance objects are identified in the asset database. The funds are provided by links with the budget part, and the created and calculated orders are available for budget planning automatically. The accounting of orders is made by the assigned cost center, and the human resources and the necessary expertise to carry out the activities are ensured by information provided by the personnel module.

The order fulfillment with date, costs, and possibly condition information is documented through feedback into the system database and documented in the equipment history of the maintenance objects or the relevant technical place. Outside the ERP, this module has an interface to the job dispatching module, work organization, which is responsible for the distribution and feedback of orders. Many variants and systems are possible depending on the characteristic of the organizational activities such as printing of orders and manual feedback to the central system up to the use of mobile devices.

5.2.4 Project Module

The second major block within the asset management, in addition to operation and maintenance, is the calculation of project cost and project handling. In general, projects are identified by three different possible paths:

- Condition-related renewal,
- Development from target network planning and new construction, and
- Externally decided reallocation/changes.

Here, the majority of the projects of an infrastructure system is defined within the first two of these paths by the system management and thus within the predictable area. All projects have to be planned in the project module regardless of the way of identification.

The service provider performs a project based on a specification that describes the functional requirements of the asset management. This leads to specifications, which describe the concrete implementation, in which assets and standard activities can be defined as building blocks with associated costs as a calculation support. The necessary information such as for materials and external services can be taken from the purchasing module with the stored product prices of framework agreements or determined average prices. Projects calculated in this methodology are saved in the project module and either provided as so-called project idea for future implementation or included in the budget planning and setup for realization as the project is starting in the current and next financial period.

An appropriate choice for projects that remain as an idea in the system and those that are realized is achieved by the later being explained project prioritization tool. This means that each project, with its data regarding costs and time response, receives a corresponding status in the project module (for example, “released for realization”), and the project cash outflow is planned for the specified milestones. There are some outstanding points for milestones:

- Advanced payment,
- material delivery,
- approval of construction section, and
- commissioning,

which can be implemented in the system. As in general, the project handling is usually complex and consists of several parts, a monthly control of the cash outflow planning of the project process is most purposeful. As a result, the project module is the second concrete platform in addition to the maintenance module, where tasks, activities, and developments are included and can be controlled, which are appointed by asset management. The difference to the maintenance module is that projects have likely longer runtime than one fiscal year, and therefore, a multi-year process is possibly needed regarding planning, budgeting, and controlling. The interfaces of the project module to other systems are the same as in the maintenance module with the addition that there must be a strong link to the procurement and material modules. Therewith, the use of the specified technological standards is ensured with the submitted materials and assets, and not to allow individual or even exotic solutions.

5.2.5 Procurement and Material Module

The tasks of the technical asset management also include the ensuring of adequate resources for the long-term safe operation of the infrastructure system. This includes the necessary service capabilities, materials, and assets, including an adequate supply of spare parts. Depending on the chosen business model of the company (Chap. 4), the asset management is indirectly responsible by the use of an internal general service provider or directly by market orders. The procurement and material module within an ERP supports the following areas:

- Material list (technology and price),
- Supplier database,
- Stock management,
- Frame contracts, and
- Procurement and demand function.

The approved equipment types, materials, spare parts, consumable materials, etc., are performed in the material lists; the use is provided obligatory. The procurement of special materials is possible beyond of these identifies standard material (e.g., to repair historic capital equipment and individual special solutions). But in this case, a separate verification process has to be implemented, to make reasonable the motivation of using more costly procedures. In this way, a controlling of the relation between standard procurement and special material is made possible. The identification and registration of the standard material is carried out by the asset management, or at least proofed and released. A corresponding specification, related to the infrastructure company, is required for each material or equipment. This describes the special requirements for the authorization for use and is provided in the purchasing module. In principle, the specification is the basis for the procurement of materials and services (directory of services as specification).

Standardized material is also particularly suitable for warehousing due to the regular use. In particular, because as a rule, there is always a delivery date that is opposed to the immediate availability, and also, the infrastructure systems need to be ready for operation for 24 h a day. Therefore, to work on weekends or at night is normal, short-term availability of such materials is only possible due to a constant accessible spare change and material storage. Even with project-based “just-in-time” deliveries, overordered quantities or unforeseen minority quantities can be balanced by the stock management. Standard materials provided for storage are accordingly the material in the ERP module. The complex processes of the stock management itself, which is provided in this module, will not be described here in detail.

All materials and services also have a reference to the possible sources of supply. Suppliers with their specific delivery options, prices, and quality characteristics are also provided in the procurement module. The assignment of several reliable and good quality supplier for a material is a degree of its availability and therefore also for the risk for the infrastructure system in the procurement case. The procurement department is encouraged to achieve a quality and rise in prices or to find alternative manufactures by an appropriate development of the supplier market in case of monopoly situations, quality problems, or extraordinary price increases for materials. In addition, the asset management must constantly look for alternative and improved technological solutions. This is done, for example, by creating a replacement concept for a specific technology by a more efficient and more modern technology, or by reviewing and changing the specification for enlargement the supplier market. This process is also referred to as a product cost optimization. The indication of such problems and the need for action by the asset management, particularly in the areas of spare parts, are provided by the direct linking of standard material lists, supplier lists, and price observations. Another aspect of the supplier database is the already mentioned quality assessment of services and materials.

As part of its legal duty of selection, the client has to examine whether the manufacturer and supplier are able to provide a service or delivery. In the area of materials logistic, this takes place either through the assurance of compliance with recognized standards, but also quality assurance and incoming inspections of delivered materials are more and more in use. In the service area, however, the so-called audits take place, which checks the compliance with the applicable environmental and occupational safety regulations and laws in both areas, the office of the service provider and on site. The company is thus qualified as an approved service provider. The approval is also stored in the procurement module and renewed periodically. If intolerable quality defects occur, the supplier will be blocked in the system and its service or its materials are therefore no longer available. In case of important materials or services, this can have a major impact on project management and planning of investment management.

The pure procurement function is implemented within the module by usual procedures for tender offers (in compliance with legal regulations), termination, and administration of frame contracts resp. volume commitments as well as realization of individual orders. This purpose, as shown in Fig. 5.3, refers to the (1:n) relationship between material and supplier.

The procurement and material module has another important controlling function for the asset management to that effect that the material consumption can be directly recorded and an assignment takes place to the activities of maintenance work or projects depending on the system. Thus, there is a tool to check the plausibility of measures provided for the planning quantities, possibly even to verify. The interaction of volume and financial planning is implemented within this module by linking purchase quantities and price lists and thus generation of specific prices. This offers the possibility to monitor the development of costs in the infrastructure sector by the asset management by arranging a characteristic shopping basket with the specific distribution of assets and services over the

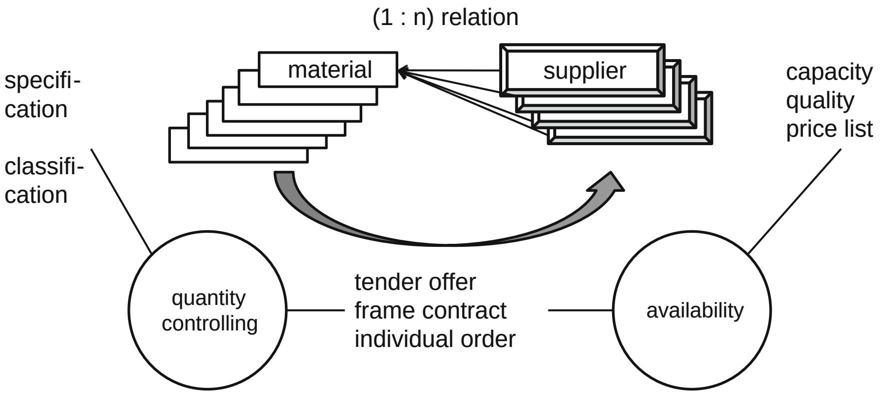

Fig. 5.3 Relations of the procurement module

annual purchasing volume and to control its cumulative price development over a period of several years. This allows one hand to estimate the overall development, but also to identify the segments with the highest cost driver effects and to initiate countermeasures.

5.2.6 Staff Module

The staff module “human resources” (HR) essentially consists of the following components:

- Human resources management
- Staff management, and
- Payroll accounting.

The staff module in the ERP world has to be more isolated due to data protection issues and only occasionally integrated in the processes of infrastructure management. Only the necessary information for operation is available for the ERP links, usually without direct reference to individuals. Essentially, the information deals with the total capacity, i.e., how many employees are in which area of activity and what competence with respect to education and training is available for the company internally. Looking to the future, there is also the question of the demographic development for the assessment of medium-term opportunities and needs for action in these areas.

Specific calculation variables can be calculated by key figures such as hourly rates inside the different segments of qualification but also the productivity within sectors of activity. This can be used in turn as a basis for calculating the operating activities.

A more or less direct link between the personnel module consists on the one hand to the budgeting area, since the corresponding unscheduled staff resources are checked for plausibility and on the other hand for the mobile use control, which is covered in Sect. 5.6 in detail.

5.3 Geographic Information Systems (GIS)

The software developments based on geographic information systems is becoming increasingly widespread in the IT sector. Also, new tasks are created by the investment cycle, for example, in electricity infrastructure in Germany and growing new topics, such as distributed generation in the network, which can be effectively solved on the one hand by a renewal of the system documentation and on the other hand only by the expansion of functions of such IT systems. Figure 5.4 shows an example of the different functions and their interaction in a modern IT environment.

The networking of geo-information and other system information in these systems with the already described further databases of the system documentation—in particular with

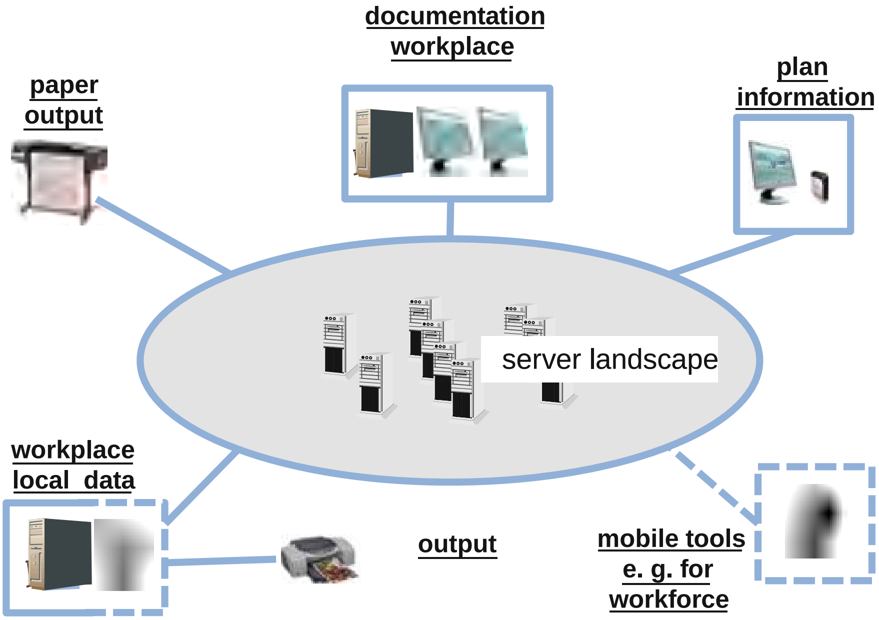

Fig. 5.4 Environment for digital planning work and geo-information systems

the ERP system, but also with operational functions such as network control system or the mobile workforce system—are governed by the links in this IT environment. Here, again the principle applies to avoid redundant data storage and for the design of simple and uniform data transfers between systems.

Geo-information systems primarily include geographic information of the assets, i.e., location and position, which are determined by recognized coordinate systems such as the Gauss-Krüger system. Additional technical data and operational information make it an important tool for the asset management next to this level of information. As both, age structures and technologies can be geographically visualized and network structure information is included, that is of outstanding importance for network planning and network operation, GIS is getting to an important IT-instrument for the asset management. In addition, this information is more and more available for mobile devices, so that they can be used as a basis for the mobile workforce program.

The official basic mapping is a basis for the digital plan work and geo-information systems, which in general exist at the land surveying office and can be made digitally available for the infrastructure companies. This information is mapped on the overview level of the topographic maps. The topographic level is left by increasing the imaging depth and the cadastral maps are on the lower level with floor plans of buildings as well as field sectors. Several layers with different information are shown in this basic level. Figure 5.5 shows an example with superimposed medium voltage lines and associated substations.

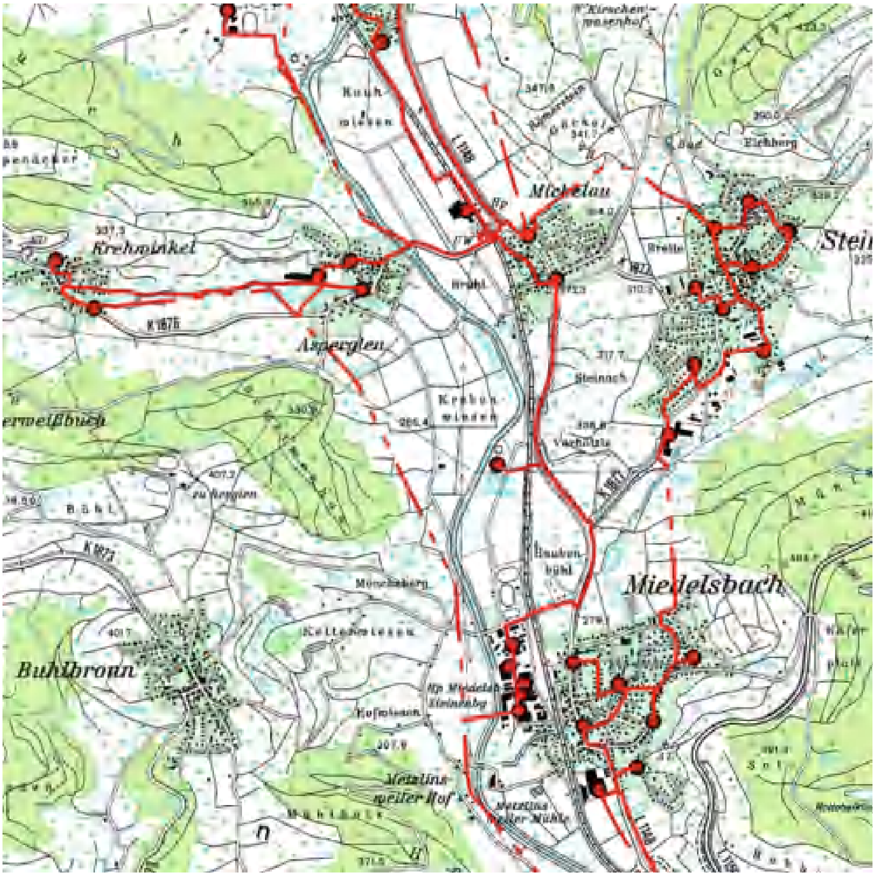

Fig. 5.5 Example: topographic map (TK25) with medium voltage lines and substations (source EnBW)

Already at this level, for example, the asset management can derive a gain of information about pattern recognition, e.g., historically expanded unusual accumulation of assets that can be optimized by a renewal cycle and the realization of a target network. Or it will be recognized by additional information, where the distribution of overhead lines and cables in an area opens the possibility of a unified network development with only one technology.

The planning work can be divided into three main categories:

- Survey maps,
- As-completed drawings, and
- Special drawings.

The above-mentioned information is contained in the **survey maps** that allow an easy assessment and measures dissipation and creates additional benefits, such as, for example, the finding of assets on site.

The **as-completed drawing** includes accurate and the scale preserving mappings—adapted by the base maps—of assets including dimensioning of lengths and distances to other objects. The as-completed drawings (Fig. 5.6) have particular importance for the planning information during construction activity to avoid damage and also the assignment to land regarding the legal situation for the arrangement of these assets on public or private land.

The **special drawings** provide a specific purpose and are defined by the respective company depending on the occasion. Operating plans may be an example for this category. These show interrelated infrastructure assets, galvanic connected to networks, and the ability to connect such parts, e.g., in case of failure or even while working in the network.

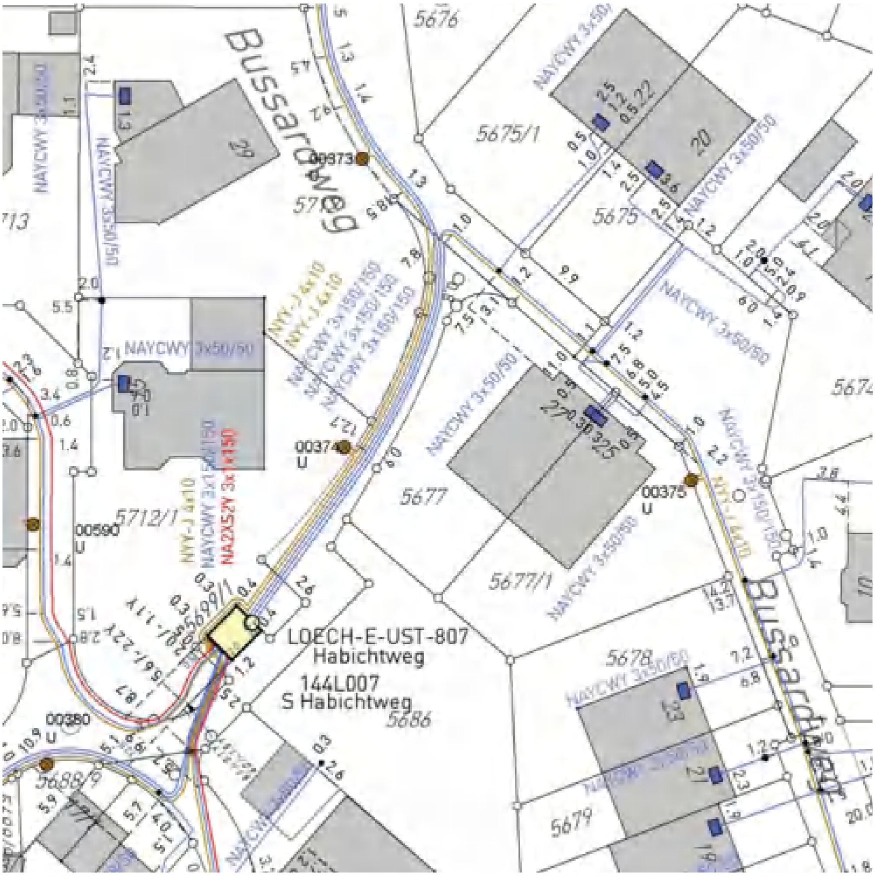

Fig. 5.6 Example: as-completed drawing current, scale 1:500 (source EnBW)

The information content of the drawings can be quite diverse and confusing while viewing all contents, which is why the systems are usually able to fade in and out the information in the basic map. Figure 5.6 shows a functional example of an as-completed drawing for a power supply network. Additional plan examples for as-completed drawings and survey maps can be seen in the relevant literature, for example, [3, 7].

The visualization of the operating state in the operating plans is exemplified presented in Figs. 5.7 and 5.8 for medium and low voltage networks.

This information is primarily used for the operating mode; hereby, a network fitter from outside the network company can recognize the associated circuits and, where appropriate, serve the separation points or unlock the necessary parts to work from the network. The colored presentation of the low voltage feeders and sub-networks creates a good protection function, for example, against confusing faulty switching.

This information is also of importance in case of the standards of the asset manager, since the protective sections (fuses), average circuit lengths in the networks, the

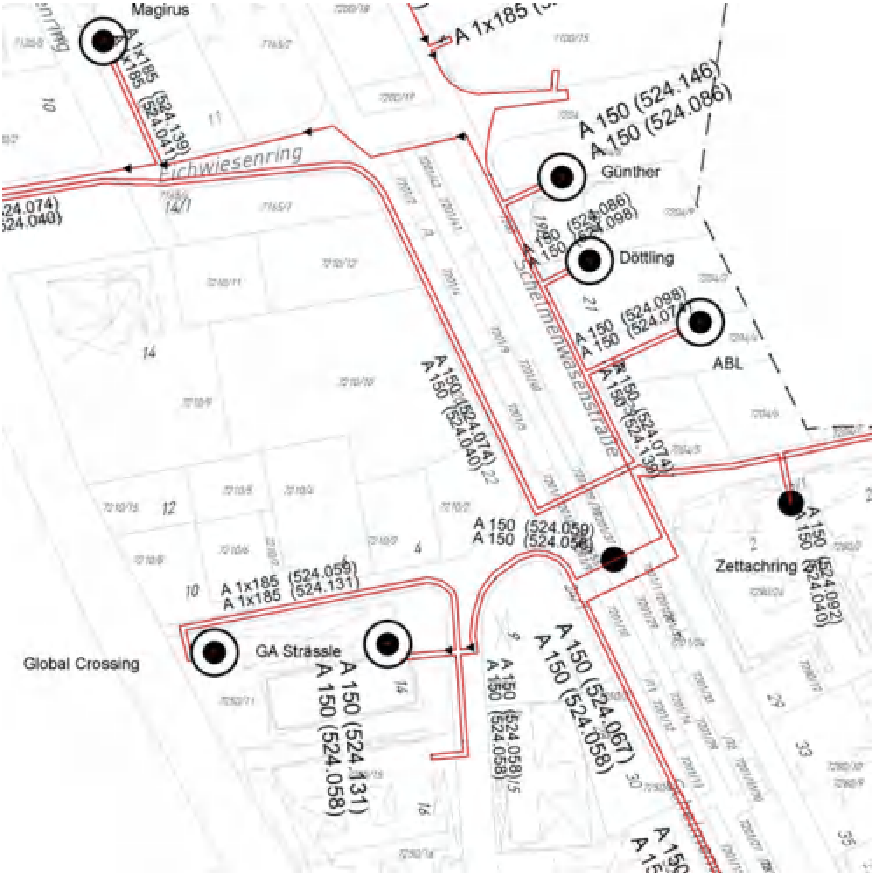

Fig. 5.7 Example: as-completed drawing medium voltage, scale 1:2500 (source EnBW)

Fig. 5.8 Example: as-completed drawing low voltage, scale 1:500 (source EnBW)

assumption of the target network, and quality issues such as voltage or pressure maintenance could be directly determined from the data model definitions. These values are available as indicators for the network development or quality performance.

The creation and continuation of plan maps, e.g., for the public electricity supply, was controlled by German Standard DIN 2425 (1983) in the past. This DIN standard has been withdrawn in the year 2005 based on the described progress within the digital plan maps. The current requests in Germany are fixed by the rules and regulations of the VDE that take these developments into account. Here, a related application rule [3] was set into force by the Forum for Network engineering and Network operation (FNN) in the year 2010. Therewith, an orientation framework has been created for infrastructure companies again, which describes the minimum requirements from the data acquisition and data management up to actualization and keeping of data.

5.4 Asset Strategy Planning Systems (ASP)

The asset management, in its role and with the tasks particularly in the renewal in accordance with Sect. 1.3.8, is also responsible for the long-term sustainable preservation of asset substance of the infrastructure. The development of substance is to be controlled in line with the requirements of the asset owner resp. the client. This includes the analysis, preparation, and presentation of scenarios with suitable parameter variations to make the implications of temporary definitions transparent, for example, in case of the amount of investment concerning the long-term development of the system (10–25 years). The simple nature of such analysis regarding the consideration of quantities and age structure reaches very quickly the technically limits concerning both the processing time and the significance in case of a larger number of equipment. This is especially a challenge at a necessary, regular, annual review, and adjustment of the results of the analysis. Therefore, a support by a software system with automated analysis and evaluation functions and interfaces to the system databases is required for the implementation of this task of asset management. Such systems for the asset strategy planning (ASP) are indeed emerged in recent years more and more frequently on the market, but only a few specialized systems are currently available or in use [10–12].

The basic structure of an ASP system is a rule-based knowledge platform that simulates the aging and the technical lifetime consumption of the infrastructure system and identifies the necessary exchange rates over the years for the conservation and development of substance. The basic procedure is presented in detail for various examples in Sect. 3.4 (asset simulation). The infrastructure system is broken down into various systems and equipment classes, and their aging chains as a function of service life and maintenance requirements are provided. Additional information, such as failure rates or technological system failures, gives further input for the simulation.

Basis for an ASP system are, e.g., program structures, such as business dynamics [8]. Thereby, closed control loops are themselves linked together with reinforcing or weakening factors in various ways; thus, the effects of various influences on the overall system and the reaction on the defined system boundaries are analyzed (Fig. 5.9). In this figure, four different areas are shown: financial aspects, market/customer needs, and resources and asset base, divided into different criteria. The lines or arrows represent the relationships between the criteria. The representation corresponds to the causal chains in Sect. 3.4.1 (Fig. 3.45, cause and effect chains) to derive an asset simulation.

Another possibility is the application of fuzzy logic structures as the analysis of a human expert is modeled by so-called fuzzy rule sets (Sect. 2.1.3).

The structure and development of the system have a self-learning character, i.e., the asset management is able to verify the results of the analysis and to check the accuracy of the predictions regarding the quality, failure rates and potential for optimization by the application, and long-term analysis with the collected experience. Factors, aging chains, and decision rules can be sharpened and updated accordingly. Thereby, fundamental changes such as innovation and technology change are taken into account. A virtual world is basically built up by an ASP system, and the infrastructure system is simulated (Fig. 5.10). The benefits of a virtual world as a testing environment are as follows:

- Low-cost laboratory,
- Variability of time and space,
- Repeatability of actions,

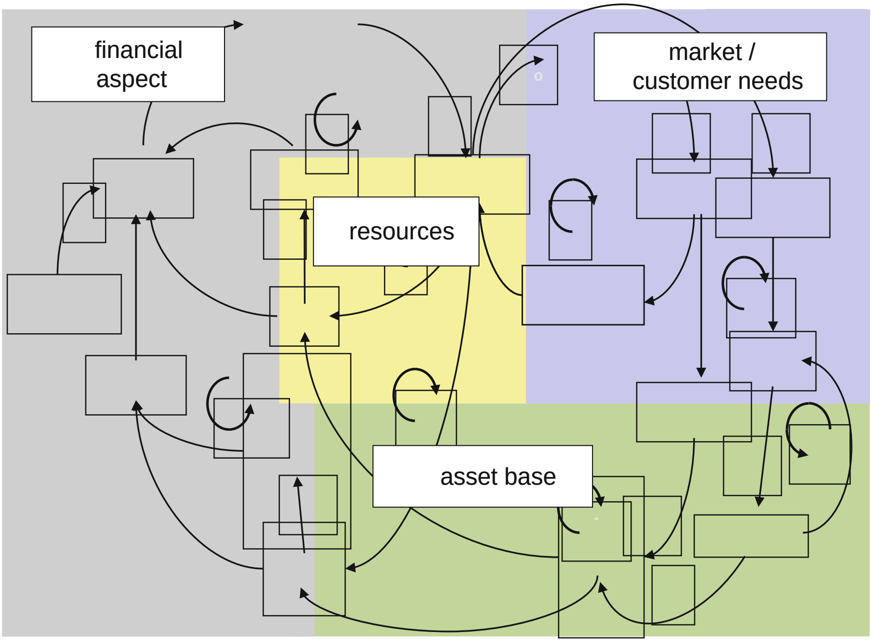

Fig. 5.9 Simulation of the entire system by linked control loops

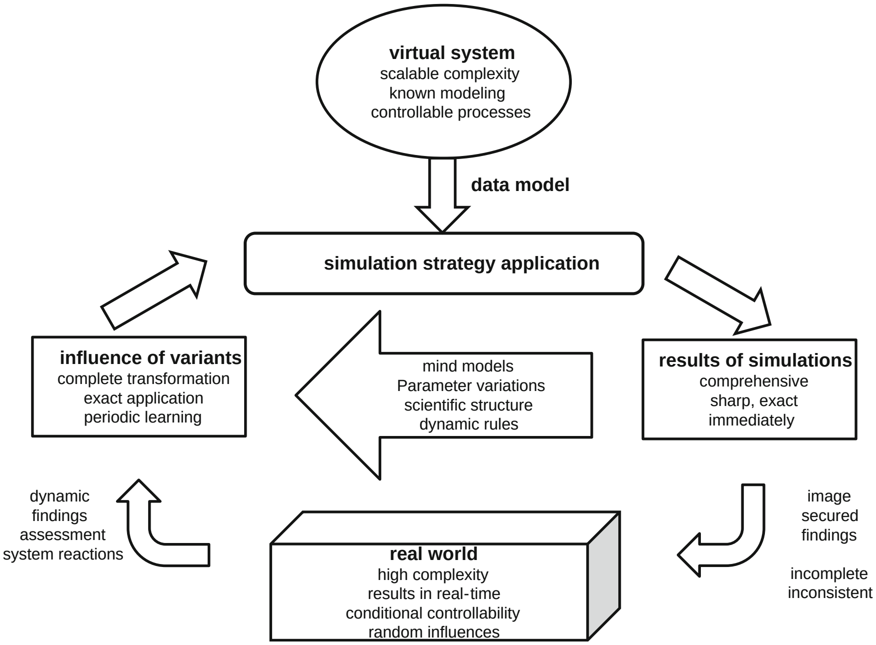

Fig. 5.10 Simulation as a basis for real measures

- Simulation of not feasible, expensive, immoral, or dangerous decisions,
- Reduction of response time, and
- Testing of extreme situations.

The input data for the ASP system are again the detailed asset data from the asset documentation, which are summarized in a preliminary stage to infrastructure segments. For this purpose, the system requires a data interface to the ERP system as well as the GIS system for easy updating of the database. As the asset data varies, the simulations and analysis on the current data should be verified annually due to additional construction, renewals, and other changes each year, such an interface is absolutely necessary. The required analysis data, such as failure rates and fault data as well as technological information, may also be transferred by this interface.

Further information is available in the commercial data and maintenance information that lead to the assessment of CAPEX and OPEX impact on the particular scenarios and strategies. These data are included in the ERP system, particularly, in the maintenance and purchasing module and has to be maintained annually. All these data are summarized in the virtual world to a segmented system model and are available for the simulation.

A significant part of the simulation have the so-called aging chains, which are developed and defined for each segment on the basis of operating experience, manufacturer information, and know-how of equipment experts. Figure 5.11 shows an example of such aging chain. It represents the respective equipment condition in four stages and also shows how the transition occurs from “as new” via “reliable” and “aged” to “exchange” depending on the time and how this transition is influenced or reversible by measures, if necessary. These measures include renewal, conducting overhauls, repair, to put out of service. The exposure time in each state region can be determined using the transition

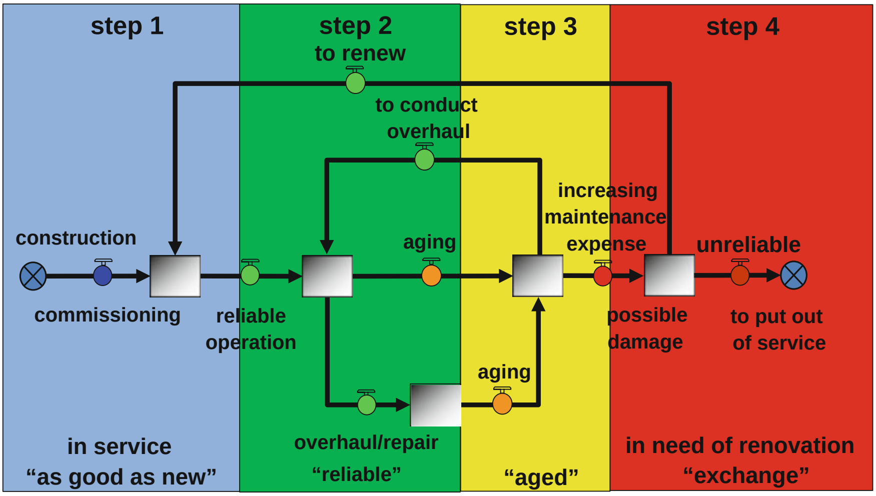

Fig. 5.11 Schematic representation of the aging chain of an equipment segment

rates between the states, so that this behavior is in accordance with the representation of Markov chains corresponding to (Fig. 3.44). The transition rates are presented by the aging process of Fig. 5.11.

The analysis is to be seen as a base for the most different applications and strategy decisions of the asset management. As the main result, the development of the “optimal” renewal strategy is in the foreground in accordance with the given boundary conditions and the distribution of OPEX and CAPEX. In addition, the determination of other financial performance indicators is possible, for example, return on equity or cash flow, as it is shown, for example, in [1]. Calculating these indicators, through different scenarios, and making the consequences of pursuing a decided strategy transparent is the core function of an ASP system. Segment-based renewal rates are calculated as a result of data analysis of the considered time period. The determined renewal measures lead to the necessary budget resources assessed with the necessary financial values that are needed in this long-term distribution for the implementation of the strategy.

Additional results are the exemplary illustration of the trend over years of indicators such as asset substance and quality of supply in the power supply. Two exemplary use cases are shown in Figs. 5.12 and 5.13; first, the optimum of the outage and replacement costs is presented, taking into account the quality of supply. Second one is a comparison between the operating costs (OPEX) and capital expenditure (CAPEX) of different maintenance strategies.

Figure 5.12 shows the dependency of the outage and replacement costs on the quality of supply. A low quality of supply results in high outage costs due to the high number of outages; however, in this case, the costs for the renewal of equipment are small. With a high quality of supply, the cost distribution is reversed accordingly. Due to these circumstances, an optimum of the total costs can be derived in case of the agreement of the optimal maintenance strategy, if the necessary quality of supply will be kept. In addition,

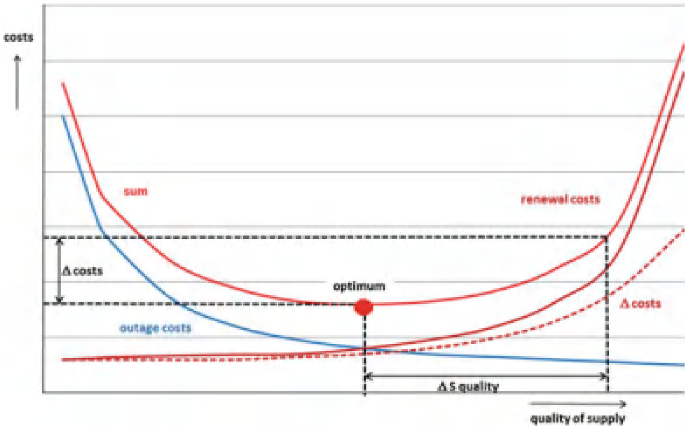

Fig. 5.12 Application examples for ASP analyzes, cost comparison, optimum costs, and quality of supply

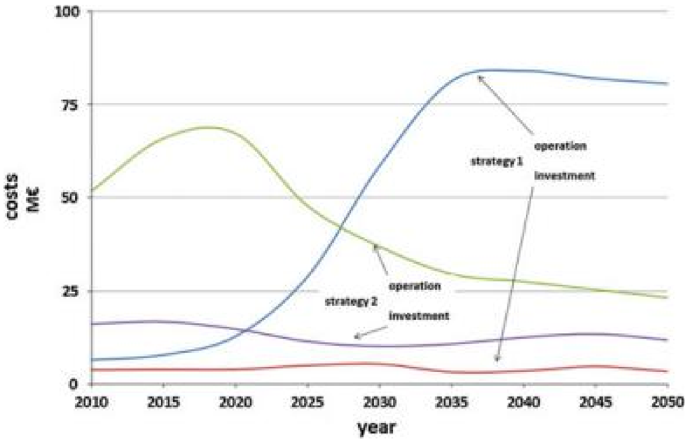

Fig. 5.13 Application examples for ASP analyzes, strategy comparison, operating, and capital costs

it can be seen that which additional financial costs arise when a deviating quality of supply is to be achieved. A similar example is described in Sect. 3.2.6.3 with respect to a risk-optimized maintenance strategy.

Figure 5.13 shows the result of the simulation with an ASP calculation tool for determining the long-term effects of two different investment strategies. Hereby, the operating and investment costs are calculated over the entire simulation period and can therefore be compared and evaluated. The use of such a program is also illustrated in reference publications [2].

The results are not suitable due to the statistic approach of the complete infrastructure system to identify directly individual equipment or systems for the renewal at a defined time. For this task, the project prioritization systems are used that will be described in the following chapter. But the calculation is the neutral basis for the development of short-term and medium-term budget plan. Without such simulation, a renewal of planning would always depend on subjective assessments of the operating personnel on the one hand and of historical investment cycles and disturbance events on the other. Deeper insights are only possible with ASP analysis into the expected financial expenses as well as the ways to obtain a constant work load over a longer term period with equal or better quality.

5.5 Project Prioritization Systems (PPS)

The renewal rates are determined due to asset segments by the analysis of a long-term period by means of ASP as described in Sect. 5.4. A dedicated identification of the necessary projects and measures, however, is not the task of these systems; this is carried out by a project prioritization system (PPS). Basis for such a system is a risk analysis to assess the probability of failure as well as the evaluation of the consequence if a maintenance measure of equipment is not carried out. A risk analysis can be performed in different ways, and examples are presented in detail in Sect. 3.2.6.

The basis for such a system is a project or measurement reservoir where the identified renewal measures are included and which is constantly filled with the measures currently emerging. The occurring identification events of the asset management regarding the projects are essentially given as follows:

- Target structure planning,
- Technological exchange programs,
- Condition assessment,
- Failure rates, and
- External driven changes.

The reservoir is thus a database, list, or something near filled with project proposals. The individual projects for comparative evaluation are covered with attributes that allow prioritization on the basis of the relevant factors. Ideally, these projects are already mapped as project ideas in a system, so they can be imported from the project module of the ERP system and finally transferred with little effort in the budget plan. This again demonstrates the necessary connection between PPS and ERP for transferring data from the system database (technical objects which were identified as renovation projects) in the PPS and back into the project module.

The necessary attributes, which are used within the PPS system for decision making, can be still divided into two categories, in “can do” and “must do” (knockout criterion), with a corresponding classification in the latter category results to a mandatory implementation of project or measure. Possible criteria with attributes are exemplified in Table 5.4.

In addition to the prioritization criterion, the projects must be checked during the second consideration concerning interdependencies (operational feasibility) and possible

Table 5.4 Prioritization criterion

Criteria	Attribute	Knockout criteria
Compliance with standards and laws	Surely complied, interpretable, not complied	Yes
Safety of persons	Excluded, possible, probably	Yes
Quality influences	High, medium, low	No
Probability of outages	High, medium, low	No
Cost risk of damage	High, low	No
Consequential risk	Given, improbably	No
Implementation costs	Rough calculation for each project	No
Implementation time frame	Immediately, in the medium term, variable	Yes

alternative scenarios (structural changes, etc.), and then, an economic analysis has to be performed, unless this is necessary and reasonable to implement within the framework of the infrastructure system.

At the end of prioritization, a ranking list of projects is generated. On the basis of this ranking can be selected, in accordance with the funds provided in the budget, which projects can be implemented in addition to the identified “must do” projects. It is ensured according to fixed the strategy on the basis of ASP analysis that at least enough budget funds are available for the realization of the “must do” projects, as this would be regarded as minimal strategy. In general, such minimum strategy will not be considered as optimal because of lack of sustainability. The order of the prioritization enables the asset management to identify the projects—beyond a funding of the minimal strategy—which costs have the greatest effect in terms of risk minimization and maintenance of asset value by implementing. Besides, the definition of the necessary budget height as a top-down approach also the identification, prioritization, and implementation planning are supported as “bottom-up” approach within the asset management by a system of objective criteria and decision-making patterns. Since both approaches get results through different paths and systems, but based on the same databases and system documentation, the comparison of a detailed project list with the renewal rate for the considered years gives the opportunity to check the plausibility of the project budget planning and the multi-year application. Furthermore, the accuracy of strategy analysis can be verified. An implementation of project prioritization in the same or similar classification or even in the same algorithm like the strategy analysis leads to self-validating results. For this reason, a system separation is necessary to preserve the plausibility—or at least a separation of the methodology.

5.6 Mobile Workforce

Information from the operation, authorized through his responsibility, is for the technical asset management in several respects of great importance. On the one hand, the execution of the strategy, predetermined by the asset management, is documented by feedback of the instructed activity. This is of extremely importance for the confirmation of compliance with laws and standards and thus from risk of liability reasons, but also to the approval authority. The resulting data are used for legal security of the infrastructure company and represent an important part of the data landscape of the infrastructure. Furthermore, the information concerning the condition resp. the need for repair of equipment and assets will be recorded by protocols, received from the operation as well as inspection or maintenance. These data are indispensably required for different analyzes, already described, regarding the identification of technical lifetimes and risks.

The operation department forms together with the management of the network, so to speak, the “eyes and ears” of the technical asset management of the infrastructure assets. The combination of these information areas, supplemented by costs and time required for the activities, is the basis for the analysis cycle presented in Fig. 5.14, which allows the asset management to review and improve continually the maintenance strategies.

The ability to identify areas and assets that show need for action and renewal, for example, due to their maintenance requirements and hence possibly uneconomic operation, is possible with these data, in conjunction with the system documentation.

Applications called "mobile workforce systems" are more and more in use in work organizations to make the resulting data in the operational IT technology available. These systems obtained, with the help of mobile device, information from the central data systems for the operating personnel and can also resubmit information. The data transmission environment of such systems is exemplarily presented in Fig. 5.15.

Mobile service units are the source of such systems, which execute customer services for heating systems or household appliances and had to react quickly to customer requirements from the call centers. With the distribution of digital telephone systems, telephone companies were the first infrastructure companies which had developed such systems and adapted it to their needs. Meanwhile, mobile workforce systems are in use for many utilities to varying degrees and depth. In particular, the required increase in efficiency in case of the work load of the operating personnel and always service reduced assets leads to both an expanded geographical operating range and greater quantity structure of assets, which should be supervised by an assembly fitter. The use of the systems is always mandatory required due to the loss of local knowledge.

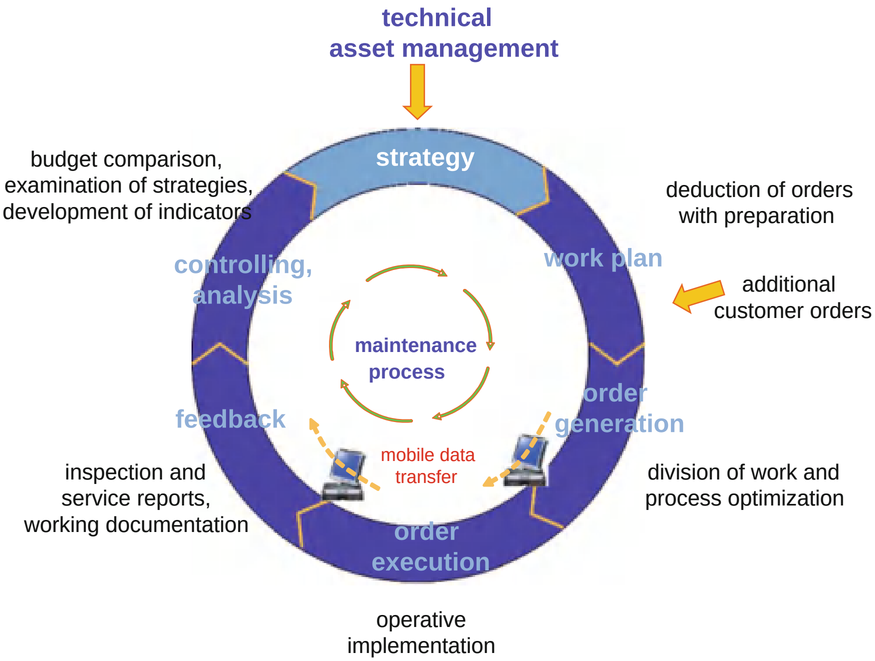

Fig. 5.14 Cycle of review and improvement of strategies based on the operating data

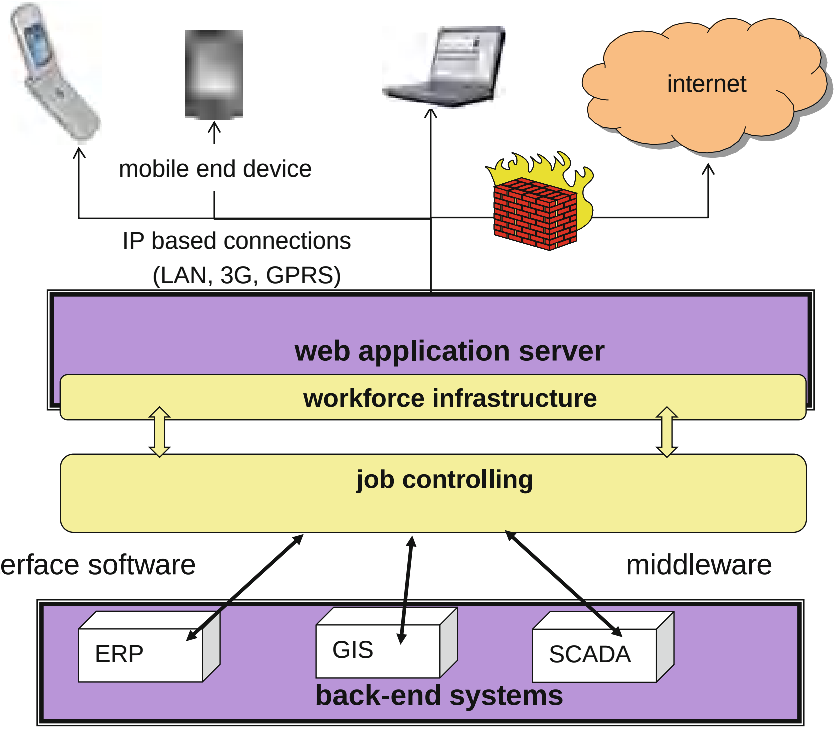

Fig. 5.15 System environment for mobile workforce systems

As in the entire system landscape, the access to the system documentation is on fundamental importance in case of workforce systems, both read and write access for identification of protocols, conditions, and equipment histories. The systems themselves are important for two areas of the infrastructure company. They are a basic management tool for the service provider besides the task of automated strategy implementation, checking, and controlling of the technical asset management. They enable not only the control and submission order but are also the information level for the mobile service units, since at least some of the backend systems will be transferred to mobile devices and thus are available on-site.

The operational plans from the GIS, described in Sect. 5.3, can be seen as a good example. Particularly in the case of outsourcing these tasks, the use of such system is the basis of economic performance by the service provider, as the reference of the work plan to the technical properties of the ERP system enables an individual strategy implementation. In addition, the local knowledge of the mobile service unit is no longer mandatory based on the information from the onboard IT device. Necessarily, this also means a combination of the individual assets, i.e., access or integration of the comprehensive infrastructure of the order into the backend systems of the assigned technical asset management.

5.7 Network Planning and Network Control Systems

Tools for digital calculations of the infrastructure are another important part of the system landscape of the asset management. These tools have in case of all infrastructure systems the function to verify the performance of the system and to identify bottlenecks and target structures for growth or change. This applies for road constructions with traffic management and to avoid congestion as well as for pipe networks to consider the flow volume and for power grids with electrical impedances. The following standard programs for transmission and distribution networks are used for calculation, exemplary for power grid in detail according to Table 5.5. In the following, the consideration for this infrastructure system is therefore shown as an example in detail. A transfer to other systems is in general easily possible.

In the field of gas, water, and district heating networks, load flow programs are used with which the pressure and the flow velocity resp. the temperature in a system can be determined. Some examples of calculation programs are listed [12] in Table 5.6.

The execution of network calculations requires a digitized mathematical view of the infrastructure system. The knowledge of each equipment is only interesting for the identification of the electrical parameters of this equipment. On a simple level, an electrical supply network consists of substations or switchgears that are connected by line connections (cable or overhead line). In the case of the digital calculation, the network is

Table 5.5 Standard calculation programs for electrical systems

Program	Description
Short-circuit current	Calculation of short-circuit currents in case of different faults for the rating of assets, such as selection of switchgear and substations
Load flow	Current and voltage distribution in consideration of a predetermined power flow, such as determination of the cross section of cable connections
Reliability	Calculation of the reliability of supply under consideration of failure rates of equipment
Protection	Setting of the protection to interrupt the short-circuit currents, response time, and tripping current
Harmonics	Influence of harmonics by power electronics, use of filters to keep the voltage quality

Table 5.6 Standard calculations for water, gas, and district heating networks

Network	Calculation
Water	Flow rate, water pressure, time-dependent consumer profiles, cross section, fire water plans (pressure, fire water quantity)
Gas	Flow rate, gas pressure, cross section, consumer profiles
District heat	Flow rate, district heating pressure, cross section, consumer profiles, temperature and energy losses, flow, and return line

represented by nodes with many connections and meshes, which are closed by these connections. These connections are characterized by electrical parameters, mainly the electrical impedances, the power capacity and the short-circuit withstand capability in case of a failure. These parameters are given by the manufacturer's specifications and guarantees, as far as the limits of the equipment for switching and controlling are concerned. Here, the equipment with the lowest power threshold for the performance of the entire node represents the so-called bottleneck.

The power calculation tool forms a data set with the characteristic values of assets, which is the mathematical image of the network and which is the basis for all mathematical analysis and operations. This record is used as the basis for two tasks:

- Network structure planning
  The infrastructure system is subject to constant change, customers will be reconnected, industrial sites are shifting, the energy supply changes from central to distributed generation, etc. The network structure planning reproduces such changes and pursues a target network development, which represents a long-term structure due to the defined boundary conditions and assumptions given by the asset management (load growth, risk acceptance, operating reserves, etc.). This structure planning is finally implemented by the development and renovation projects.

  The network structure planning relies on an updated annually "original record," which provides the solid basis and an obvious initial point for the creative planning process. By a pure offline process, the standard calculations (load flow and short-circuit calculations) are performed by planning variants and the optimal target network is determined for each network region. The existing network with the analysis of possible and necessary renovations and developments is within this target network. These are, for example, new buildings on the basis of external development information that can also be based on general economic development on specific customer projects. A detailed description of the individual steps is specified in detail in Sect. 2.1.7. In relation to the processing of a network development strategy in light of the required boundary conditions, the network structure planning is a pure asset management task, as especially in the planning phase, the course for the quality and also the operating costs of the infrastructure system are provided. Planning systems are now well established and widely available from the major manufacturers and specialist suppliers in the market, for example, [12].
- Network control systems (SCADA)
  The complex operating processes of infrastructure systems are now being conducted through the use of power system control and remote control devices by control center, in the electric network through network control centers. This guarantees a quick response time in case of failures and is also the only way to undergo these safety-related infrastructure a permanent and safe monitoring of the geographically distributed networks. A detailed description of such network control systems can be found, e.g., in [5].

The tasks of the “supervisory control and data acquisition” (SCADA) are assigned to the network operation, but they provide the safe operation of the infrastructure system, but also the data acquisition, and thus the information input with regard to load data, failure rates, and equipment availability. These data, in turn, are important input data for the strategies of the asset management. The SCADA system is an online system; it gets its information in near real time from the sensors in the asset and has direct access via remote control on the switching and control devices in the network. The basis of the system is again the aforementioned data record to perform load flow calculations, short-circuit calculations, and operational monitoring. However, this needs to be adjusted constantly for asset operation because each construction project and any equipment change lead directly to a change of the boundary value and network characteristics. This must immediately be added (commissioning) in the operating system to avoid miscalculations and thus resultant prevent human errors.

For the above-described tasks (network structure planning and network control tasks), the same basic data sets are to be compiled with the difference of the permanent update in the network control and the creation of the raw data record in the structure planning. It is created on the basis of assets from the system database and is automated in the optimal case. There are two possibilities depending on the extent of the systems.

If the ERP resp. the GIS system is able to calculate the electrical equivalent values from the technical parameters and limits, this is done directly in these systems. The electrical characteristics are transferred into the calculation system, and here, the basic data set is created by using an intelligent interface that is able to allocate the assets of the network structure in the right place with the right combination. Changes need to be added into the ERP for the network control system in a timely manner to allow a partial update of the operating record.

In case of the second possibility, the related parameters are directly passed into the calculation tool and are converted into corresponding electrical equivalent values, in which these are already in the correct logical network structure. Also in this case, a timely update of changes is required and possible. It is important in this context that both network planning and network operations use the same database in order to avoid a divergence of “theoretical” planning and “real” operating and to maintain the discussion skills of operating and planning areas for network structure development. The creation of the record and the maintenance of the limits/constraints is the responsibility of the asset manager.

The planning systems are not usually associated with direct interfaces to the asset database; the records are generated by transition systems. An information transport is in the reverse direction from the SCADA systems by normally decoupled systems to ensure the self-sufficient and safe operation of these systems. Important information for asset management includes:

- Load data of equipment,
- Load curve and simultaneity factor,
- Power sources and data,
- Outages, location, and duration,
- Reaction time of equipment,
- Availability of maintenance tasks,
- Operating parameters (current, voltage, etc.), and
- External influences (construction sites, etc.).

This information is considered in the network development strategy and also in the definition and determination of planning assumptions to implement a mirrored operating risk structure in the target network planning related to the operating conditions. If the risk is too high, either the outage costs predominates the savings of investment or in any network action, temporary measures are required to preserve the operability. If the network is overdesigned, the specific network costs are too high and the investment funds had not been optimally allocated. Such bad planning is hardly to correct over decades due to the given long lasting lifetime of infrastructure. Thus, these data represent one of the most important basic information to estimate the third strategy area of the technical asset management—the network development—besides maintenance and renewal. The data itself will be archived and are available in the SCADA systems and in subordinate or parallel databases, such as the fault database. The special feature of these operating data is that they cannot virtually be recorded nowhere and thus can remain free of redundancy in these systems in their entirety. Only the exact outage assignment to further in-service equipment shall be provided in the maintenance module (equipment history), if it is valuable equipment.

5.8 Conclusion

The importance of documentation and data systems is presented in this chapter. The need to collect and to process only the “right” data in the models is shown in particular in view of the cost of data acquisition, storage, and processing. The asset management—in its modern form in the development and implementation of efficient system operating strategies—needs a system landscape as a basis to perform IT support data-based analysis and to draw the necessary conclusions. The various individual programs play an important role in their different special functions. They provide the unique working basis for asset management and also for the investment service due to their networking and the associated principles of redundancy-free data collection and maintenance on the one hand and

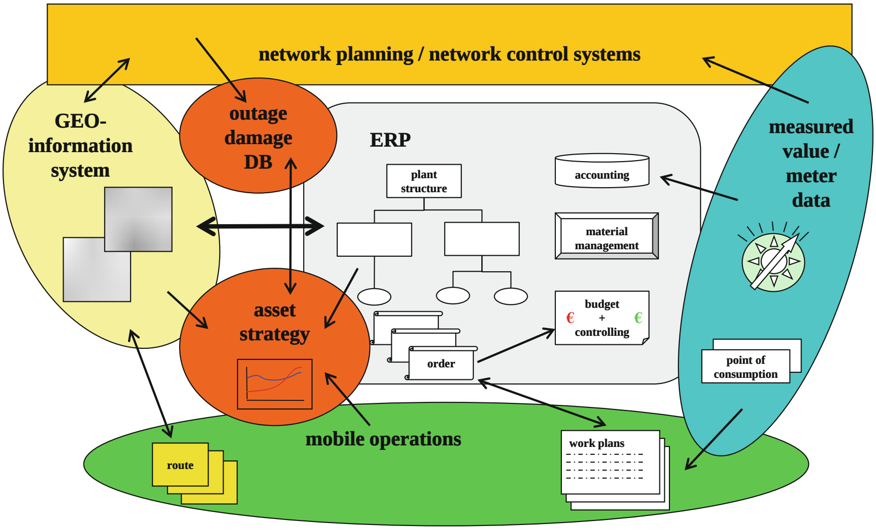

Fig. 5.16 The data system environment at a glance

the formation and processing of consistent data sets in the individual programs on the other hand. The entire system landscape and the interaction of the individual programs are illustrated in summary in Fig. 5.16.

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Glossary

Abbreviations of National and International Organizations

BSI British Standard Institution (Britisches Institut für Standardisierung)

CENELEC Comité Européen de Normalisation Electrotechnique; European Committee for Electrotechnical Standardization (Europäisches Komitee für elektrotechnische Normung)

CIGRE Conférence Internationale des Grand Réseaux Électriques à haute tension; International Council on Large Electric Systems (Internationale Hochspannungskonferenz)

DIN German Institute for Standardization (Deutsches Institut für Normung)

DKE German Commission for Electrical, Electronic & Information Technologies (Deutsche Kommission Elektrotechnik Elektronik Informationstechnik)

DVGW German Technical and Scientific Association for Gas and Water (Deutscher Verein des Gas- und Wasserfaches)

EnWG Energy Economy Act (Energiewirtschaftsgesetzt)

FNN Forum Network Technology/Network Operation (Forum Netztechnik/Netzbetrieb)

IEC International Electrotechnical Commission (Internationale Elektrotechnische Kommission)

ISO International Organization for Standardization (Internationale Organisation für Normung)

PAS Publicly Available Specification (Öffentlich Verfügbare Spezifikation)

VDE Association for Electrical, Electronic & Information Technologies, Germany (Verband der Elektrotechnik Elektronik Informationstechnik)

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