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Asset Management for Infrastructure Systems

Energy and Water

 Springer

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ISBN 978-3-319-17878-3 ISBN 978-3-319-17879-0 (eBook)
DOI 10.1007/978-3-319-17879-0

Library of Congress Control Number: 2015938312

Springer Cham Heidelberg New York Dordrecht London
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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 “Asset Management” 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 “Electrical Power Systems” 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.

The authors are grateful to the following colleagues who helped in the translation: Y. Tsimberg, R. Wakefield, A. Krontiris, C. Balzer.

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
December 2014

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Contents

1	Introduction	1
1.1	Basis of the Asset Management	1
1.2	Development of the Investment Management During the Last Decade in Europe	4
1.3	Motivation for an Investment Management.	6
1.3.1	Legal Issues	6
1.3.2	Impact of Regulation on Infrastructure Companies	8
1.4	Challenges of Transmission and Distribution System Operators (TSO and DSO).	9
1.5	Activities of the Asset Management	10
1.6	Conclusion.	14
	References.	14
2	Tasks of the Asset Management	15
2.1	Development of Strategies	15
2.1.1	Overview of Maintenance Strategies	17
2.1.2	RCM Strategy	24
2.1.3	Maintenance by Fuzzy Logic	43
2.1.4	FMEA Method	57
2.1.5	Aging Behavior of Equipment	70
2.1.6	Lifetime of Electrical Equipment.	83
2.1.7	Strategy for System Development	85
2.1.8	Renewal Strategy	103
2.1.9	Short- and Long-Term Considerations	110
2.1.10	Project Development and Assignment	111
2.2	Developing and Securing of Standards.	113
2.2.1	Intern Regulations.	113
2.2.2	National and International Standardization Processes	114
2.2.3	Standard for Maintenance of Electrical Systems	116

2.3	Securing the Resources	119
2.3.1	Material and Service	119
2.3.2	Operating Staff	122
2.3.3	Reserve and Special Situations	123
2.4	Conclusion.	123
	References.	124
3	Control Functions.	127
3.1	Economic Control Functions	127
3.1.1	Budget Planning and Structure	128
3.1.2	Budget Controlling	135
3.1.3	Calculation of Economics	140
3.2	Technical Control Functions.	158
3.2.1	Outage Statistics.	158
3.2.2	Data Files of Outages	162
3.2.3	Assessment of the Network Asset Value	163
3.2.4	Assessment of Condition	167
3.2.5	Monitoring/Diagnostic.	169
3.2.6	Risk Analyses	177
3.3	Indicators.	208
3.3.1	Target Values of the Participating Groups (Stake Holders).	209
3.3.2	Selection of Indicators in Case of a Maintenance Measure.	211
3.3.3	Benchmarking	213
3.4	Asset Simulation.	216
3.4.1	Development of a Long-Term Strategy	216
3.4.2	Input Data	221
3.4.3	Application of Dynamic Simulation.	222
3.4.4	Simulation: Condition Assessment	224
3.4.5	Simulation: Statistical Failure Rate	231
3.4.6	Conclusion Asset Simulation	235
3.5	Optimization of Maintenance	235
3.5.1	Game Theory	236
3.5.2	Knapsack Problem	245
3.6	Statistic	249
3.6.1	Probability	250
3.6.2	Characteristics of Probability Distributions	250
3.6.3	Equicontinuous Distribution	260
3.6.4	Discrete Random Variable	271
3.6.5	Best Fit Calculation	275
3.7	Conclusion.	280
	References.	281

4	Integration into the Business Organization	285
4.1	Functional Allocation in the Area of Asset Management	286
4.2	The Role Model of the Management of Infrastructures	287
4.3	Corporate Organization	292
4.3.1	Decision Criteria	292
4.3.2	Service Provider Model	294
4.3.3	Network Manager Model	295
4.3.4	Asset Manager Model	295
4.3.5	Asset Owner Model	296
4.4	Influence of the Infrastructure Systems on the Organization	297
4.4.1	Economies of Scale of Systems	297
4.4.2	Effect of System Homogeneity of Infrastructure	300
4.5	Conclusion	300
	References	301
5	System Landscape in the Area of Asset Management	303
5.1	Asset Management Data	303
5.2	Enterprise Resource Planning (ERP Systems)	305
5.2.1	Asset Documentation (AD)	308
5.2.2	Finance Module	311
5.2.3	Operation and Maintenance Module	313
5.2.4	Project Module	314
5.2.5	Procurement and Material Module	315
5.2.6	Staff Module	318
5.3	Geographic Information Systems (GIS)	318
5.4	Asset Strategy Planning Systems (ASP)	323
5.5	Project Prioritization Systems (PPS)	328
5.6	Mobile Workforce	330
5.7	Network Planning and Network Control Systems	333
5.8	Conclusion	336
	References	337
	Erratum to: Control Functions	E1
	Glossary	339

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.

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 € prior 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.

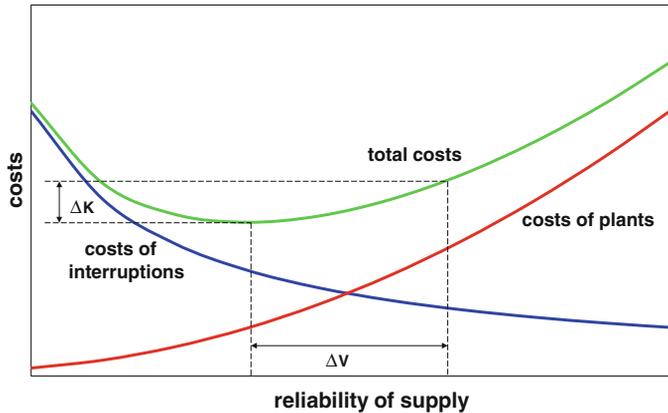


Fig. 1.1 Evaluation of the optimum of costs and reliability of supply

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 exemplarily 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.

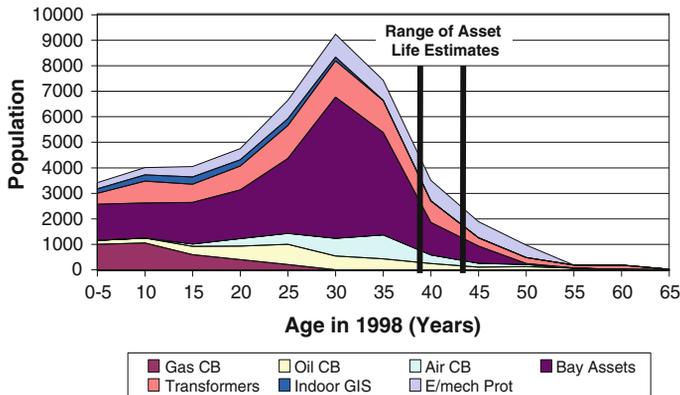


Fig. 1.2 Number of assets and age distribution (status 1998) [9]

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 SF₆-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.

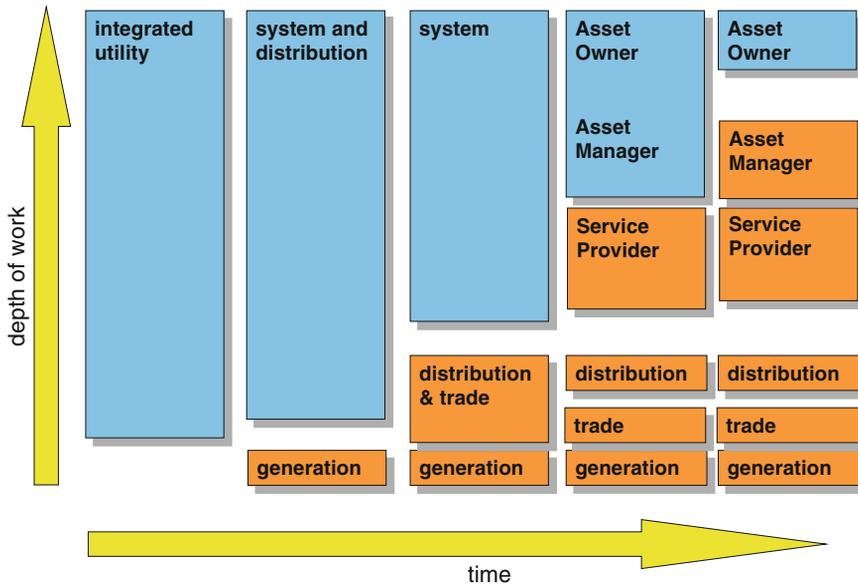


Fig. 1.3 Temporal evolution of utilities

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:

$$EO_t = KA_{\text{dnb},t} + (KA_{\text{vnb},0} + (1 - V_t) \cdot KA_{\text{b},0}) \cdot \left(\frac{VPI_t}{VPI_0} - PF_t \right) \cdot EF_t + Q_t \quad (1.1)$$

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

EO_t	revenue caps of system charges
$KA_{\text{dnb},t}$	permanent non-influenceable costs
$KA_{\text{dnb},0}$	temporary non-influenceable costs
V_t	factor for the reduction of inefficiencies
$KA_{\text{b},0}$	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_i).

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

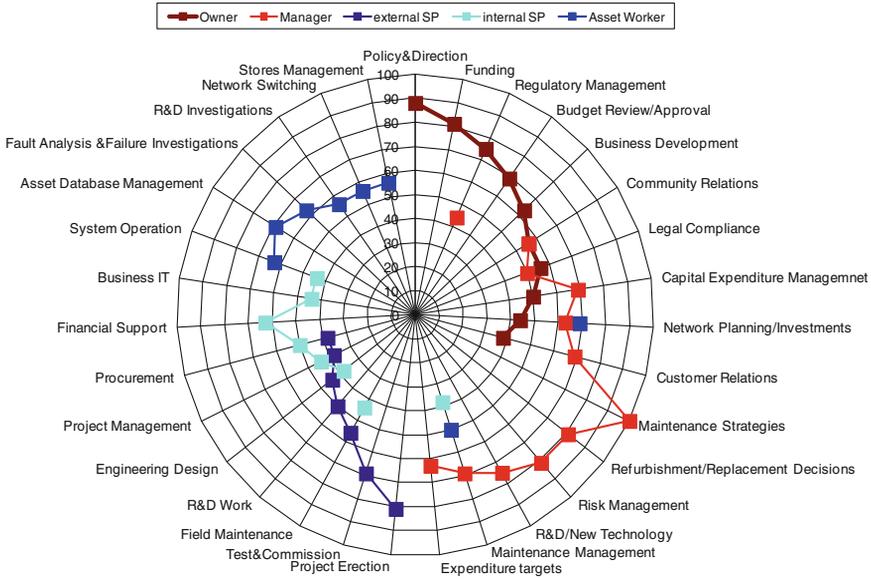


Fig. 1.4 Divisions of responsibilities in the area of asset management [4]

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.

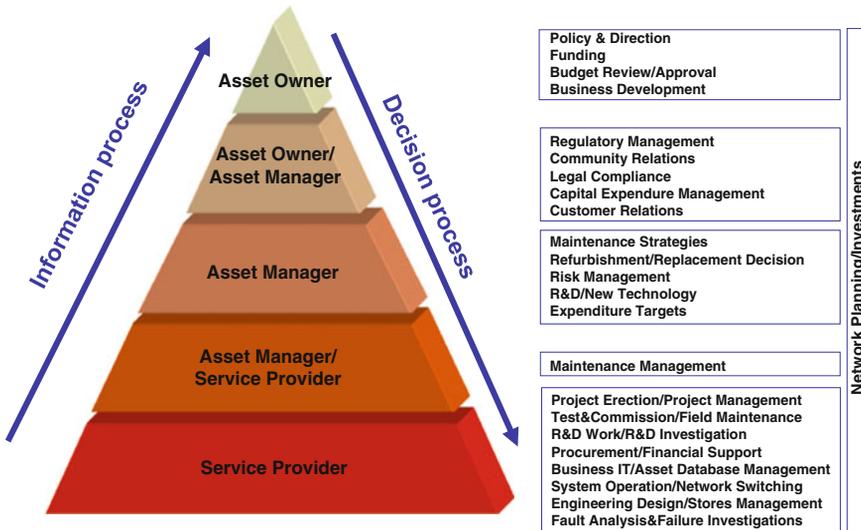


Fig. 1.5 Pyramid of the asset management process [1]

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 maintain 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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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.

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 disassembled 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