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Transmission Asset Risk Management

Working Group C1.16

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EXECUTIVE SUMMARY

International developments in asset management resulted in new standards for asset management which emphasize risk management as one of the key processes for asset management decision making. Within Cigré there was a need to understand these developments in relation to asset management in electricity transmission systems and the related major risk for the electricity transmission companies: asset aging.

While the working group recognizes the facts that Asset Management comprises the management of all risks for the business value arising from the assets and their environment and the fact that risk management can be applied for informed decision making on any topic, the focus of this Technical Brochure is limited to improving insight into the application of asset management in electricity transmission companies, quantifying the risks due to an ageing asset base and identifying methodologies for assessing optional asset management strategies for how these risks can be managed.

Risk management has been implemented in many in Electricity Transmission Companies as a key process for asset management decision making. Asset management decision making can be found in different functions in the organization. To make a thorough analysis and understanding possible a division is commonly used to describe organizational issues, namely:

- Strategic asset management
- Tactical asset management
- Operational asset management

The role of an asset manager is to link the notions of business risk and asset risk together to make the right decisions for the assets and the company as a whole. Risk management consists of several steps: risk assessment, risk treatment and risk monitoring and review. These steps are organized in an improvement cycle namely: the risk management cycle. The asset manager uses risk assessment matrices to derive the risk criteria for his decisions. Risk indicators are developed to monitor the electricity transmission assets for risks.

Fundamental to asset management is the concept of continual improvement. The overriding process of the asset manager is continual improvement of his quantitative asset management decision making according to the risk management cycle for asset management. The basis for strategic and operational asset management is continual improvement of the criteria and indicators for risk assessment.

One of the common issues that asset managers face is the "end of life" issue. Uncertainty is inherent to the definition of end of life of an asset. A probabilistic forecasting approach represents the range of possibilities in future asset failures and can simulate alternative scenarios useful for a TSO with regard to budgets over a planning period. Use of mathematical models in asset management for TSO can permit the introduction of more advanced financial method such as the value at risk method. The use of advanced models may contribute to more innovation and a more effective asset management process. Co-operation between asset managers and asset experts to use common models and methods for collecting useful data for the "end-of life" issue is encouraged.

Contents

Appendices:

1 INTRODUCTION

In December 2006 the Cigré Technical Brochure 309 on Asset Management of Transmission Systems and Associated Cigré Activities was published. One the recommendations was to further develop risk management and share experiences in the application of risk management to decision making processes of the electricity transmission companies.

International developments in asset management resulted in new standards for asset management which emphasize risk management as one of the key processes for asset management decision making. The development of ISO-standards on risk management demonstrates the international trend that risk management is becoming more and more a formalized process for informed decision making in businesses all over the world.

Within Cigré there was a need to understand these developments in relation to asset management in electricity transmission systems and the related major risk for the electricity transmission companies: asset aging. Therefore a new Working Group was set up in December 2006 which has completed the work which is reported in this Technical Brochure. The scope and objectives for this working group are described in Appendix I.

1.1 Definition of Asset Management

This Technical Brochure builds on asset management concepts derived from Technical Brochure 309. In TB 309 the following definitions of Asset management are given.

Asset Management of a Transmission and Distribution Business operating in an electricity market involves the centralization of key decision making in the network business to maximize long term profits whilst delivering high service levels with acceptable and manageable risks.

Asset Management activities and practices attempt to optimally manage assets and their associated performance, risks and expenditures over their life cycle for the purpose of achieving the required level of quality of service in the most cost effective manner.

In this sense Asset Management is regarded as a total business concept that comprises the management of risks for the business value arising from the asset base itself (e.g. aging of the assets) and the risks arising from (in-)adequate response to changes of the environment (e.g. load growth). The holistic Asset Management business model implies that asset management is more than maintenance management of specific types of assets, it comprises the complete asset base and all risks that can impact on the business value. Therefore Asset Management includes maintenance management aspects as well as system planning aspects.

1.2 Focus of the Technical Brochure

While the working group recognizes the facts that Asset Management comprises the management of all risks for the business value arising from the assets and their environment and the fact that risk management can be applied for informed decision making on any topic, the focus of this Technical Brochure is limited to improving insight into the application of asset management in electricity transmission companies, quantifying the risks due to an ageing asset base and identifying methodologies for assessing optional asset management strategies for how these risks can be managed. This is in alignment with the Terms of Reference as given by the Technical Committee.

Risk management is used to help an organization make informed decisions. Asset management decision making can be found in different functions in the organization. To make a thorough analysis and understanding possible a division is commonly used to describe organizational issues, namely:

- Strategic asset management
- Tactical asset management
- Operational asset management

These categories of asset management are illustrated in the cases contributed by participating companies and are fully described in the appendices. Aspects of these cases are used in the main text to clarify the generic risk management model.

In the Terms of Reference several topics related to Transmission Asset Risk Management were mentioned to be part of the scope of this Technical Brochure. These topics are discussed in this Brochure under these three levels of decision making.

1.3 Contents of this Technical Brochure

The following chapters describe risk management and examples of the way it is applied by electricity transmission companies. In chapter 2 a summary of risk management is given. In chapter 3 a model for the asset management decision making process within an Electricity Transmission Company is proposed. The model proposes three levels of decision making, which are further treated in the following chapters. In chapter 4 Strategic decision making is explained and which processes are recognized by the participating electricity transmission companies to belong to this level. In chapter 5 Operational decision making is explained along with processes for the collection of data or asset condition assessments that are involved. Chapter 6 combines the processes described in the previous chapters. This involves processes in which information from strategic and operational level are combined to take tactical decisions. Chapter 7 is dedicated to one of the key risks for asset managers: the asset replacement issue due to an aging asset base. In chapter 8 Conclusions and Recommendations for further investigations are given.

2 SUMMARY OF RISK MANAGEMENT

In this chapter a summary of risk management is given. This information is needed to understand the generic decision making model that is introduced in the following chapters.

The risk management concept is used to identify and assess the consequences of events in terms of the key business values of companies and to compare the corresponding risks in order to prioritize risk treatment measures. In the ideal situation, all risks are expressed in financial terms so that return on risk treatment costs becomes a discriminating parameter for comparing risk treatment options. Asset risk management comprises all risks from capacity shortage to asset failure.

2.1 Risk analysis and risk management

Risk is defined as the product of the probability of an event and its consequences. [1] The term risk is generally used only when there is at least the possibility of negative consequences. In some situations, risk also arises from the possibility of a deviation from the expected outcome or event.

In this Technical Brochure the term risk includes several other factors beyond the reliability of the power system. This Technical Brochure explains the link between the management of business risks by electricity transmission companies and the risk management of the power system and the physical assets involved.

The management of risk involves the analysis of events for a system (organization, network etc.) that may have a negative impact. And it involves the design, decision making, execution of the measures to treat the risk and the evaluation of the effectiveness of the measures.

Utilizing risk management on a regular basis i.e. to identify and assess the risks helps a company or organization to account for possible future events with a negative impact on the organization and its environment. It creates awareness of risks and the possibility to evaluate the actions or decisions to be taken to treat i.e. minimize or mitigate the risks.

Risk analysis is applied for decision support; for example to choose between alternative measures to be taken with regard to maintenance of assets or to provide support in go/no go decisions, for example whether to invest now or a few years later in network reinforcement in a specific area of load growth.

Risk analysis is also applied to enhance control of risks. A risk analysis made explicitly has the advantage that risk information can be shared and discussed between experts and managers. It provides insight into the largest unknown factors and forms a basis to take action (risk management).

Asset managers use risk analysis to quantify and support arguments that underpin necessary budget levels for maintenance, reinvestment etc. Management of the risk for the company that derives from the network assets is the main task of the asset manager in electricity transmission companies.

Risk analysis can be applied to several topics. For example on projects: the timely and cost effective erection of a substation of sufficient quality involves many risks varying from the time – consuming permitting procedures from authorities, to the variable and long delivery times from equipment manufacturers that are part of a sellers market. Risk analysis is also applied to processes, for example, network operation and the development of emergency restoration plans. Another well known example is the Failure Mode Effects and Criticality Analysis used on specific assets and asset groups to decide on maintenance measures (Reliability Centered Maintenance).

2.1.1 RISK MANAGEMENT DEFINITIONS

The standard ISO/IEC 73 [1] presents definitions of generic terms involved in risk management. The risk management process is presented as a set of different subprocesses. Risk management is a set of coordinated activities to direct and control an organization with regard to risk. Risk management includes risk assessment, risk treatment, risk acceptance and risk communication. Risk evaluation is the process used to assign to the probability and consequences of a risk. (see Figure 2.1-1)

Risk management			
	Risk assessment		
		Risk analysis	
			Source identification
			Risk estimation
		Risk evaluation	
	Risk treatment		
		Risk avoidance	
		Risk optimization	
		Risk transfer	
		Risk retention	
	Risk acceptance		
	Risk communication		

Figure 2.1-1 Risk management – Sub process relationships – From [1] (modified by [50])

2.1.2 ESTABLISHING THE CONTEXT AND RISK CRITERIA

Like in any other survey or analysis the objective needs to be well defined in a risk analysis. But in many cases, when risks on a certain topic are to be analyzed, experts on the topic are invited to brainstorm sessions facilitated by a risk manager. When the objective and scope of the topic under survey is not clearly defined these sessions tend to go out of control. Therefore, the scope of and the reason to perform the risk analysis needs to be defined. The scope may consist of a specific asset, a group of assets of the same type, a subsystem (regional electricity network) and the reason to perform the risk analysis may be a deviation from a norm or limit-value for performance or condition or many other possible topics.

For a risk analysis the unwanted top events need to be defined, for example events with significant negative impact on the company as a whole and its financial position, events which may impact the performance or security of supply, or the quality of service or public or personnel safety and the environment. Many companies define their key business values and the range of potential impacts from these top events can be directly expressed in terms of the key business values.

2.1.3 IDENTIFYING, ANALYZING AND EVALUATING RISKS

A risk is quantity associated with an unwanted event that may or may not occur and which may lead to a failure to get the desired output. The output can be defined in terms of financial performance or performance on security of supply, quality of service, safety & environment or any other key performance measure in a company. Risk is the product of the probability of an event and its consequences. Characteristic for risk is that uncertainty is involved.

Risk = f(probability, consequence)

Figure 2.1-2 Definition of Risk

Risk assessment attempts to answer the following fundamental questions [3]:

1. What can happen and why?
2. What are the consequences?
3. How likely are they to occur?
4. Is the level of risk acceptable or does it require further treatment?

A risk description can not be expressed as a question or as one word. It needs to be as specific as possible. In Figure 2.1-3 and Figure 2.1-4 two examples of a risk description are given. A risk description should be as systematic and complete as possible and regarded from different perspectives. In addition to technical risks, which are the primary concern of this brochure, financial business risks can also be described. Internal business risks, for example a lack of up to date procedures or external risks, like the relationship of the business with the neighboring citizens and municipalities can be documented.

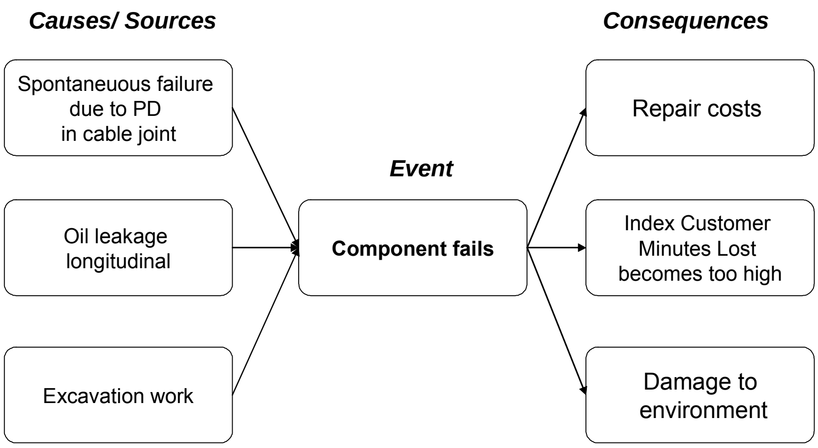


Figure 2.1-3 Example of risk description for a component failure

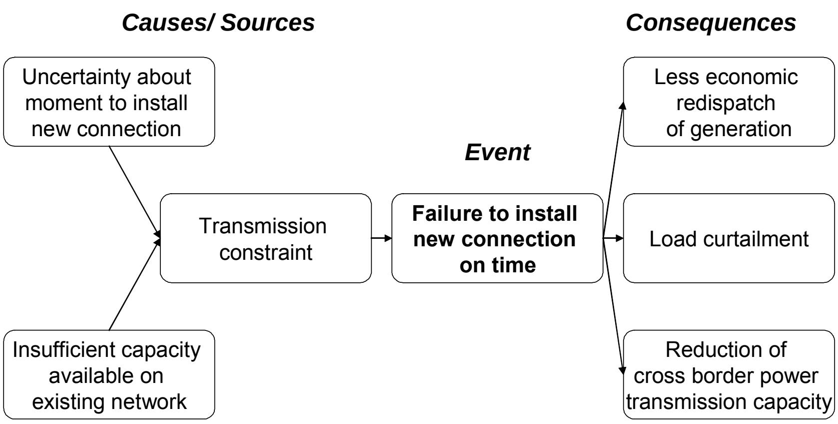


Figure 2.1-4 Example of risk description for a project delay

When the risks have been identified and described, the next step is to assess the severity of the consequences to be able to select the most important risks for risk treatment. To enhance objectivity in risk estimation, the probability and the consequence are estimated separately and later combined to form an assessment of the risk. Estimation can be discriminated into qualitative estimation and/or quantitative estimation. Qualitative estimation means determination of the order of magnitude of the consequence or probability or division of the consequences or probabilities into categories. Quantitative estimation means using a calculated or approximate value for the probability and the consequence.

When probability and consequence categories are estimated the risk can be assessed by using a two dimensional risk assessment matrix as illustrated in Figure 2.1-5. This matrix shows, which risks have high priority for treatment, which risks have medium priority etc..

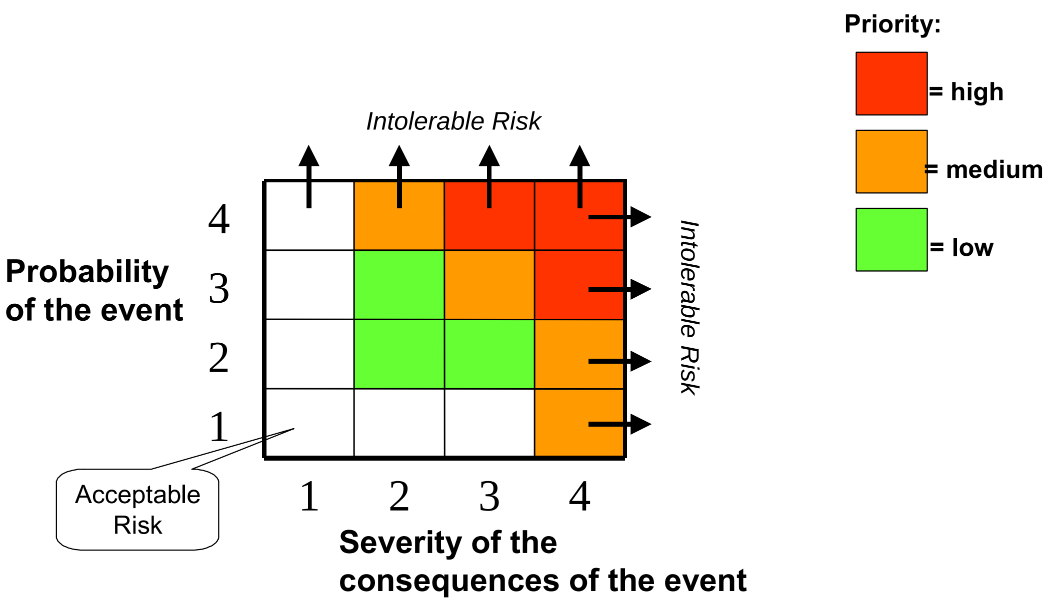


Figure 2.1-5 Risk assessment matrix

2.1.4 Risk Treatment

Asset Managers in electricity transmission companies need to determine the possible options for risk treatment, which includes the decision to postpone treatment. Asset Management then uses risk analysis to enable and justify risk management decisions as follows.

First the potential optional treatment measures need to be identified, for example wait and accept the current risks, take action by investing in maintenance procedures, or refurbishment or ultimately replacement of the assets. Risks can be treated or modified, by such technical solutions, but also by improved operating procedures. As illustrated in Figure 2.1-6 preventive measures inhibit the causes or source that might lead to the unwanted event, while corrective measures mitigate the consequences of the event.

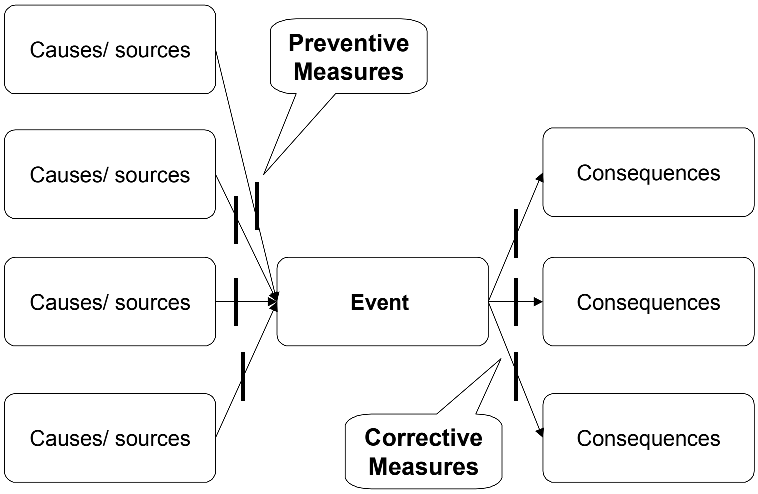


Figure 2.1-6 Preventive and corrective measures depicted in risk description

The company may decide to accept the consequences of a risk. This is called risk retention. The company may decide to retain the risk or to transfer the risk to another party. For example the company may transfer the risk to an insurance company or to a supplier of equipment. Risk transfer will not take the risk away but it will reduce the risk to a party, because the other party is more capable to bear or manage the risk. Risk transfer will increase operational expenditures. There is always a certain level of risk acceptance where risk treatment is impossible or too expensive.

As an example, consider the possibility that your home burns down, causing you financial trouble. See Figure 2.1-7. You can do nothing and accept the full financial impact if it should occur, or you can invest in some risk reduction treatments, such as smoke detectors or an automatic sprinkler system. Obviously the costs for these two treatment alternatives are quite different. [54]

To decide on the alternatives of risk treatment measures the concept of return on risk reduction is introduced [55]. To determine the return on risk reduction first the reduction of risk caused by the alternative risk treatment measures needs to be estimated. As illustrated in Figure 2.1-8.

Technical measures	**Procedural measures**
Use fireproof materials	Emergency evacuation plan
Preventive measures	**Corrective measures**
No open fire in the house No candles No smoking	Install fire extinguisher Install smoke alarm
Risk retention	**Risk transfer**
-	Get fire-insurance
Risk acceptance	
You need a home to live so you accept a certain risk	

Figure 2.1-7 Example of risk treatment for the possibility that your home burns down, causing you financial trouble

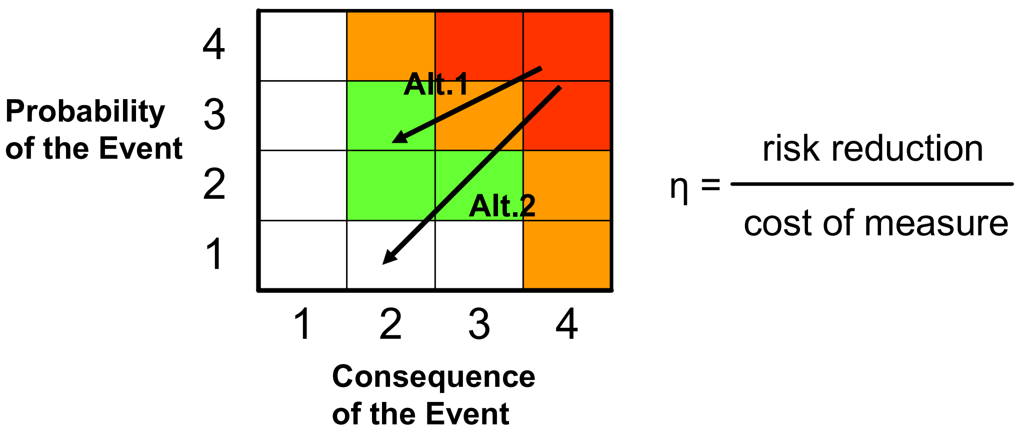


Figure 2.1-8 Risk reduction of two alternative risk treatment measures

From the example it can be seen that alternative 2 has the largest risk reduction. Risk reduction may be expressed quantitatively if possible in financial units or qualitatively by risk points. The return on risk reduction of a risk treatment measure is then given by the formula: η = risk reduction / cost of measure.

The return on risk reduction is used to evaluate alternatives, but also to prioritize risk treatment measures when the budget is limited.

2.1.5 Monitoring and review

Risk Management is a process that should be continually monitored, reviewed and improved. In the Risk Management Cycle risks are identified, evaluated and treated. The core of the process is the identification and assessment of risks and the decision to accept or reduce the risk.

- the analysis and assessment of the risks within and for the infrastructure along the business value model
- the decision to accept or reduce the risk
- the design and planning of the risk-reducing measures e.g. adaptation of maintenance plans, initiating investments in replacement or refurbishment
- the execution of the risk reducing measures e.g. execution of an asset replacement project

After the decision is made, a new situation exists and the asset manager continues analyzing the risks in the adapted infrastructure. This representation is in accordance with the Plan-Do-Check-Act cycle widely diffused through quality standards applied by most utility companies nowadays. In this way, grid operators use the risk management process as an improvement cycle [4] and [53]. ISO standard 31000 (draft standard) [2] proposes a dynamic representation of the risk management process (see Figure 2.1-9).

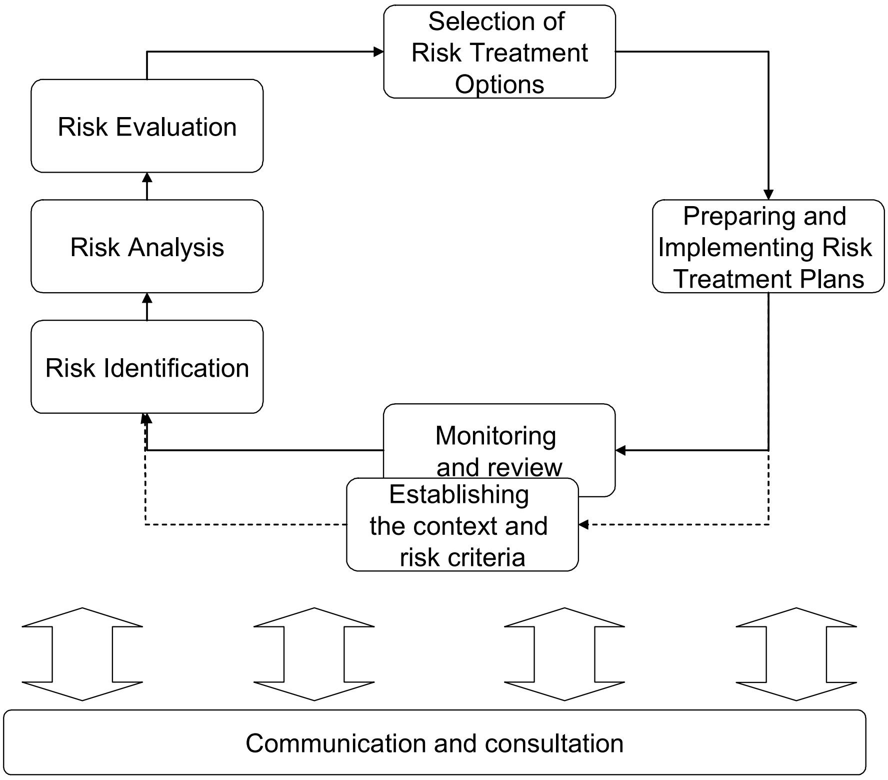


Figure 2.1-9 Risk Management Cycle see also [2]

2.2 Risk attitude

To get data for risk analysis of electricity transmission equipment requires effort. The probability of asset failure may sometimes be derived from historic data within the company but due to the small populations it is difficult to get reliable results (discussed in more detail in 5.1). To perform analysis on large populations international cooperation of electricity transmission companies is necessary and some results can be found in Cigré publications. [41]

In the absence of data and analysis electricity transmission companies may rely on the opinion of their experts giving estimates on residual life of aged assets. In expert opinions two aspects need to be considered: the accuracy of estimated value and its information value. For example the estimate that a specific transformer can be kept in operation for the next 10 years within a range of 8 to 12 years has more information value than an estimate of 10 years with no range at all. Experts should always be asked to give three estimates: upper limit, lower limit and average.

Estimating consequences of a risk is generally easier. From business values and key performance indicators it is generally clear what measures the company considers to be important. The financial records of the company, historic data on unplanned outage costs, historic data on the costs of safety incidents etc. can be used to determine estimates for consequential costs and which consequences are acceptable and which are not for the company.

The decision to accept a certain level of risk depends on the risk attitudes of people or companies. The risk attitude may be neutral, risk avoiding, or risk seeking. Risk attitude is different from individual to individual and from company to company. It is determined by: financial position, reputation, possible influence on risks (or the illusion that this is possible), environment etc. The risk assessment matrix shows the risk attitude of a company. One of the key aspects of risk management for asset managers is the question of how much to invest in order to reduce a risk. This is discussed further in section 6.5.

2.3 Publications on Risk Management related to Electricity Industry

2.3.1 ISO STANDARDS ON RISK MANAGEMENT

ISO 31000:2009 [2] (formerly ISO 25700) provides principles and generic guidelines on risk management. The standard can be used by any public, private or community enterprise, association, group or individual. Therefore, ISO 31000:2009 is not specific to any industry or sector. Other standards related to Risk Management:

- ISO Guide 73 Risk Management Vocabulary [1]
- Draft ISO 31010 Risk Management - Risk Assessment Techniques [3]

2.3.2 CIGRÉ PUBLICATIONS

A good introduction to risk management is given in Cigré Technical Brochure 248: Guide on Economics of Transformer Management [43]. In TB248 risk is defined as: the dangers an unwanted event represents on humans, environment and economical values, or the expected loss of utility. Risk management must involve risk analysis. To be able to make decisions, risk perception and acceptability must be determined, the risk profile or the degree of risk aversion, and the factors to be evaluated in the analysis must be found.

Perception of risk differs from objective measures and introduces an element of distorting, or politicizing, risk-management decisions. This is not the same as saying there is a true risk perception that management does not perceive, based on a "true" calculated risk without uncertainties. Our subjective judgements, our beliefs and our societal bias against unwanted events with a severe consequence, but a very low probability, may influence, or distort, our understanding of the risk analysis.

Our risk profile, i.e. how risk averse we are, may also substantially influence our decisions. We tend to avoid (insure) the low probable, high risk, events that may easily get us into bankruptcy or severe financial problems. In our context here, the identification of these low probability events with severe consequences is paramount in a risk-management approach.

Risk acceptance vs. risk aversion, is a subject of controversy and heated debates, but using the results of risk assessment in a relative way it is possible to rank projects and compare their risks with other business risks. Cost-benefit analysis will give added value to the ranking. Regulators often try to define or assess absolute levels of risk, as relative ranking gives a better risk management strategy when allocating resources and discussing regulatory control. A more objective method may be to calculate a normalised risk exposure for comparison purposes and use the level as an acceptance criterion.

For serious undesirable events and accidents, a (log-log) frequency-number chart (F-N curve) may be used to define acceptance criteria. The probability P per time interval (i.e., the inverse of frequency per time interval) of the event is the ordinate (log P). The cost consequence C (for example in the oil business C is the number of fatalities) is put on the abscissa (log C). By constructing this risk profile, three levels (bands) or categories may be defined:

1. Not acceptable/tolerable, risk-reducing activities must be applied.
2. Acceptable/tolerable. No need for risk reducing activities.

3. A band in between where it is necessary to prove the risk is As Low As Reasonably Practicable – ALARP.

An illustration of an F-N curve is given in Figure 2.3-1. The ALARP area is between the boundaries of the two straight lines. The two diagonal lines are lines of equal risk level.

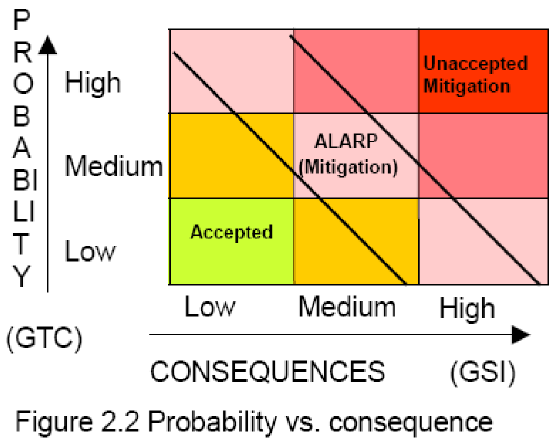


Figure 2.3-1 Probability vs. Consequence

It is important to stress the fact that calculating probabilities of fatalities or serious accidents, and analyzing the associated economic costs, does not entail an acceptance of such accidents. All accidents are unwanted and intolerable. The ideal and long-range policy is to avoid all accidents and this policy stimulates the continuous focus on improving the health and safety of work in a utility. But we do accept the risks involved in the events analyzed, if the probability of the events is sufficiently low, or if the consequences may be lessened by some means.

2.3.3 EURELECTRIC: RISK MANAGEMENT IN THE ELECTRICITY INDUSTRY

The document "Risk management in the electricity industry" [18] established by Eurelectric forms a practical guide for risk management in utilities, including description of process, elements of organizational structure, tools, methodologies and skills. This document includes the three following main parts:

- Risk identification and prioritization,
- Risk strategy,
- Risk governance and control.

For the electricity sector, Eurelectric identifies four main types of risk:

- Market risk,
- Credit risk,
- Operational risk,
- Business risk.

The Eurelectric document has been created for helping players in electricity industry that are more exposed to risks than before. Exposures to market and regulatory risks have been significantly increased and have now an important impact for the values of the companies: profit margins, reputation, etc.

2.3.4 SINTEF: CURRENT RISK EXPOSURE IN THE DISTRIBUTION SECTOR

Risk management concepts for distribution systems have been defined by Sintef in their DSAM project [50], which includes a more detailed survey.

Risk is defined in IEC 60300-3-9 as: Combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event. Risk analysis attempts to answer three fundamental questions:

1. What can go wrong?
2. How likely is it to happen?
3. What are the consequences?

The answer to the first question defines a number of risk scenarios (S) which is a description of threats or hazards considered to be feasible. The answer to the second question is a probability statement regarding the likelihoods of different scenarios (p). The answer to the third question is a qualitative or quantitative description or evaluation of the consequences (C) of the different scenarios related to individuals, professionals, populations, property or the environment. Each risk scenario might hence be described by three parameters: <S,p,C> and the total risk picture is given by listing all risk scenarios with their associated probabilities and consequences.

Risk scenarios can include threats or hazards, events and trends. Adverse weather, failure of aging overhead lines, overloading of components and failures due to lack of maintenance, are all examples of risk scenarios. From a risk perspective, risk scenario identification is an important part of the risk management process. Risk identification is the process to find, list and characterize sources of risk. As IEC 60300-3-1 defines risk as "Combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event", to identify and classify the hazardous or unwanted events is necessary as part of the overall risk management process.

Risk literature is to a large extent focused on discrete events; but in the management of aging distribution systems, discrete events might be the triggering mechanisms for exposing the underlying risk potential. As an example the insulation voltage withstand for a MV cable has decreased for years due to water-treeing. After some time the voltage withstand level is below the voltage rise that might occur during single-phase-to-ground fault. The cable might very well be in service for several more years despite its state, but if such an event occurs a cable fault might be the result. Figure 2.3-2 illustrates the ageing phenomena together with normal operating stresses and random event stresses.

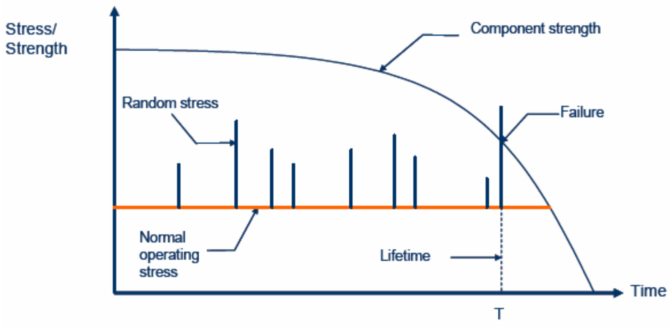


Figure 2.3-2 Component strength/stress time function

At time T the component strength is not high enough to withstand the combination of normal operating stress and the random stress occurring at this particular moment in time which leads to a failure. Hence in the RISK DSAM context not only events, but also system and component state trends are of importance for risk management. In Figure 2.3-3 a flowchart is shown to illustrate the relationship between the different risk management processes, [IEC 60300-3-1].

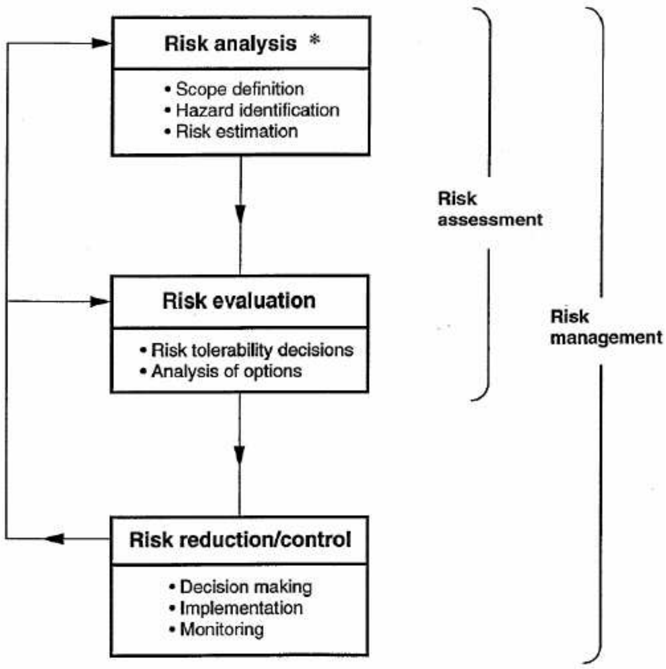


Figure 2.3-3 Risk management relationships, [IEC 60300-3-1]

2.4 Risk Indicators

Risk indicators are needed in asset management for risk monitoring, control and decision making. A risk indicator might be defined as follows [51]:

- **Risk Indicator**: Parameter which provides information about risk.
  - Note 1: A risk indicator can give information about risk performance or risk exposure information
  - Note 2: A risk indicator should address probability aspects or consequence aspects or both.

Risk indicators can be classified as follows:

- Risk performance indicators giving **historic** risk performance information
- Risk exposure indicators mainly giving **present** and **future** risk expectation information with respect to different threats and uncertainties

Parameters providing risk information have "always" been used, but not necessarily labelled as" risk indicators" and used within a formal risk management concept. When the gauge showed that the pressure in a steam boiler was reaching dangerous levels, the stoker knew that he was in a risky situation and might take action to reduce the pressure. The pressure measurement is a risk indicator. It provides information about risk and can be used to manage risk. When the pressure is low, the risk exposure for the over-pressure threat is considered to be low – when the pressure is high, the risk exposure is high.

As asset condition information important in transmission system asset management, condition monitoring will provide relevant input to estimate risk indicators. Health indices for equipment are examples of low-level risk indicators as they provide risk information and can be used in risk management. End of life estimates or fault rate expectations are other examples of risk indicators.

Risk indicators play a role in work processes and decision making. Some indicators are useful in asset management planning and decision making, while others are useful in every day work such as the daily maintenance of the transmission system. Risk indicator information or data are typically collected at the operational level in the organization and aggregated upwards in the organizational pyramid as illustrated in Figure 2.4-1.

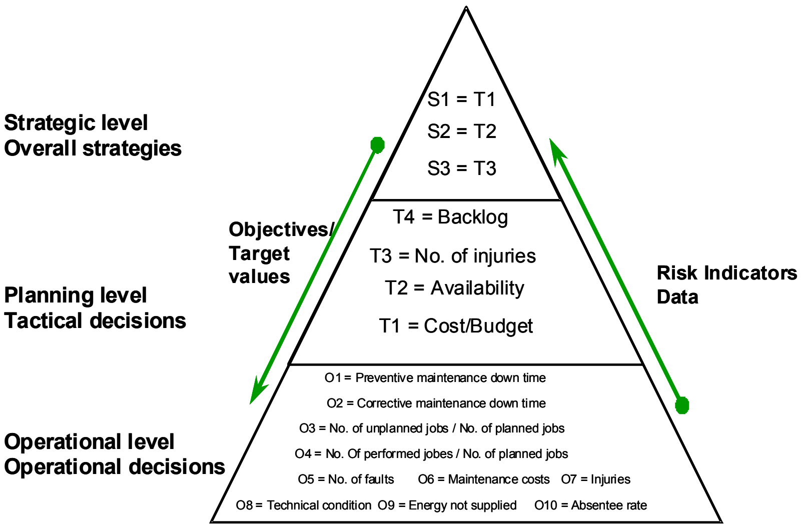


Figure 2.4-1 Example of data and objective flows

Risk exposure can be estimated by using appropriate simulation models that can provide relevant risk indicator information. The indicators themselves are also relevant as part of the input to such simulation models. The principle is illustrated in Figure 2.4-2:

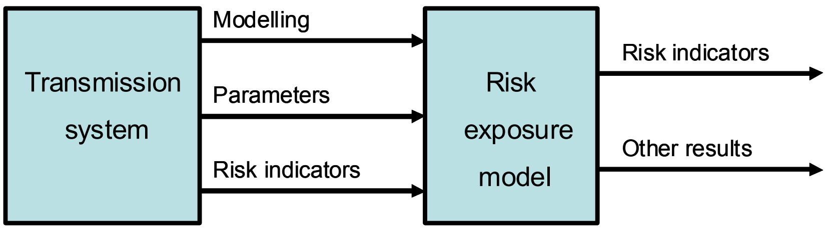


Figure 2.4-2 Risk exposure simulation process

The set of risk indicators used as input to the risk exposure model are different from the set of risk indicators provided as output from the model.

The term simulation model should be given a broad interpretation. It is not necessarily a computer model, but a metaphor for the process of analysing a system or process in order to predict or assess its actual behaviour or state.

Risk exposure models could range from simple rules to more advanced computer based simulation models. An example of a simple risk exposure model could be: When the damp pressure gauge displays "Red", the risk exposure is "High".

Risk indicators are also helpful when classifying risk elements in risk matrixes as the consequence metrics are examples of risk indicators. In this technical brochure, a number of risk indicators are given e.g. financial risk indicators, quality of service risk indicators, safety risk indicators, legal risk indicators, environmental risk indicators.

Figure 2.4-3 illustrates a methodology for the establishment of risk indicators in general. The figure is based on [52]. The principles described in the steps below are considered to be relevant guidelines for the establishment of risk indicators within the asset management context.

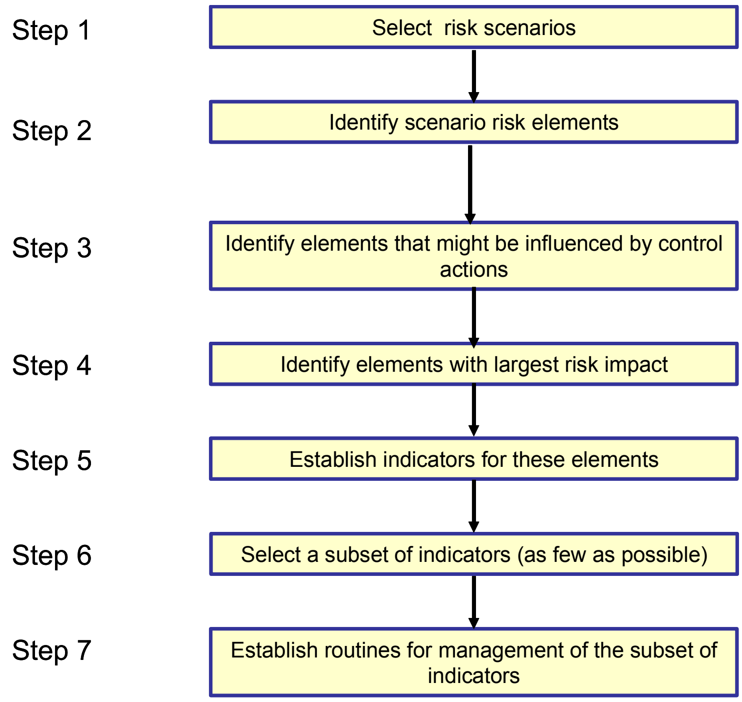


Figure 2.4-3 Development of risk indicators

The following questions form a checklist that should have a positive answer when evaluating a risk indicator:

- Is the risk relevant?
- Is the indicator unambiguous and well-defined?
- Is it linked to the company objectives and values?
- Are the resources required to provide the indicator proportionate to the expected benefits?
- Is it easy to use in decision processes?
- Do the users find it relevant for the chosen purpose?
- Is it accepted by the involved stakeholders?
- Can the indicator be influenced by present or future control actions (or does is it only give historic information)?

2.5 Conclusion

Chapter 2 provides a summary of risk management. Risk is the combination of the consequences of an event and likelihood of the event. Risk management consists of several steps: risk assessment, risk treatment and risk monitoring and review. These steps are organized in an improvement cycle: the risk management cycle. To assess and prioritize risks a risk assessment matrix is used. This risk matrix documents the risk attitude of the company. The asset manager uses risk assessment matrices to derive the risk criteria for his decisions. Lastly the electricity transmission assets are monitored for risks using risk indicators.

3 RISK MANAGEMENT IN ELECTRICITY TRANSMISSION COMPANIES

This Technical Brochure concerns Transmission Asset Risk Management, that is, the application of risk management in the asset management processes of electricity transmission companies. Discussing risk management in electricity transmission companies may be confusing. Several questions are obvious, "which type of risks are we talking about?", "in which context?", "what is the scope of the risk analysis?". For the technical expert, a risk analysis means a study related to the failure mechanisms of an asset. For a senior manager a risk analysis means a study of the business opportunities and threats for the company. The area of attention of the asset manager is in between. One of the roles of an asset manager is to link the notions of business risk and asset risk together to make the right decisions for the assets and the company as a whole.

In the C1.16 Working Group several examples of risk management and risk management methods for electricity transmission assets have been documented. To structure the examples and methods in the Technical Brochure a definition of the differing activities and responsibilities of asset managers is proposed to form a roadmap throughout this Technical Brochure.

3.1 General management concepts

This section outlines the management concepts used in this generic risk management model.

3.1.1 ASSET OWNER – ASSET MANAGER – SERVICE PROVIDER ORGANIZATION STRUCTURE

Many electricity transmission companies have adopted an organization structure where a separation is made between Asset Ownership, Asset Management and Service Provider roles. See Figure 3.1-1 with examples of possible activities for the specific roles. The objective of role separation is to obtain better efficiency for the organization. [4], [5]

- The Asset Owner may be the government, the board of a corporation or an investor that owns the network assets and is ultimately responsible for the network. The asset owner focuses on the overall business strategy, the business values, the business performance and business risks.
- An Asset Manager is engaged by the Asset Owner and assigned responsibilities for the management of the network assets. The asset manager focuses on improvement of return on assets over their full life cycle. The return considered is not only financial return, but return on all business values as set by the asset owner. The asset managers role is to balance the business risks (derived from business values), the business performance and expenditures on assets.
- The actual work on the network assets is undertaken by Service Providers who are engaged and controlled by the Asset Manager. Service Providers could be either internal or external to the business and could cover such factors as maintenance, engineering, operation or corporate services. The service provider focuses on efficiency of work delivery: project execution within the limits of quality, time and budget.

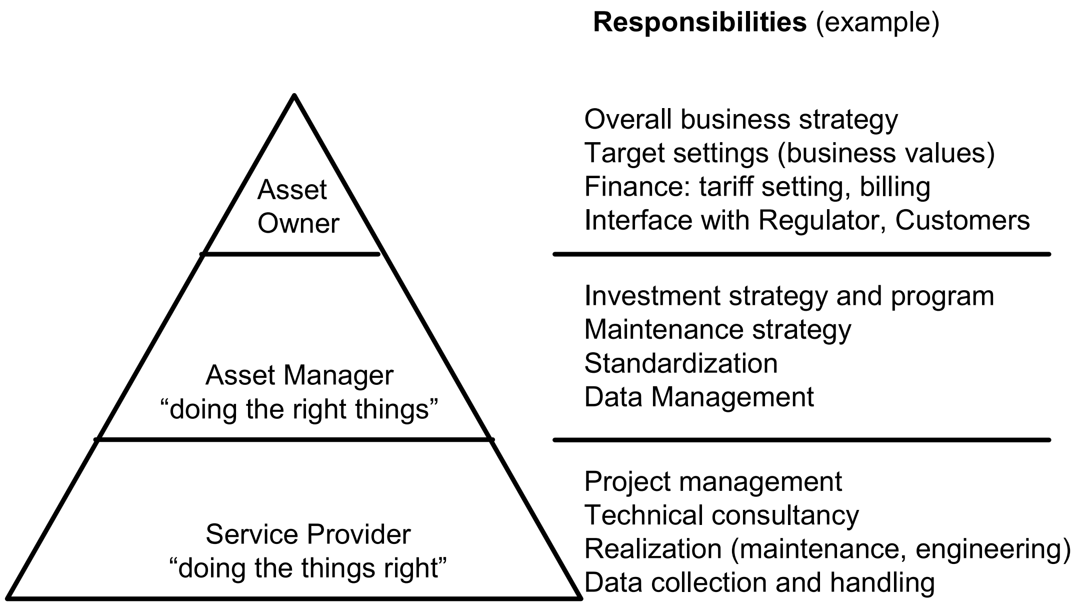


Figure 3.1-1 Organizational structure: Asset Owner – Asset Manager – Service Provider

3.1.2 IMPROVEMENT CYCLE

A well-known concept for improving operational excellence of organizations is the Deming-cycle or Plan-Do-Check-Act-cycle. In the previous chapter on Risk management also the Risk Management Cycle was introduced: Perform Risk Analysis – Decide Risk Treatment – Execute Risk Treatment – Evaluate Risk Treatment. Figure 2.1-9

The concept of the improvement cycle is used in our generic risk management model. The objective of the asset manager is to improve the return on the assets involving all business values (not only financial) as agreed with the Asset Owner. To be able to reach this objective, all risks that threaten the objective need to be treated. This needs a continuous process of risk identification and risk treatment.

3.1.3 SYSTEM APPROACH

Organizations may be modeled as systems. In this Technical Brochure to analyze the risk management and decision making processes within the asset manager role the asset management system (= organization) is divided into three subsystems, in which Asset Management decisions are prepared. The three subsystems are called Strategic Asset Risk Management, Tactical Asset Risk Management, Operational Asset Risk Management.

Note that there may be other divisions possible to describe decision making within electricity transmission companies. One description used historically within Cigré is the division Corporate – System – Equipment (CSE) [6]. However, the focus in this brochure is on decision-making and the support to decision-making that is provided by risk management so the more frequently used division in Strategic – Tactical – Operational (STO) is applied. In this model a reliability analysis of an asset group, subsystem or system fits in the operational decision level. In this vision STO and CSE divisions are different aspect systems of the same system: the electricity transmission company.

3.1.4 Management by exception

As pointed out in the previous chapter scope definition is very important before starting a risk analysis. A reason to initiate a risk analysis may be a concern that a pre-set norm will be exceeded. For example an asset that exceeds a limit for its condition or a group of assets exceeding a limit in the number of failures are reasons to start a risk analysis. Another example is assets whose duties may exceed their ratings on a statistical basis as load or short circuit levels increase in a planning period. One way to manage the risk is to bring the assets to a better condition by maintenance or replacement and to set new norms for the condition or number of failures. This means that not all assets are to be managed, but only the ones exceeding the limit: management by exception, the norms are derived from risk treatment measures.

3.1.5 Draft ISO standards on Risk management

Concepts of risk management processes in this brochure are partly based on the ISO standards on risk management which are currently under development by ISO.

- Draft Guide 73: Risk management vocabulary. The guide gives definitions to all terms relevant to risk management and is currently under revision. [1]
- Draft standard 31000: Risk management – principles and guidelines on implementation. This standard aims to describe the general risk management process and how to implement this in an organization. [2]
- Draft standard 31010: Risk Management - Risk Assessment Techniques. This standard aims to give an overview of risk assessment techniques. [3]

3.2 Risk Management Structure used in this Technical Brochure

The proposed structure for asset management, is one commonly used in organizations namely as they relate to: strategic, tactical and operational decisions. The starting point for this structure is the type of asset management decision which requires the contribution of every level in the organization to be taken into account. One of the important aspects of asset management is the holistic approach. In many cases the asset manager needs to make his decisions as far as possible taking into account the whole asset base and the overall strategies of the company. [4] The proposed structure for asset management takes into account the organizational model for infrastructure namely: Asset Owner – Asset Manager – Service Provider.

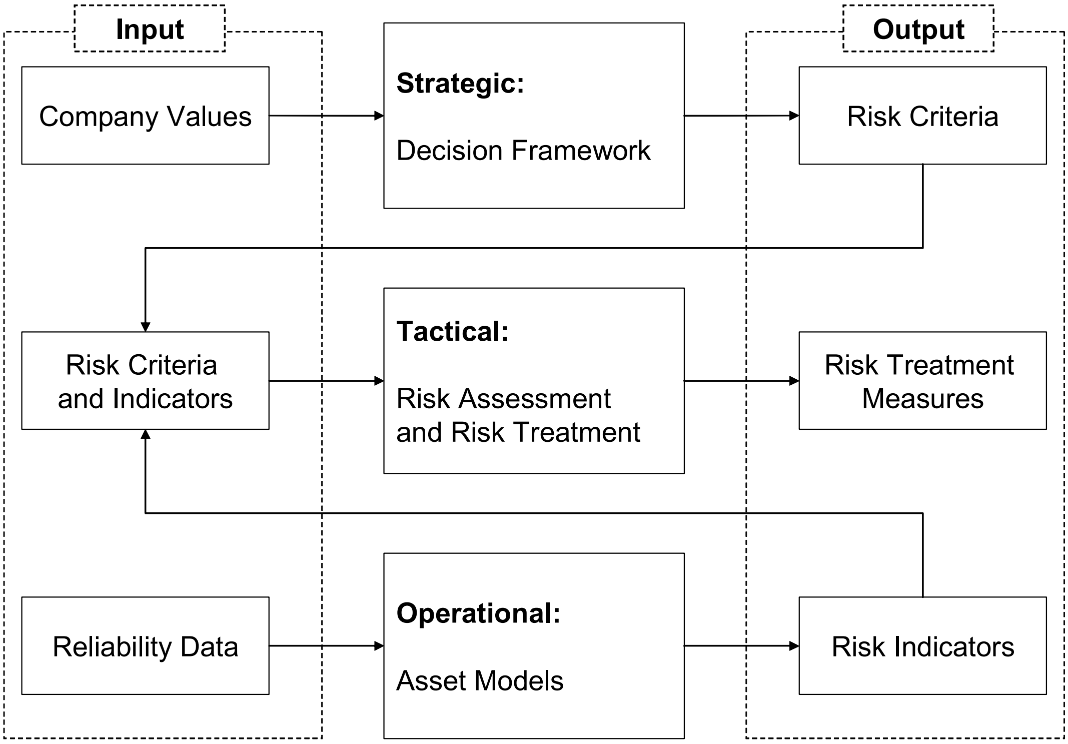


Figure 3.2-1 Asset Risk Management Structure

In Figure 3.2-1, the meaning of the block "operational" is in this case the information needed by the asset manager to be able to manage the operation, the work by the service provider, effectively; in other words: to implement operational asset management. The meaning of the block 'strategic" is in this case the information the asset manager needs to make the right asset management decisions for the organization taking into account the business values and the overall strategy. The block "tactical" refers to quantitative asset management decision making.

A fundamental feature within each block is the concept of continual improvement. The primary process of the asset manager is improvement of the risk management cycle. In the risk management cycle, risks are assessed and treated on a continual basis by the asset manager. This cycle leads to an improved insight into the assets and their associated risks and this leads to better risk treatment and thus to better asset management. In the risk management cycle an evaluation is made of the options the asset manager has for risk treatment: repair, refurbishment or replacement of assets or to invest in extension of the grid. The synergy between system development and asset management is an important advantage for the company. [41]

The basis for the strategic block is continual improvement of the decision making framework and the criteria for risk assessment. In most of the companies participating in C1.16 this framework of risk criteria has the form of risk matrices. These risk matrices need to be periodically reviewed to determine whether the risk matrices continue to conform to the risk attitude of the company. For example, an internal or external event could take place with such an impact on the company that the management needs to sharpen the risk criteria. Also because of an external development, management could decide to add a new business value. See section 4.5 and appendix E for examples.

The basis for the operational block is continual improvement of the insights and models of aging and failure mechanisms of the assets. In so doing knowledge and insight into the key parameters, involved in asset aging and failure improves and risk indicators can be determined with a higher degree of accuracy. Risk indicators are important for the asset manager to get the right information from the service provider. The development of asset aging and failure models and risk indicators may vary from scientific research to practical choices made by maintenance engineers. These developments continue to take place within electricity transmission companies and research institutes. See the examples in appendices A through G and reference [50].

3.3 Transmission Asset Risk Management: Tactical level: Risk Management Cycle

Figure 3.3-1 illustrates the risk management cycle. The risk management cycle is reviewed periodically for example for setting up a maintenance and investment plan or because of an internal or external event that makes it necessary to review the risk assessment and priorities for investments etc.

The investment- and maintenance plan is executed in the Execution Process. In many organizations this means that the asset manager defines and funds assignments for the service providers. The execution process leads to changes in the transmission grid, for example the improvement or maintenance of asset condition by performing maintenance on assets, replacing assets or extending the network. As a result of these actions, the risks from the assets for the transmission company decrease. This can be seen from the risk indicators and is monitored in the ongoing asset management monitoring process.

Apart from changes in the established risk indicators, events can take place (for example changes in internal or external context) that may lead to the review of risk indicators, the risk assessment and risk treatment. For example: failure of an asset, without any change in the predicting risk indicators or external events like extreme weather conditions may motivate a review of asset risk indicators. The review ensures that the risk control and treatment measures continue to be effective. One of questions asked by the asset manager should be: "Do the measures sufficiently treat the business risk from key assets in poor condition?".

In the risk assessment process risks are identified, analyzed and evaluated. These risks are identified by risk indicators and internal and external events. The assessment of risk is in many of the participating companies done by the asset importance versus asset condition chart [41]. The final step in the assessment is the proposal of risk treatment options. These risks and risk treatment options are filed in the risk register of the asset manager. Finally using the risk register and evaluation methods, like the assessment of risk reduction. See section 6.5, decisions are made to put risk treatment options into the investment- and maintenance plan.

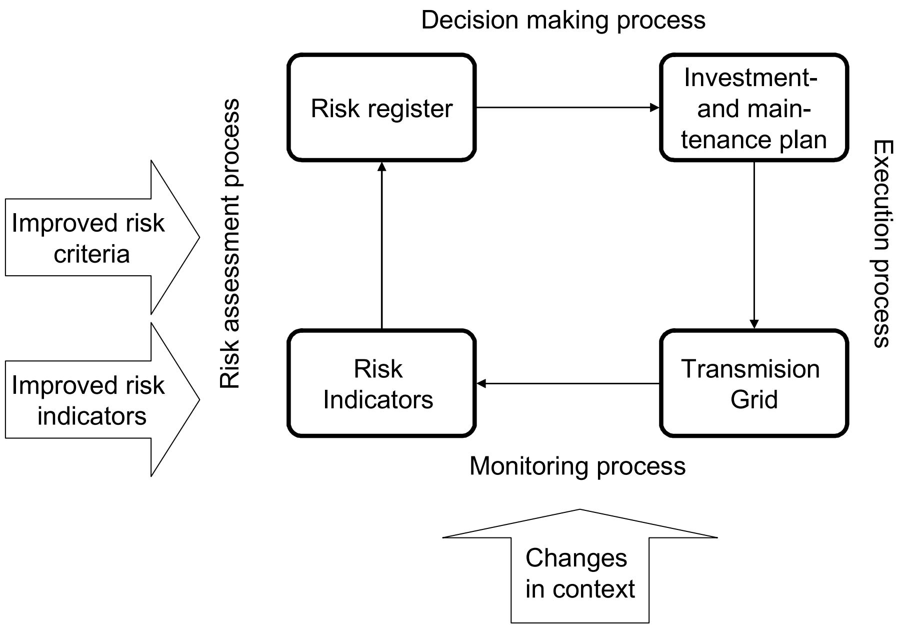


Figure 3.3-1 Risk Management Cycle: Continual Improvement of AM decisions, [4] and [53]

3.4 Transmission Asset Risk Management: Operational level: Continual Improvement of Risk Indicators

This process facilitates the asset management process by developing risk indicators from asset aging and failure models. An important question is how an asset manager determines which risk indicators need to be collected by the operations staff i.e. the service provider.

To enable the asset manager to make the right risk assessment and risk treatment options the asset manager needs to have data available: asset data, data on internal and external developments like asset condition and loading growth [4]. From all of the considerable amount of data, the goal is to find those parameters, which indicate potential risks for the assets of the company. Therefore risk indicators need to be developed [51]. Risk indicators for risks resulting from aging assets may be developed according to the process shown in Figure 3.4-1.

With the help of risk indicators the asset manager determines the work to be executed on the assets. The options include: do nothing, repair, refurbish, replace and extend. Depending on the decisions made, changes in asset performance take place which ultimately can be seen in the failure statistics. Next to deterministic failure models, statistical data is used to set up failure models, from which eventually the key parameters for asset failure are determined: the risk indicators. See the examples in appendices A through G.

As well as failure statistics to be collected there may be internal and external developments, which imply that a review of the failure model and risk indicators is necessary. For example: the publication of general available reliability data, scientific development in failure models or failure of an asset outside the failure modes foreseen in the failure model. Examples of risk indicators include: Asset condition indices or minor faults that lead to major faults. The review process is needed to detect changes in the external and internal context including changes to the risk itself.

The questions the asset manager could ask is: "Does all of the information on asset condition and asset failure confirm the asset model?", "Are the parameters indicative for asset condition?".

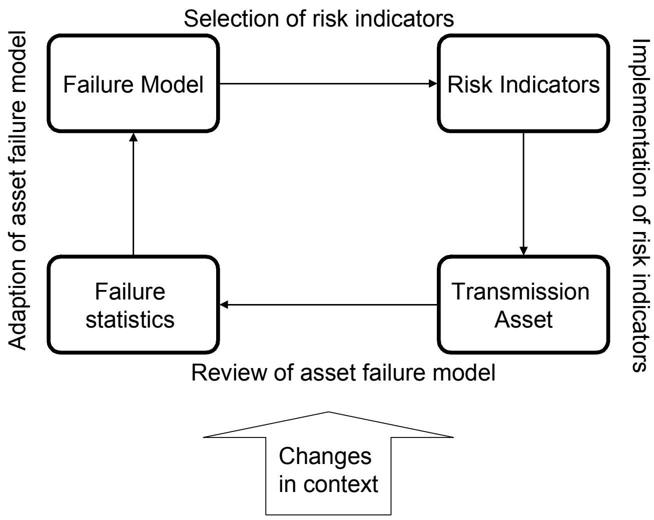


Figure 3.4-1 Continual improvement of risk indicators

3.5 Transmission Asset Risk Management: Strategic level: Continual Improvement of Risk Criteria

This process facilitates the asset management process by defining risk criteria from company's key performance indicators and business values etc. The question here is how an asset manager models the decision making and risk attitude of the asset owner correctly to use this for asset management decision making? How does an asset manager communicate which risk criteria he uses for the decision making concerning the assets of the asset owner? See Figure 3.5-1.

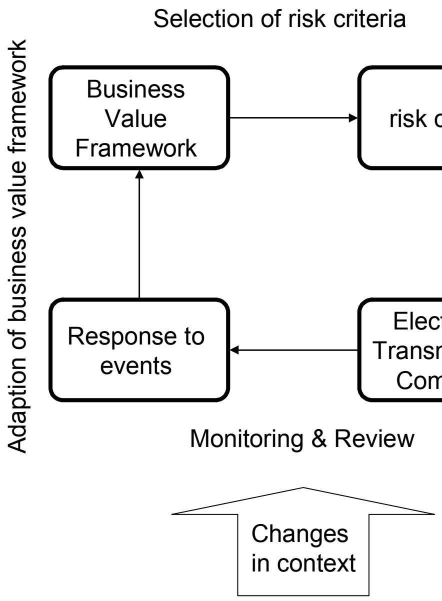


Figure 3.5-1 Continual Improvement of Risk Criteria

In the business value framework the company values of the electricity transmission company are arranged. This framework consists of risk matrices and it documents the risk attitude of the company. From the framework, risk criteria may be derived (limits for impact categories and likelihood categories). The asset manager then uses these risk criteria to develop his investment- and maintenance plans.

In the review and monitoring process, events, changes and trends are studied for possible changes that could motivate improvements in the framework. If a large internal or external event impacts the company, management will take actions with or without regard of the decision framework. For the asset manager this is an opportunity to review the decision framework. Such events will possibly lead to a change in risk criteria. Another example is adding a new business value to the framework caused by an external development.

3.6 Conclusion

Risk management in Electricity Transmission Companies is applied at every organizational level. The role of an asset manager is to link the notions of business risk and asset risk together to make the right decisions for the assets and the company as a whole. To facilitate transmission asset risk management, an organizational structure of the differing activities and responsibilities of asset managers is proposed.

The proposed structure for asset management takes into account the organizational model for infrastructure namely: Asset Owner – Asset Manager – Service Provider. Risk management by the asset manager is divided in three levels of asset management decision making supported by risk management: strategic, tactical and operational asset management.

Operational asset management is the development of information needed by the asset manager to be able to effectively manage the work by the service provider. Strategic asset management is the development of information the asset manager needs to make asset management decisions that conform with the organization's risk attitude and key performance indicators (KPI's). Tactical asset management refers to quantitative analysis to investigate optional tactics to support and justify asset management decision making.

The primary process of the asset manager is continual improvement of quantitative asset management decision making according to the risk management cycle for asset management, including the basis for strategic and operational criteria and indicators for risk assessment respectively.

4 STRATEGIC ASSET MANAGEMENT – RISK MANAGEMENT ON STRATEGIC LEVEL

In the previous chapter the risk management structure was discussed generally. In this chapter the methodology to develop and maintain the decision making framework, the business impact and business risk assessment matrices is described.

4.1 Introduction

Like asset management decision making, the performance of a system or process within the company can be defined on several aggregation levels in the organization.

An example from another management area within a company is employee health. The company defines a KPI for employee health: for example, the percentage of absenteeism caused by sickness. This is a strategic KPI for the company but how is this arranged internally in the company? How does the sickness percentage relate to the workload or the percentage of employees joining the company sports program? There is a relation between these operational performance indicators and the strategic performance indicator. While it is easily understood that a improved performance on the operational level improves performance on the strategic KPI's, it is sometimes very difficult to find a direct relationship.

This also applies to asset management issues. For example: how is the total amount of oil refill in oil-pressurized cables linked to the company striving to be a "green" company. Or: how does the Lost Time Incident Frequency Rate relate to the percentage of employees using safety equipment correctly. The asset manager needs a method to handle this arrangement problem, because all of the asset management activities need to be executed in the field and still properly attributed and linked to the company strategic goals.

The connection between strategic and operational KPI's is not easy to make. Therefore the Business Value Framework is introduced. All KPI's are related to an area of performance of the company often called Business Values. By reducing the impact or risk on a business value the performance in that area will be improved.

Therefore in North America and the United Kingdom government organizations are increasingly adopting Enterprise Risk Management as a model that should be followed by agencies of the government, such as regulators and the utilities they control in order to provide a mechanism to link measurable business values with risk-based decision-making processes. [10], [11]

4.2 Development of Business Value Framework

To create transparency electricity transmission companies have introduced the Asset Owner – Asset Manager – Service Provider organization model. The Asset Owner is generally a different entity from the asset manager and owns the assets or represents the stakeholders of the company, sets out the company mission, vision and strategic objectives.

For the Asset Manager to be able to take or propose the right decisions for the asset owner it is necessary to understand these requirements as set out by the asset owners and stakeholders. To facilitate this a Business Value Framework is derived from the Asset Owners requirements and agreed between Asset Owner and Asset Manager.

The assumption of this business value framework is that if the objectives, the values of the asset owner are clear, the risks, concerning the assets with regard to the business values are also clear. The performance of the electricity transmission company is measured in KPI's. The KPI's are related to the business values and therefore with the business risks.

In many companies, the mission, vision and KPI's have already been established. If not, a session should be held with the senior management of the company to establish the business value framework. Questions like "what is the companies mission", "what are the strategic objectives", "what is agreed upon what is important for the company as a whole", "what are the key performance indicators" etc. need to be answered. From these questions the business values can be derived and defined. The KPI's are grouped in performance area's linked to the business values. See Figure 4.2-1 the example is derived from the corporate risk matrix of a Canadian utility. [10]

Examples of Business values/ performance area's	**Description**
Safety	The company values safety of employees and third parties. The business value "safety" contains performance elements like Lost Time Incidents etc.
Financial	The company values a sound financial position and system. The business value "Finance" contains financial performance elements
Quality of Service/ Reliability	The company values a good quality of service. The business value "quality of service" contains performance elements like Customer Minutes Lost etc.
Environment	The company values the environment. The BV contains performance elements like cost of environmental damage etc.

Figure 4.2-1 Example of Business Value Framework

4.3 Development of Business Impact Framework

From every business value one (or more) practical norms are defined to quantify the consequence of an event. The norms will differ from one company to another. For example, the business value "Service Quality/ Reliability" is translated into a norm for "Customer Hours Lost".

The impact of an event on the KPI is then categorized. It should be kept in mind that this Impact Framework is a tool to categorize risks and should be kept simple to use. Three to Five categories are recommended with a logarithmic scale between the categories and with intuitive category names, like catastrophic, severe etc.

The questions that need to be answered are: "which KPI's are part of the Business Value under consideration", "which ones dominate the business value?", "what events/incidents are considered?", "what incidents are outside the scope?", "at what impact level is an event or incident considered to have a catastrophic impact on the company?".

It should be noted that events with an extremely high impact (like natural disasters) may be out of scope for the asset manager and that events with a very low impact may lead to larger impact when the frequency of occurrence is expected to be relatively high. This means that besides the impact (consequence) the risk needs to be considered (consequence X probability).

Norms for some business values are easily expressed in numbers and others are more difficult to express in numbers. Key to the impact framework is that when an incident is considered to have an impact in a certain category on one business value (for example severe on service quality) it should fall in the same category when the incident is regarded for another business value (for example financial). So in the example in Figure 4.3-1, derived from the corporate risk matrix of a Canadian utility [10] the cost of energy not supplied should be the link between service quality/ reliability and financial. Note that this link is not necessarily a physical link, but may be a link in the perception of the Asset Owner. This should also apply for business values like corporate public image but is then much more difficult to determine.

Severity

Per incident	Safety	Financial	Reliability	Environment
Impact class 5	Fatality (ies)	Impact totalling >= 10 M$	Customer hours lost >= 7 Million	Reportable environmental incident with regulatory prosecution and/or uncertain mitigation
Impact class 4	Permanent disability	Impact totalling 5 M$ to 10 M$	Customer hours lost 3 to 7 Million	Reportable environmental incident with regulatory fines and mitigation possible
Impact class 3	Lost time injury/ temporary disability	Impact totalling 1 M$ to 5 M$	Customer hours lost 1 to 3 Million	Reportabel environmental incident with long term mitigation (> 1 year)
Impact class 2	Medical aid injury/ illness	Impact totalling 0.5 M$ to 1 M$	Customer hours lost 0.25 to 1 Million	Reportable environmental incident with short term mitigation (<1 year)
Impact class 1	First aid injury/ illness	Impact totalling < 0.5 M$	Customer hours lost < 0.25 Million	Non-reportable environmental incident

Figure 4.3-1 Example of Business Impact Matrix

4.4 Development of Business Risk Assessment Matrix

To be able to establish a risk-based prioritization of candidates for asset investment in the transmission network, not only the impact of possible events need to be assessed, but also the likelihood of the events. From impact and likelihood, the risk of the event may be determined. To decide on risks that need to be reduced forms a better basis for prioritizing the investment decisions (both OPEX and CAPEX) in the network. To have a structured approach for risk assessment the risk assessment matrix is developed as described earlier. As an example of a risk assessment matrix see Figure 4.4-1, derived from the corporate risk matrix of a Canadian utility [10]

Severity of Impact

Probability of Occurence

	Impact class 1	Impact class 2	Impact class 3	Impact class 4	Impact class 5
>= 90% likelihood that event will occur within next year (5)	Moderate	Moderate	High	Extreme	Extreme
>= 50 % likelihood that event will occur within next year (4)	Guarded	Moderate	High	Extreme	Extreme
>= 10 % likelihood that event will occur within next year (3)	Guarded	Moderate	Moderate	High	Extreme
>= 1 % likelihood that event will occur within next year (2)	Low	Guarded	Moderate	Moderate	High
< 1 % likelihood that event will occur within next year (1)	Low	Low	Guarded	Guarded	High

Figure 4.4-1 Example of a Risk Assessment Matrix

In case of the Canadian utility all matrices above have been combined into one figure as shown in Figure 4.4-2. [10] The impact criteria, which are based on the company's KPI's, are listed in the lower part of the left hand column, while the likelihood categories are tabulated in the upper part of that column, and they form the vertical axis of the risk matrix. Across the horizontal axis of the matrix are listed the magnitudes of the impacts for each of the impact categories. At the bottom of the table is a listing of the severity classifications and importantly the corporately mandated actions for each level of risk.

This table would also include the definitions of the severity classifications in financial terms. For example, if the risk matrix is applied for a specific asset or asset management option, the impact magnitudes for each of the impact criteria are estimated in financial terms and totaled, and the likelihood of the event is estimated. These two quantities are multiplied to determine the business risk.

BCTC Corporate Risk Matrix

LIKELIHOOD GUIDELINES	LIKELIHOOD OF OCCURRENCE						
90%	(9 in 10) or greater likelihood that event will occur within next year.	5	Moderate	Moderate	High	Extreme	Extreme
50%	(1 in 2) or greater likelihood that event will occur within next year.	4	Guarded	Moderate	High	Extreme	Extreme
10%	(1 in 10) or greater likelihood that event will occur within next year.	3	Guarded	Moderate	Moderate	High	Extreme
1%	(1 in 100) or greater likelihood that event will occur within next year.	2	Low	Guarded	Moderate	Moderate	High
<1%	<1% (1 in 100) likelihood that event will occur within next year.	1	Low	Low	Guarded	Guarded	High
IMPACT CRITERIA			**1**	**2**	**3**	**4**	**5**
Safety			First aid injury/illness	Medical aid injury/illness	Lost time injury/ temporary disability	Permanent disability	Fatality (ies)
Financial			Impact totaling < $500,000	Impact totaling $500,000 - $1 Million	Impact totaling $1 Million - $5 Million	Impact totaling $5 Million - $10 Million	Impact totaling ≥ $10 Million
Reliability			One of: < 250,000 customers hrs lost or < 2 GWh of energy not served or delivered.	One of: 250,000 – 1 million customers hrs lost or 2 -7 GWh of energy not served or delivered.	One of: 1 - 3 Million customer hrs lost or 7 - 20 GWh of energy not served or delivered.	One of: 3 Million - 7 Million customer hrs lost or 20 - 50 GWh of energy not served or delivered.	One of: ≥ 7 Million customer hrs lost or ≥ 50 GWh of energy not served or delivered.
Market Efficiency			Customers and rate payers lodge complaints to BCTC	BCTC customers and rate payers lodge complaint to Government or the Utilities commission	Government or BCUC enquiry conducted into BCTC practices and policies	Government or BCUC impose strategic and operational changes upon BCTC	Failure to deliver required level of service resulting in loss of license to operate
Relationships			External opposition resulting in short term delays or minor modifications to work plans.	External opposition affecting BCTC's ability to implement its work plans is constrained and/or substantive modifications of its work plans are required.	External opposition resulting in increased regulatory oversight; shareholder scrutiny and/or restricted access to work sites.	External opposition resulting in increased regulatory/ legislative/court action or government intervention resulting in a loss of responsibilities impacting BCTC's corporate mandate, including restricted access to major project sites.	External opposition resulting in loss of license to operate and/or imposed corporate restructuring
Organization & People			Negligible impact on service delivery and staff.	Impacts the efficiency or effectiveness of some services, but would be dealt with internally.	Portions of the organization experience unexpected attrition or reduced attraction factors.	The ability to achieve the corporate goals is threatened or there is a significant increase in the cost of service.	Unexpected loss of multiple critical staff including senior leadership and the ability to deliver critical services.
Environment			Non-reportable environmental incident	Reportable environmental incident with short term mitigation (<1year)	Reportable environmental incident with long term mitigation (> 1year)	Reportable environmental incident with regulatory fines and mitigation possible.	Reportable environmental incident with regulatory prosecution and/or uncertain mitigation.

Severity Classification	
Extreme	Must be managed through a detailed plan by an Executive.
High	Detailed research and planning required at senior management; Executive attention is required.
Moderate	Management responsibility must be specified; Manage by specific monitoring or response procedures.
Guarded	Managed by routine procedures - regular monitoring required.
Low	Managed by routine procedures.

Figure 4.4-2 Example of a Corporate Risk Assessment Matrix [10]

The severity of the business risk is then compared with the corporately mandated definitions. If the risk is in the range defining a moderate risk, then management must take the proscribed actions. As an example of a risk treatments measures see Figure 4.4-3, derived from the corporate risk matrix of a Canadian utility [10]

Risk severity classification (↑)

	Description of risk treatment measure
Extreme	Must be managed through a detailed plan by an Executive
High	Detailed research and planning required at senior management; Executive attention is required
Moderate	Management responsibility must be specified; Manage by specific monitioring or response procedures
Guarded	Managed by routine procedures – regular monitoring required
Low	Managed by routine procedures

Figure 4.4-3 Example of Risk Treatment Measures

4.5 Example: Introduction of a new business value Sustainability

A Network Operator from the Netherlands has been working with the Asset Management approach for a number of years. Business values, a risk matrix and a risk policy, describing the framework to prioritize and select which risks to develop mitigation measures for, are in place and have been refined a number of times based on discussions with the Asset Owner as well as practical experience with the way Asset Management is implemented in the processes of the company. The Asset Management process is certified according to international standards.

Nevertheless, a growing number of people throughout the company is feeling uncomfortable with the way in which electrical losses are treated in decision making using the Asset Management process, namely as operating expenditure. Due to the relatively low energy prices a network operator pays for loss compensation compared to the investment required to reduce them, relatively high losses tend to be accepted. However, the question whether this outcome of the Asset Management process was justifiable in the light of the corporate social responsibility (CSR) of the organization became increasingly pressing.

When it is widely felt that the outcomes of the Asset Management process perhaps no longer reflect the true preferences and values of the company, action must be undertaken. In this specific case, the solution was in principle straightforward. Because the idea that sustainability was not treated properly when only seen as a financial and legislative topic, the conclusion was that sustainability clearly had "value in itself" and was not only a factor affecting the already existing business values compliance and economy. Therefore, the idea to create a business value sustainability was launched and a research project was started on the question how to "measure" sustainability.

It turned out that the "ecological footprint" method was the most suitable method to quantify sustainability for the network operator, because it can be used to compare depletion of various natural resources, both for one-off as well as for recurring activities. By using the ecological footprint, the environmental impact of various alternative solutions could thus be compared. The ecological footprint is calculated using readily available tables for converting such quantities as car-km's, power and gas losses, usage of resources such as copper, aluminium and steel, to a common measure, namely "hectares earth surface". The number of "hectares earth surface" can be used to distinguish effect categories in the risk matrix, which, in combination with frequency of occurrence give the risk level as is the case for the other business values. Finally, comparing environmental risks with economic risks, monetarization is possible as well.

As the Asset Owner is responsible for the business values and the risk matrix, the definition of the new business value, its quantification and its incorporation in the risk matrix were submitted for approval and thereafter incorporated in the Asset Management processes and the supporting document templates and calculation models.

4.6 High Impact Low Probability Events

Some companies have different processes for normal risks and extreme risks (also known as High Impact Low Probability events) as is described by this case from an Electricity Transmission Company in Switzerland.

Once all the risks are identified according to the Business Value Framework (see Figure 4.2-1) they can be categorized as follows:

1. Operational risks resulting from daily business activities
2. Extreme external risks resulting from major events like pandemic disease, climate change, sabotage or terrorism, systematic technical failures, geopolitical events
3. Project risks resulting from investment in construction and development projects

These three risk categories need different management attention. For each category the method of analysis, the availability of appropriate data and the periodicity of the risk assessment and reporting must be considered in a specific way.

For operational risks the causes, probabilities and the impacts can usually be derived from available historical data. Such risks are assessed and reported rather frequently, e.g. once or twice a year. On the other hand extreme external risks and project risks are to be investigated separately due to the lack of historical data. Most of the external extreme risks have severe or catastrophic impact. Only estimations or simulations are possible to get a reasonable approach. Nevertheless the results have a more or less speculative character. Such risks are reported less frequently, e.g. every two or three years only. Project risks are assessed and reported according to the specific project management requirements.

Finally for the sum of all possible risks each company should determine the amount of the necessary risk capital and has to bring into line with the accepted risk appetite.

Figure 4.6-1 Risk appetite – Hedging of company Risks

In practice the required risk capital can be determined very often approximately by taking into account the operational risks only.

4.7 Continual Improvement of Risk Criteria

The development of a business value framework, business impact framework and risk assessment matrix and the resulting risk criteria is described in this chapter. This process facilitates the asset management process by defining risk criteria from the company's key performance indicators and business values. Fundamental to this process is the concept of continual improvement: in the review and monitoring process, events, incidents and trends are studied for possible changes that could motivate improvements in the framework.

In the division of Strategic, Tactical and Operational asset management decisions, strategic asset management considers the longest time frame. On the strategic level, fundamental business objectives generally will not and must not change too quickly to be able to manage the company properly. Because of this, it might seem that the decision framework derived from the business value and strategic objectives is fixed and needs no maintenance when once set. However, the decision framework does need to be evaluated for possible improvement on a regular basis. It is impossible to foresee all possible incidents and to scale them properly into the decision framework. So when incidents occur they should be analyzed and if applicable, the impact or risk assessment matrix needs adaptation. This process is pictured in the figure below.

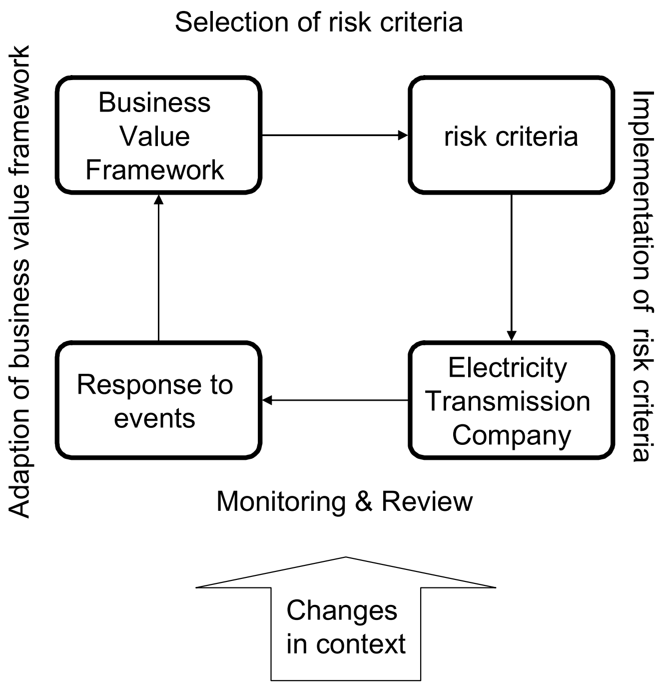


Figure 4-1 Continual Improvement of Risk Criteria

The questions to be asked when performing incident analyses for the purpose of evaluating the decision framework are the following:

- Was the event an accepted residual risk?
- Was the risk identified and assessed?
- What measures were taken according to the decision framework?

5 OPERATIONAL ASSET MANAGEMENT – RISK MANAGEMENT ON OPERATIONAL LEVEL

In this chapter the current status on operational asset risk management is described by several examples from the working group. The objective is to give an explanation of the development and improvement of failure models and data on asset aging.

- Asset Data for business case analysis
- Risk of equipment performance
- Value at Risk
- Asset Health Indices

5.1 Asset Data for business case analysis

5.1.1 INTRODUCTION

For asset managers, the essence of business case analysis is to evaluate optional strategies using quantitative technical and financial calculations which demonstrate which strategies over the planning period best support the KPI's of the utility. This implies directly that there is a need to estimate the performance of the assets in question over the planning period if option A is selected or option B is selected and so on.

There are several possible approaches for doing this; but all of them involve acquisition of data and information on the prior operating history of the assets. For this purpose, company specific data is preferred because it will likely represent most accurately the past and prospective performance of the assets in the physical and operating environment that exists in the utility. Industry data is also useful for comparison or in the absence of adequate company data and as well in recent years, model data may be useful [12, 13].

This section focuses attention on the kinds of data and information that are needed, the potential sources for such data and methods for the analysis of the data that may be used to put it in a form that can be used for business case analysis.

5.1.2 DATA

The objective in data acquisition is to obtain as homogenous a set of data as possible for the assets being considered. In this regard consistency of definitions and terms is important as the lack of consistency can lead to mixed results. The first and most obvious form of data are the data describing the assets in question, for example name-plate information which can be used to assemble demographic data for the population (asset type, manufacturer, in-service date, ratings and so on). In addition, data on the types of asset applications, loading and operational history, maintenance history, maintenance records, failure records, and repair records outage records and so on are relevant and useful.

The types of data that asset managers need depend on the types of decisions that they are trying to justify with a business case analysis. Such decisions involve by necessity some form of investment that is being considered. For example: replacement of assets at end of life (reactively or proactively), investments in refurbishment versus ongoing repairs, or investments in monitoring systems to minimize in-service failures of assets near end of life and so on.

For replacement decisions, failure data relevant to the assets in question are needed. As well, data related to the causes for failures and replacements may be important. In the past many utilities carried out post-mortem investigations on equipment failures and documented and recorded such data in data bases; but in recent years, restructuring and downsizing has had the effect of interrupting or neglecting this important practice. Nevertheless, data mining efforts can be useful in identifying data from which failure and replacement information may be inferred. For example, inferences from purchasing records, maintenance records, protection system records, work orders, orders to operate, diagnostic and/or monitoring records and so on may be relevant and useful. Considerable effort may be needed to piece together data that can be used to infer what has happened in the past in order to get homogenous groupings of data.

For other types of decisions, other types of data are needed. For refurbishment historical data describing when in the life of an asset such investments have been made and the effectiveness of the resulting refurbishments in terms of life extension are needed. Similarly for investments in diagnostics and monitoring systems, or investments in more frequent periodic condition assessments, data on when in terms of asset life or condition such investments were made and the effectiveness in terms of avoidance of in-service failures and/or life extension are needed. In the following section, methods for the analysis of failure/replacement data are described in order to illustrate the methodology; however these statistical analysis methods are adaptable to other types of data.

5.1.3 Data Analysis

Business case analysis involves the need to estimate the numbers of failures or replacements or other metrics going forward in time over the business planning period. The estimated numbers of failure/replacements for each year going forward over the planning period are a function of the asset class demographics and the likelihood of events of interest (failures and/or replacements) happening over the business planning period.

The actuarial methodology (section 6.5) used for that purpose requires a function that describes the likelihood of assets operating up to each year forward in the planning period, and in those specific years, either failing or needing to be replaced depending on the strategy being analyzed. The function that provides this information is the hazard rate function or as it is commonly referred to as the bathtub curve. Therefore it is necessary to derive the hazard rate function from the available data.

Fortunately, well established statistical methods [14] are available that can be used to develop the hazard rate function and the cumulative hazard function from current and historical asset population data. These functions are well described in standard statistical texts or on the web as in [15]. The following simple hypothetical example, assuming a maximum of 50 years useful service life, illustrates the method for the case of equipment failure/replacement.

The first requirement is to obtain comprehensive data for the population of assets in question. This includes not only data on failed assets but also assets in the same population that continue in service. It is important to include these surviving assets, because obviously the fact that they continue to operate is relevant to the analysis. As shown in Table 5.1-1 below, assets in the population are listed in order of their service life in a simple tabular form preferably in a spread sheet. In this example, failed units are shown in bold face type. Next a column for the reverse rank is filled out. The hazard rate is then calculated for the failed units only; but clearly these point estimates for the hazard rate function are influenced by the numbers of surviving assets in the population. Next the cumulative hazard rate can be calculated.

Asset Service Life (Years)	**Reverse Rank K**	**Hazard Rate 1/k**	**Cumulative Hazard**
2	30		
4	29		
5	28		
7	27		
9	26		
11	25		
12	24		
14	23		
15	22		
16	21	0.048	0.048
18	20		
19	19		
22	18		
23	17	0.059	0.107
25	16		
27	15	0.067	0.174
29	14		
30	13		
31	12	0.083	0.257
33	11		
34	10		
37	9	0.111	0.368
39	8	0.125	0.493
41	7		
42	6		
44	5	0.2	0.693
45	4		
47	3	0.333	1.026
48	2		
50	1		

Table 5.1-1 Example population data

It is then convenient to tabulate the service life and cumulative hazard rate in a separate table to facilitate plotting as shown in Table 5.1-2.

Service Life	**Cumulative Hazard**
16	0.048
23	0.107
27	0.174
31	0.257
37	0.368
39	0.493
44	0.693
47	1.026

Table 5.1-2 Summarized hazard function data

For business case analysis, a continuous function is required as opposed to a few point estimates, therefore it is useful to carry out a curve fitting calculation. This is readily done in a spread sheet by setting up corresponding data using standard statistical functions (Normal, Weibull, Extreme Value etc.) adjusting their parameters to optimize the fit and then comparing the results for the various functions to select the function which gives the best fit as determined by goodness of fit, or other methods.

Table 5.1-3 shown below illustrates a portion of such a table for the case of a Normal distribution curve fit. It is necessary to vary the statistical parameters (the mean and standard deviation) in order to move the fitted curve into the best fit with the point estimates derived from the population data. Least squares fitting can be used to optimize the fit. The resulting curve is shown in Figure 5.1-1 below.

		Service Life	**Normal Cumulative Hazard**	**Hazard Rate**	**Normal Density**	**Normal Cumulative**
Mean	43	1	0.00052905	0.000529	0.0005277	0.00255513
SD	15	2	0.00116563	0.000637	0.0006346	0.00313484
		3	0.00192828	0.000763	0.0007597	0.00383038
		4	0.00283805	0.00091	0.0009055	0.00466119
		5	0.00391868	0.001081	0.0010745	0.00564917
		6	0.0051968	0.001278	0.0012694	0.00681886
		7	0.0067021	0.001505	0.001493	0.00819754
		8	0.00846756	0.001765	0.0017481	0.00981533
		9	0.01052951	0.002062	0.0020378	0.0117053
		10	0.01292783	0.002398	0.002365	0.01390345
		11	0.01570601	0.002778	0.0027325	0.0164487
		12	0.01891124	0.003205	0.0031431	0.01938279

		13	0.02259443	0.003683	0.0035994	0.02275013
		14	0.02681021	0.004216	0.0041037	0.02659757

Table 5.1-3 A portion of the curve fitting calculation

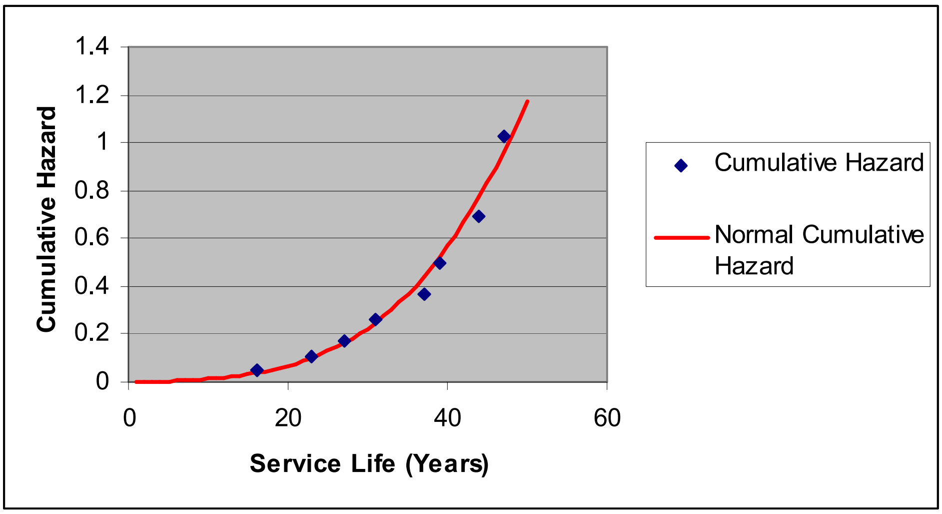


Figure 5.1-1 Example of hazard function calculation and curve fitting

Figure 5.1-2 below shows the results of this methodology when applied to a population of more than 23,000 distribution class transformers.

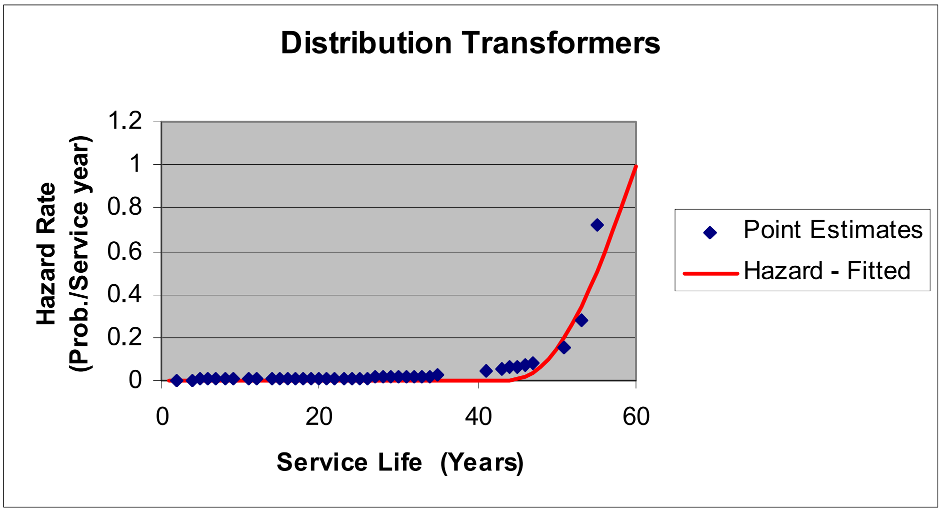


Figure 5.1-2 Hazard rate function for a population of distribution class transformers

While the population of distribution class transformers from a single utility is very large it is also very uniform in the sense that the transformers were all of a similar size, operated in a common environment, loaded similarly and maintained similarly. Therefore the point estimate data could be fitted reasonably well to a simple Normal hazard rate function. This is not always the case as illustrated in the following paragraphs.

A utility has a population of assets with a demographic distribution shown in Figure 5.1-3.

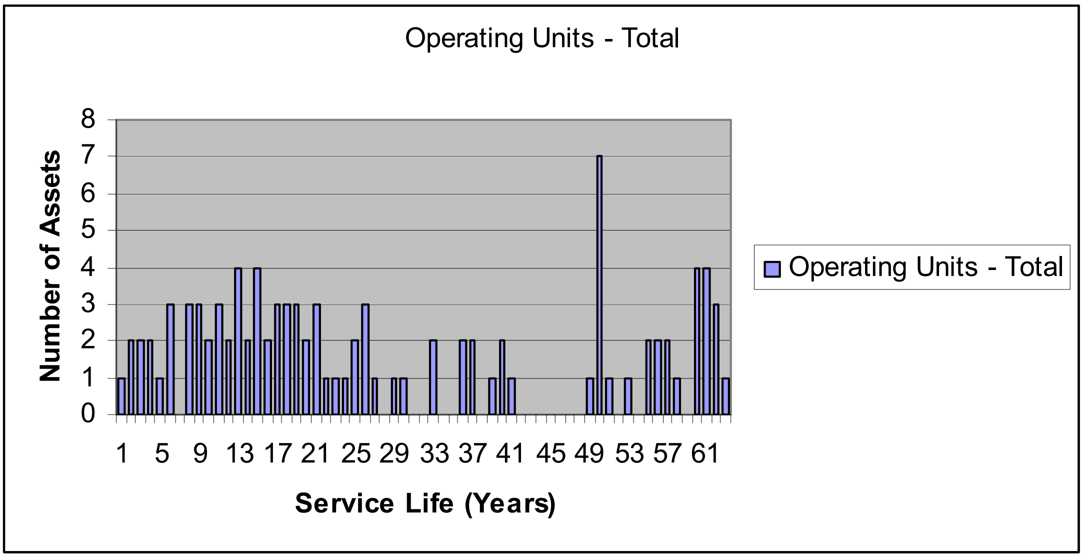


Figure 5.1-3 Asset demographic distribution for whole population

When the population is analyzed as described previously including the failure/replacement data, the distribution of point estimates shown in Figure 5.1-4 is obtained for the hazard function.

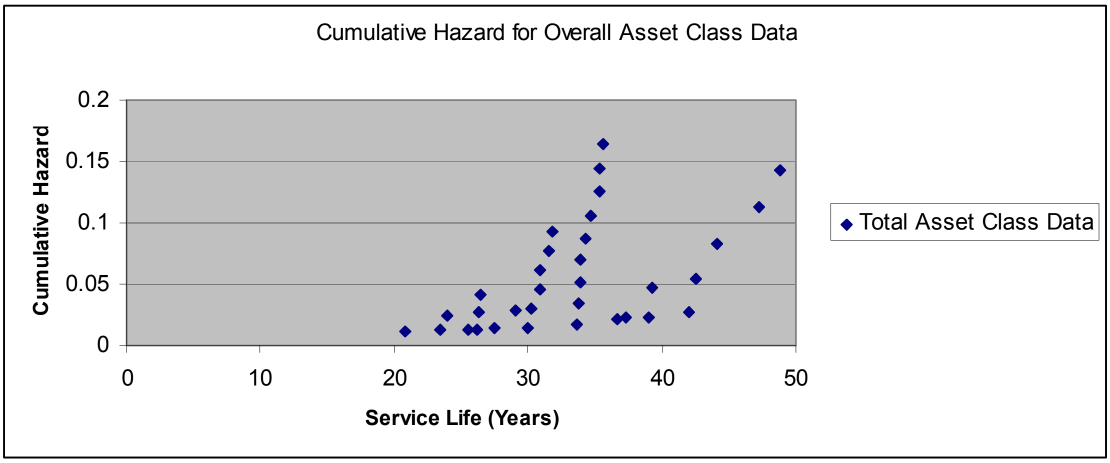


Figure 5.1-4 Distribution of point estimates for the cumulative hazard function

Clearly to get a tight fit between the point estimates and any standard statistical distribution would be very difficult for this result. However, in this case, the asset managers were aware that this population is composed of two types of units (this could be units from two differing manufacturers, two differing operating environments, two differing applications or any other physically based rationale) and therefore the population could be separated into two distinct populations. The result after grouping the data into the two distinct categories is shown below in Figure 5.1-5 and Figure 5.1-6.

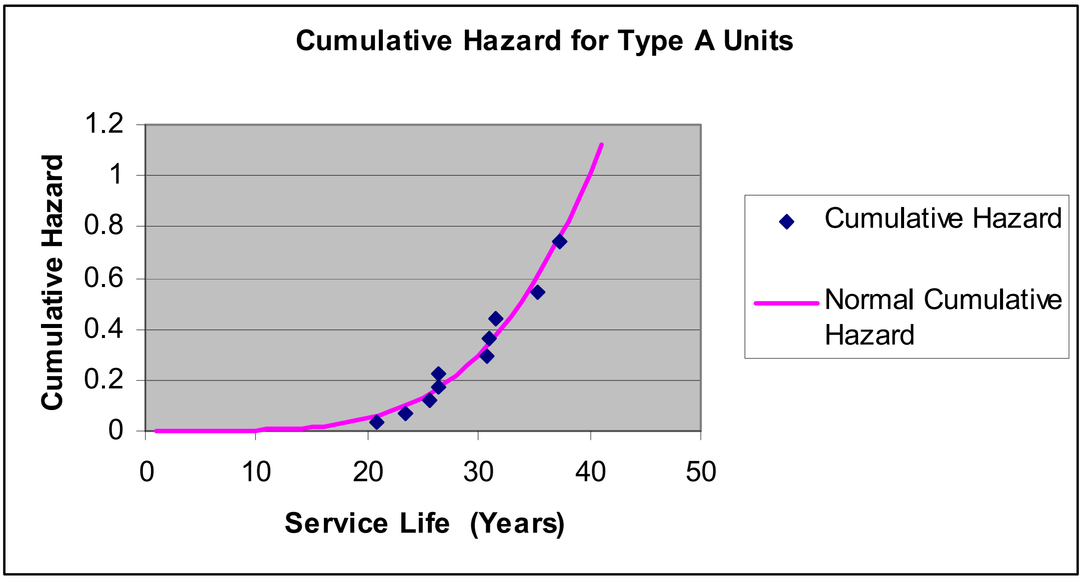


Figure 5.1-5 Cumulative hazard function for type A units

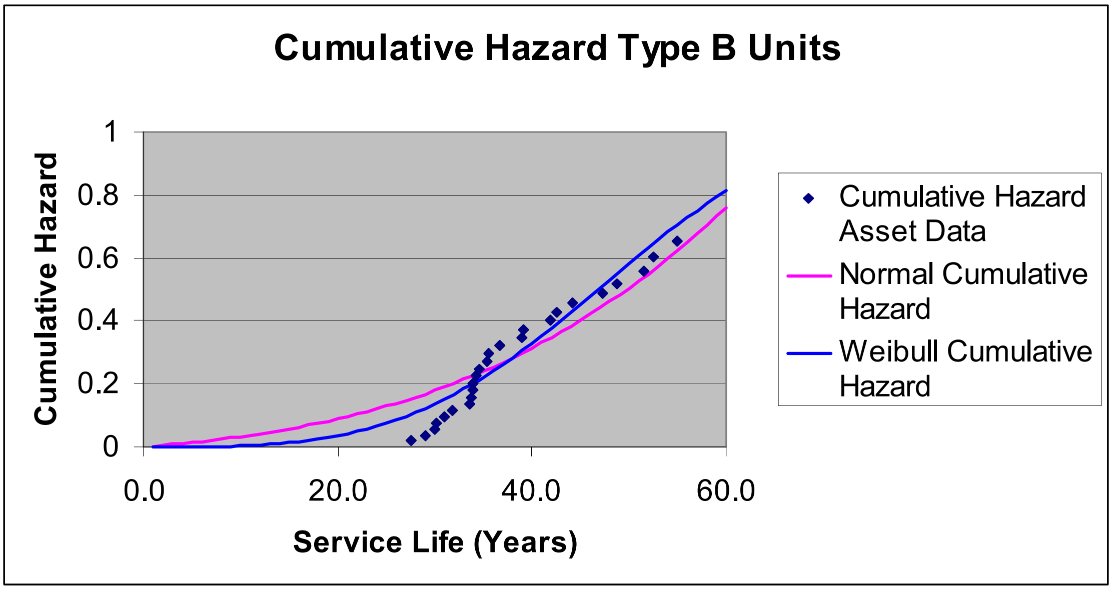


Figure 5.1-6 Cumulative hazard function for type B units

As can be seen Type A units results fit well with a Normal cumulative hazard function; but in the case of the type B units, a Weibull distribution fits better than the Normal distribution. Other distributions (for example Extreme Value Type 1, or Gumbel distributions) may be better than the Weibull or Normal, so it is preferable to try as many distributions as necessary to obtain a suitable fit. The important point in this example is that data need to be grouped as much as necessary to obtain statistically homogenous populations.

Once a suitable fit with a standard statistical distribution has been obtained the parameters for these distributions can be used to obtain the respective hazard rate function for the population of assets. This function can then be utilized in the actuarial methods described in section 6.5 to build the necessary business cases.

5.1.4 Sparse or Problematic Data

In some cases data may be limited, of questionable validity or simply non-existent. What options are available to asset managers in these circumstances? Fortunately utilities are beginning to recognize the importance of data in building credible business cases for investment justifications to senior managements and regulators. As a result several Study Committees in CIGRÉ are attempting to collect such data, and as well as some utilities have made public through the regulatory process useful data.

For example, shown in Figure 5.1-7, is a copy of a page from a report by KEMA [16] which includes their opinion on asset lives as well as those of the National Grid Company of the UK. The table includes data on the median of the life distributions and the Earliest Onset of Significant Unreliability (EOSU) and as well the Latest Onset of Significant Unreliability (LOSU) as determined by National Grid. Also included in the table are KEMA estimates for the means and standard deviations as well the standard deviations on these statistics.

Depending on the relevance of these data to specific asset populations operating in other utilities, these data may have some use for comparison purposes, at the least, and possibly for calibration purposes in the case of sparse data. For example if data for an asset population results in only a few point estimates for the hazard rate function some degree of corroberation can be attained by comparing the point estimates with industry data as illustrated in Figure 5.1-8. In this example a hazard rate function has been plotted which corresponds with the data for 132 kV transformers in Figure 5.1-7, namely a mean life of 55 years with a standard deviation of 10 years. Plotted with that are point estimates for three failures. In this case the data compares well with the industry data and therefore it would support the conclusion that the industry data can be used to represent the population from which the sparse data were obtained.

Clearly more data and better data is to be preferred over poor data or no data. Some may argue that some data, whatever the source is better than no data at all so long as it results in an acceptable answer. However the one factor which an asset manager must always defend is his/her integrity in producing business case analyses. There will always be some degree of uncertainty in such calculations, for example in the financial analysis the prospective inflation rate and discount rates must be set in order to carry out present value calculations. Both of these data are very difficult to predict and the uncertainty in these may well exceed any uncertainty in asset life data. Nevertheless, the time and effort in mining for the best possible asset life data will inevitably be rewarded with better asset management decisions and enhanced credibility and reputations for the asset managers who put these decisions forward for approval.

Asset category	NGET		KEMA	
	Median	EOSU (2.5%) / LOSU (97.5%)	Mean	Standard deviation
Transformers 400/275 kV 500 MVA – 750 MVA	45	30 / 70	50 (1.25)	7.5 (1.00)
Transformers 400/275 kV 1000 MVA	55	40 / 80	50 (1.25)	7.5 (1.00)
Transformer 400/132 kV GSP / GSP EE 240	55	40 / 80	50 (1.25)	7.5 (1.00)
Transformer 400/132 kV GSP FER 240	50	35 / 75	50 (1.25)	7.5 (1.00)
Transformers 275 kV	55	40 / 80	52,5 (1.25)	10 (1.00)
Transformers 132 kV	55	40 / 80	55 (1.25)	10 (1.00)
Shunt reactors	45	25 / 60	45 (1.25)	7.5 (1.00)
Series reactors	55	40 / 80	55 (1.25)	7.5 (1.00)
Capacitor bank	30	20 / 40	35 (1.25)	7.5 (1.00)
Static Var comp	30	15 / 40	25 (1.25)	5 (1.00)
Switchgear 400 kV GIS outd	40	25 / 60	35 (1.25)	5 (1.00)
Switchgear 400 kV GIS ind	50	40 / 60	45 (1.25)	7.5 (1.00)
Switchgear 400 kV SF6	50	40 / 60	47.5 (1.25)	7.5 (1.00)
Switchgear 400 kV PAB R	50	45 / 60	47.5 (1.25)	7.5 (1.00)
Switchgear 400 kV PAB N	40	35 / 45	47.5 (1.25)	7.5 (1.00)
Switchgear 275 kV bulk oil	45	40 / 50	47.5 (1.25)	7.5 (1.00)

Figure 5.1-7 Sample of industry asset life statistical data

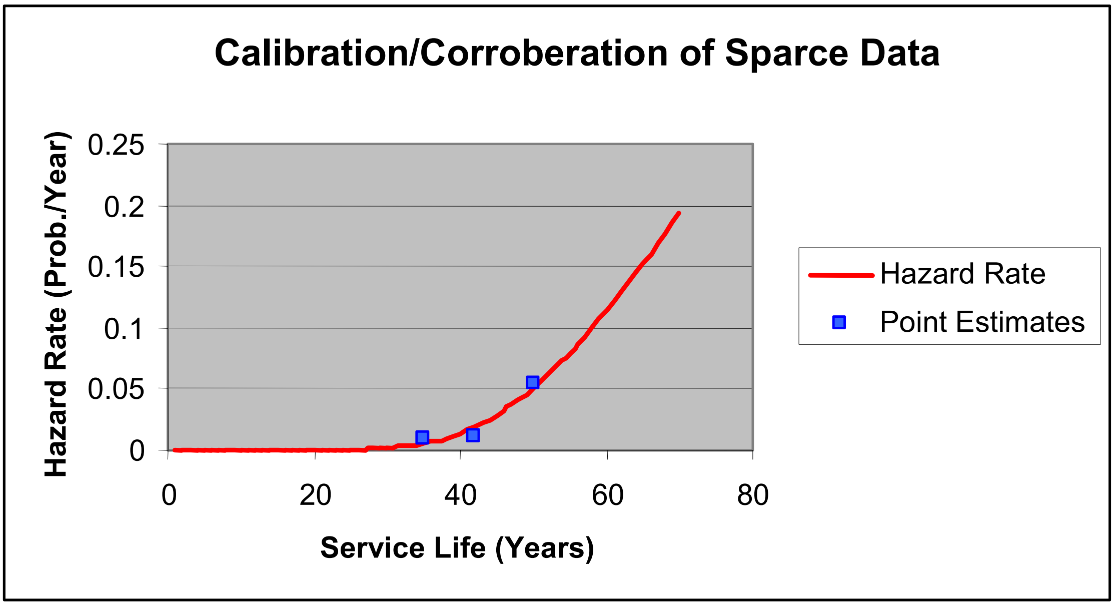


Figure 5.1-8 Use of industry data in comparison with sparse point estimates

5.2 Risk of equipment performance

5.2.1 Risk Control – Objectives for Operational Asset Management

An objective for operational asset managers and maintenance engineers respectively is the ability to control the risk of specific equipment performance. Different methods are used by system operators and range from fundamental research in combination with public statistics to practical choices based on expert knowledge of special maintenance and equipment engineers.

5.2.1.1 Modelling the relation between Maintenance and Risk

Ways to identify risks have already been described in 2.1.3. The focus of this section lies on the relation between maintenance and failure occurrences. In this content the condition of the asset is often used to express the asset behaviour.

The condition of the asset is a potential indicator for the probability of the future asset performance. But questions about applicable parameters that determine the condition are very complex to identify. Condition parameters can not only be derived from obvious information like construction year, existing technical features or average failure rates, but also information about maintenance know-how and how the service staff apply maintenance on specific assets should be considered.

Therefore the impact of maintenance on the asset condition and resultant failure occurrences has to be identified. Knowledge about findings during specific maintenance measures and the integration of expert know-how should be taken into account to model the relation between maintenance and operational risk. One approach to integrate this additional information (findings and expert know-how) is presented in the example below.

5.2.1.2 The Chain of Impact of Maintenance on Asset Performance

All network operators apply different maintenance measures to their transmission assets. The objective of these measures is to avoid failures, to keep equipment quality and to derive (preventive) actions to minimize the failure probability.

One objective of operational asset management is the risk control of asset behaviour. To achieve risk control in combination with maintenance measures the chain shown in Figure 5.2-1 has to be observed. The chain illustrates three links (boxes) dealing with maintenance information

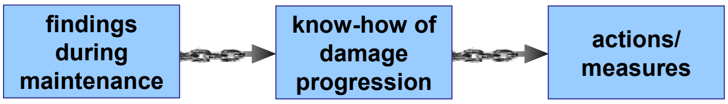


Figure 5.2-1 The Chain of impact of maintenance

The first chain link presents the knowledge about findings and damage frequencies in conjunction with applied maintenance measures. In addition, a certain measure can be assessed due to their efficiency. If the measure cannot discover any damage which has an effect on the equipment performance the measure is unessential consequently.

The knowledge by asset experts is demonstrated by the second chain link. Here, the expert know-how is directly linked to the findings in the previous chain link. Because experts are able to comment and to assess findings and know or can estimate from past experience and knowledge of the stresses acting on the asset, the progression of the damage. So it is possible to provide some information on the likelihood of future failure occurrences. Certainly, in this case it is very complex to describe this information with mathematical tools (cf. example below).

The last link in this chain illustrates the actions and measures which can be derived by the results of both previous links. Hence, the damage progression should be affected or impeded by special actions taken by the asset experts. To control the operational risk, the identification of measures to avoid future failures and to increase asset life time is crucial.

If the chain of impact of maintenance is known all relevant information is given to control the risk by applying the correct maintenance measure at the right time.

5.2.2 Example – Study of a 123 kV SF6 Puffer Type Circuit Breaker

This example demonstrates a model called m2M-Model (the progression of minor-to-Major-failure) based on heuristic knowledge (field experience and equipment know-how), previous failure occurrences and inspected data (historic maintenance records) with the ability to simulate the progression of an identified type of damage to a failure occurrence. The m2M-Model supports the operational asset management to identify the operational risk due to higher failure occurrences and due to reduced asset life times respectively. In [17] an approach to estimate optimal maintenance intervals based on failure data and the so called event free time is introduced, that also deals with calculated ageing curves. In this example, a 123 kV circuit breaker (puffer principle and hydraulic drive mechanism) is under investigation [8].

5.2.2.1 Identification of damages during maintenance measures

One way to identify damages which could be found during a specific maintenance procedure is to analyze historic protocols in a systematic way for a certain asset. Here, protocols of an elaborate procedure (comparable with an overhauling) are analyzed with respect to the findings and damage frequencies respectively (one protocol consists of more than 100 service points).

The results are shown in Figure 5.2-2. Consequently the repair of the protective coating is the measure carried out most often, namely in approximately 35% of services. In addition, defective control commands (27%) and the SF_6 pressure (22%) had to be corrected. Moreover, in the area of the control unit, the commands for pump inhibition (19%) of the hydraulic drive and the function lock (18%) of the circuit breaker are partially ineffective.

All further damage types identified by service procedures lie in the frequency range of approximately 10% and below.

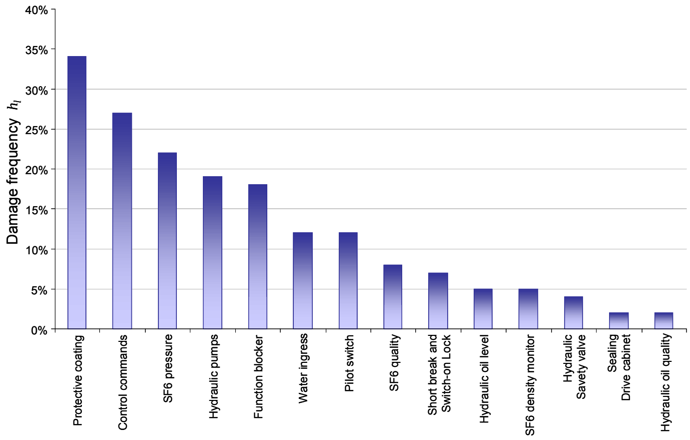


Figure 5.2-2 Damage identified during servicing

5.2.2.2 Progression of damage to a failure occurrence

As a result of a deferred service procedure, the damage (minor failure) which would normally be discovered is not remedied and therefore can subsequently progress to a failure (major failure) occurrence (m2M). The damage frequencies detected by the service procedure can thus be used as an approach for future development of failures and thus negatively influence the ageing behaviour.

The estimated failure occurrence after the normal service interval is exceeded is thus apparent as a superposition of the previously calculated failure occurrence (λ_i) with the additional failures which occur as a result of damage. Therefore, for the changed behaviour, the following failure occurrence is produced

$$\hat{\lambda}_i = \lambda_i + \Delta\hat{\lambda}_i \qquad (1)$$

with the estimated additional failures

$$\Delta\hat{\lambda}_i = \sum_{l=1}^{n} \bar{h}_l \cdot p_{l,i} \qquad (2)$$

The average damage frequency $\overline{h_l}$ relates to the service points $l = 1...n$ (cf. Figure 5.2-2). $p_{l,i}$ designates the probability to be set for service point l for a failure occurrence at time i. (see also formula (3) and Figure 5.2-3.

Many years of experience in dealing with diagnosed damage in the case of services and inspections suggest that some types of damage grow exponentially in terms of their extent. It can be concluded from this that the probability that such damage progresses to a failure also rises exponentially.

For other types of damage, it can be assumed that they had already, for example, been present since production or since commissioning of the equipment and no further change takes place. The probability of a failure as a result of such damage is then evenly distributed across the entire operating time.

In order to describe the progression of damage to a failure, a density function with two parameters was selected which is shown as an example in Figure 5.2-3 (Details about the derivation of the density function, see [8])

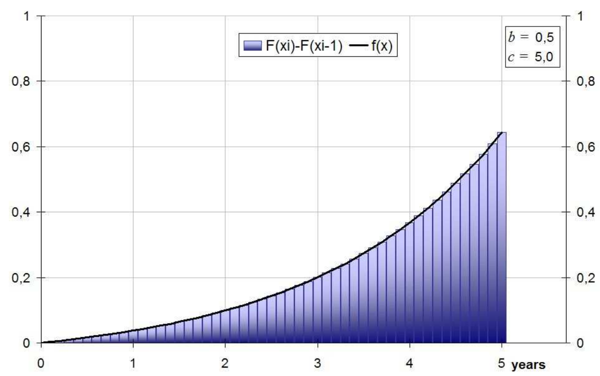


Figure 5.2-3 Density function of a damage progression

The parameter b describes the course of damage progression. The parameter c represents the maximum time until the potential failure occurrence. All of the potential damage progressions can thus be simulated with the help of a function.

The discrete individual probabilities $p_{l,i}$ are now thus produced by:

$$p_{l,i} = F_l(x_i) - F_l(x_{i-1}) \qquad (3)$$

Each service point (cf. Figure 5.2-2) can now be assigned a specific damage model. It must furthermore be taken into account that in general this approach involves the simulation of the worst case scenario since almost all the damage discovered during a service progresses into a failure with an average frequency of $\overline{h_l} \geq 1\%$.

5.2.2.3 Risk of increased ageing behaviour in case of a deferred maintenance

Figure 5.2-4 shows a comparison of the estimated ageing behaviour in three scenarios as a function of the service cycle (8, 10, and 12 year cycles). Function S8 illustrates the reference scenario with a service cycle of 8 years and is derived from historic failure occurrences. The ageing behaviour in the S10 scenario makes it clear that, despite the previously assumed worst case estimates, the fault occurrence is only slightly increased. In comparison to the reference scenario, a minimum higher increase in the failure probability can be expected here from an operating age of approximately 20 years.

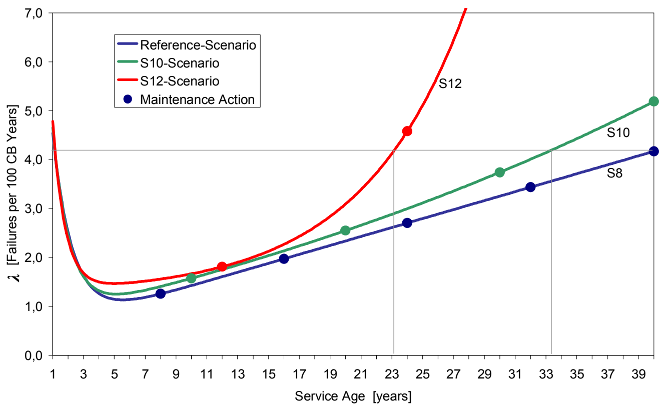


Figure 5.2-4 Forecast of the failure occurrence in the case of a deferred service cycle

If the service cycle is, however, delayed by 4 years into the future (S12 scenario), this influence is characterised by a highly exponential increase in the failure probability from an age of 15 years

In the case of current maintenance, 123 kV circuit breakers are sometimes in operation up to an age of more than 40 years [20]. But if deferred maintenance actions are considered the risk due to higher failure occurrences and maybe reduced asset life times has to be included in methods for operational asset management.

Under the assumption that the circuit breaker under consideration here achieves an operating time of 40 years when applying the actual maintenance (reference scenario), this circuit breaker will be in operation up to a failure probability of $\lambda \geq 4.0$ failures per 100 CB years (see Figure 5.2-4).

Accepted that this failure probability in the other scenarios is regarded as the maximum value, the operating period in the W12 scenario would be cut to approximately 23 years and thus reduced by approximately 43%.

5.2.2.4 Results and lessons learned

According to the m2M-Model the risk in case of deferred maintenance can be indentified and assessed qualitatively. In this case the consequence is a higher failure occurrence, so the asset performance is worse respectively, and if the worst comes to the worst, the asset life time will be reduced significantly. Furthermore the probability of this event can be delivered by heuristic knowledge (expert know-how and field experience) and by damages inspected during maintenance actions. Hence, this probability is a combination of available data (historic protocols) and assumed probability functions by asset experts.

The conclusion is that the chain of operational risk (see Figure 5.2-1) has to be known to control and assess the risk qualitatively. Information about actions and measures which should be derived by failures was not mentioned in this example. But this third part in the chain is very important to adjust the operational risk.

As a result, the example shows that useful information is often available and can be used to model the relation between maintenance and operational risk.

5.2.3 Information Required – Data and Expert Knowledge

According to the Chain of risk control and the conclusions mentioned above the following comments on useful data and functional information will be given here.

5.2.3.1 Data about historic failure occurrences and maintenance records

Scores of publications deal with systematic methods to record failure occurrences of specific high voltage assets, e.g. [20, 21]. In spite of this many network operators are not able to record data systematically mainly due to their complex business structures and to their historically grown databases. In addition, different definitions of failure types are used and in consequence data of different operators are not comparable. Even the Cigré definitions for minor and major failure are not applicable for many operators. But it is a matter of common knowledge, that historic failure records are essential to deliver ageing models for specific assets.

Which other useful data should be collected?

Maintenance protocols are often used by operators in a very simple way. Mainly these protocols – often in paper format– consist of checkpoints whose numbers depend on the specific maintenance measure. Originally a maintenance protocol was not used for the purpose of damage documentation, rather it was a guideline or a preparatory document for service employees. These records, often comprising more than 100 servicing points, can now often be largely used to evaluate images of damage [8]. Which measure is able to inspect damages or even to correct them?

5.2.3.2 Expert knowledge about failure progression on specific assets

Considering the expert knowledge it is obvious that this information is difficult to manage. But in combination with maintenance – especially if special assets are considered – expert knowledge is indispensable to assess certain maintenance points and specific kinds of damages. These experts knows the correlation between actions of the service staff (and also how they document their actions) and potential failure occurrences. In addition, asset experts can describe the progression of certain damages and anticipate future asset behaviour, because they know the interaction between different failure mechanisms and the stresses imposed on the assets.

As a result, it is possible to use this expert information in connection with mathematical tools (see appendix H) to model the relation between maintenance and operational risk.

5.3 Value at Risk

5.3.1 Introduction

As power failures are connected with more or less serious consequences, the task of the risk management is to identify, qualify and if necessarily to minimize these risks associated with such outages. The Value at Risk method (VaR) is a possibility to estimate the total risk of a power system [31].

5.3.2 VaR-Model

The prerequisite for the derivation of VaR is the definition of an appropriate amount of portfolio return and in this case the portfolio is the collection of investments e.g. in the power supply area:

transformers, cables, circuit-breakers and so on. The difference between the values of the portfolio during a time span is stochastic. The background is to calculate the value of the portfolio in the future if the assumptions regarding the probability distribution of the factors influencing the portfolio can be established. For this explanation of VaR concept the Normal distribution is used. The Normal distribution can be completely described by the expectation value μ and the standard deviation σ. Figure 5.3-1 shows a density function of a normal distribution with the expected value of 10 min. The colored area contains 95% of possible outcomes of this distribution and is called the VaR level with a confidence interval of 95 %, whereas in the opposite 5 % of outcomes exceeds the VaR.

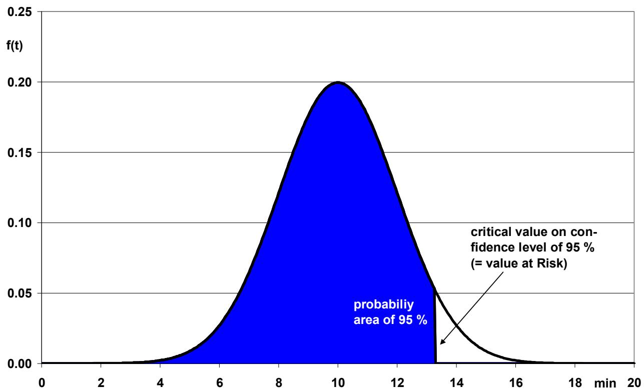


Figure 5.3-1 Graphical presentation of VaR by a Normal density function (duration of interruption)

The computation of the VaR requires the development of a VaR model [32]. According to [33] the general approach for the evaluation of VaR can be differentiated.

- ***Mapping procedure:*** Derivation of appropriated equipment portfolio including the factors which influence the portfolio and are called risk factors. The risk factors are subject to a stochastic process and are characterized by their expectation values and standard deviations.
- ***Inference procedure:*** Stochastic Characterization of risk factors (distribution of stochastic values) and as a result of this process the characterization of the risk factors regarding the statistic distribution and dependence is given.
- ***Transformation procedure:*** Combination of the results of the inference and the mapping procedures.

5.3.3 APPLICATION OF VAR MODEL TO A NETWORK

A simple example is considered to illustrate the application of the VaR concept to a number of components in a power system with their uncertainties to describe the assets of the network portfolio. Figure 5.3-2 shows the simple 20 kV network that is used to illustrate the VaR concept.

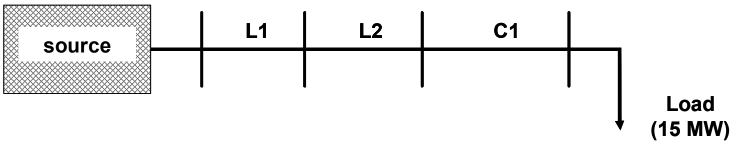


Figure 5.3-2 Simple 20 kV radial systems with overhead lines (L1, L2) and cable (C) connections

The 20 kV source feeds a load (e.g. 15 MW) radial via two overhead lines and a cable. The source and the bus bars are assumed to be ideal, so that the supply quality is only affected by the overhead lines and the cable. The value of the network portfolio is in general affected by the amount of the energy sold, values of operational asset and/or operational and outage costs. The evaluation of risk, which proceeds from the component condition and importance for the system reliability, takes place on the basis of failure frequencies and failure consequences [34]. The portfolio mapping equation (eq. 1) consists of two parts U_E and W_A, which represents the financial impact on the company as well as the present value of the system components.

$$P_N = U_E + W_A \qquad (1)$$

With P_N value of system performance

U_E financial impact on the company

W_A present value of system components

The financial impact on the company (U_E) implements several risk factors, for example:

- Price of electrical energy,
- Power consumption,
- Outage frequency of system nodes*,
- Penalties in case of an outage*,
- Interruption duration in case of an outage*.
-

The second part (W_A) of equation, which represents the present value of the operational assets, (1) includes the following risk factors:

- Financial value of the asset,
- Investment (e. g. planned replacement),
- Costs of forced outages (e. g. repair costs and costs of damages)*,
- Outage frequency of equipment*.

The risk factors which are signed by a star (*) are stochastic and therefore their distribution must be considered in the framework of VaR methodology.

5.3.4 RESULTS OF THE CALCULATION

The value of the asset portfolio can be split into two classes: The first class consists of constant values like cash values of the components and the sales revenue, which affect the portfolio value positively. The second part consists of stochastic factors including the probabilistic costs, which affect the value of the portfolio negatively (indicated by a star *). The last class is discussed further and the input data are listed in [31].

For simplification and in view of the central limit theorem the factors are assumed to be normally distributed. With the help of the transformation procedure the uncertainties of the risk factors can be reproduced for the value of the total system and in this case a Monte Carlo simulation can be used, because of the multiplicative relationship between the risk factors (outage frequency and outage duration). Finally the density distribution of failure frequency is combined (convolved) with the density distribution of failure duration to obtain the unavailability density distribution for system components. This leads to the distribution of probabilistic system costs depending on the outages (Figure 5.3-3). The red bar represents the VaR for a confidence level of 95 %. That means that 95 % of the possible outages will not exceed an amount of 46 T€ per year in this year. The result of the common reliability calculation, which uses mean values of the stochastic distribution, shows that the expected system costs are about 8.9 T€ (blue bar of Figure 5.3-3), which is less than 37 T€ of the VaR result.

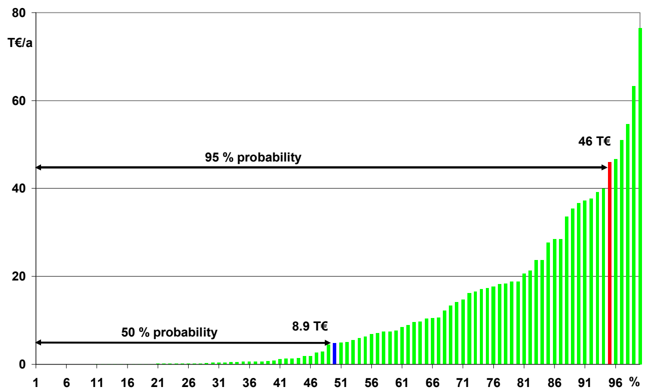


Figure 5.3-3 Result of the VaR calculation

5.3.5 CONCLUSION

While it is obvious that the results of the VaR calculation differ from the results of the conventional methods for reliability calculations, the great advantage of the VaR methodology is to give a deep insight into the risk structure of a system by analysis of its risk factors. Furthermore the development of a common basis for risk indicators can be effectively used for comparison of different systems; but in any case a great data base needs to be collected.

5.4 Asset Health Indices

In this section a method to assess the probability of asset failure is described and serves as an example of asset risk management at the operational level.

5.4.1 INTRODUCTION OF THE PRINCIPLE

To develop an understanding of the overall condition of an asset, many utilities use special indicators called "health indices". This indicator, "health index", is representative of the asset condition but in an easy way to be used by the Asset Manager in his own process for replacement strategy [4].

Even if the health index is one single overall indicator of the condition of an asset, it is in fact derived from all available condition indicators and expresses the technical condition in terms of the asset reliability of the probability of a failure. Usually it is derived by a weighing process of all available indicators.

The important asset groups requiring the development of Asset Health Indices (AHI), are transformers, circuit-breakers, protection relays, overhead lines and underground cables [4].

The document [43] presents an application of AHI for transformers.

As generally the condition of the asset is decreasing with time, the asset manager uses the relationship between AHI and the age of the asset, in order to find the time to replace or to refurbish the asset.

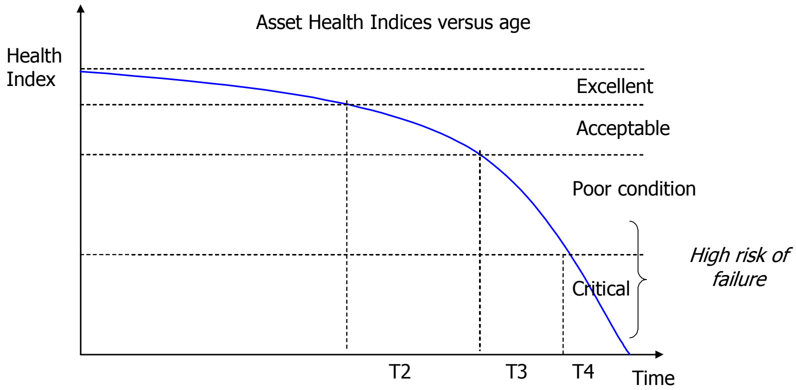


Figure 5.4-1 Asset Health Indices versus Asset Age

Figure 5.4-1 represents this relation between AHI and time:

- at the first part of an asset life (T1 duration), the condition is excellent and therefore the risk of failure is very low.
- Then the condition is decreasing, nevertheless the reliability is still acceptable (T2 period),
- Then the asset is in poor condition and the risk of failure increase (T3 period),
- For the last part, the condition is critical, the risk of failure is high and therefore the failure can occur very fast (T4 period).

The AHI is used by the Asset Manager as one of the inputs in a risk evaluation. AHI represents the technical part of the input. Next to the health indices, the Asset Manager uses information on the impact of a failure, the cost of the failure and the cost of mitigating measures. In fact, the AHI itself does not represent the impact, neither the cost. AHI is information transmitted from the operational level to the tactical level in order to implement by the Asset Manager, the condition of an asset in a risk assessment process.

5.4.2 Development of Asset Aggregate Health Indices

The simple representation of the previous paragraph helps to understand the general principle of health indices. In reality the exercise of scoring heath index of an asset is more complex. Finally the Asset Managers handle not really AHI but in fact aggregate asset health indices.

The aggregate Health Indices combines several factors using a multi-criteria assessment approach into a single indicator of the health of the asset, the system or the station.

The aggregate method follows this process: Firstly the asset is split in sub-parts, according the complexity of this asset. Then each sub-part gets a score according its own health index. The calculation of the final score, which is called aggregate health indices calculation, take into account the Health index score of each component of the whole asset. The components scores are weighted. Finally, the aggregate health index is processed as the result of all weighted sub-heath indices.

The following table presents an example of tool used for this aggregate health indices process.

Component	Weight (%)	Health index (E/A/P/C)
A	n1 %	H1
B	n2 %	H2
C	n3 %	H3
….		
Total	100 %	H

Table 5.4-1 Aggregated Health Indices $H = \sum_i H_i \cdot n_i$

The aggregate health index score gives information about the probability of failure for the asset. On the other hand, the impact of the failure has to be assessed. A similar approach is generally performed. The objective is to measure either the consequence the consequence of the failure or the importance of the asset in the grid.

5.4.3 Health Indices Example 1

Figure 5.4-2 presents an example of a description sheet filled by the operator during the maintenance or a circuit-breaker. This sheet uses the representation with the 4 time-periods developed in the previous paragraph. Thanks to this information, the asset manager gets an aggregate data on the probability of a failure for the circuit-breaker.

1. Component description	
Component:	**Operating mechanism / energy storage**
Type:	Hydraulic
2. Fault description	
Fault mode:	**Lack of energy**
Causes:	Poor gaskets Corrosion Defect pumps etc.
Fault progress:	Increasing leakage causing lack of energy and stuck breaker
3. Normal operational state	
Parameter	Description
Number of couplings	0-10 per year

4. Criteria for assessing the states	
Main state	Criteria
2	Visible corrosion, sweaty gaskets, minor leakages
3	Coupling time or tension time significantly changed Leakage
4	Major leakage (compressor starts frequently)
5 (failure)	Insufficient coupling energy (stuck breaker)

5. Duration of state 1-4					
		T_1	T_2	T_3	T_4
Typical (expected) duration of state 1-4:	time [years]	10	10	5	1
10^{th} percentile of the duration of state 1-4:	time [years]	5	5	2	0,1

Figure 5.4-2 Example of Heath Index report

5.4.4 HEALTH INDICES EXAMPLE 2

In the document [23], the objective followed is to rank all transformers of a Norwegian utility in order to find the transformers needing further scrutiny for deciding on remedial actions.

Each transformer gets a score, called: Global Criticality of transformer (GCT). This score is the result of process between the Global Strategic Impact (GSI) and the General Technical Condition (GTC).

The GSI represents the consequence of the failure. The GSI is assessed with a combination of the different values of the company, balanced by a weight for each of them (see the Table 5.4-2). Each value is scored by a figure (index) includes between 1 and 4.

Value	Weight (%)	Index (1/2/3/4)
Safety of the goods and people	27	x1
Safety of the electric systems	27	x2
Environment	18	x3
Competitiveness, financial aspects	10	X4
Image of the company	18	X5
GSI		$\sum_i x_i$

Table 5.4-2 GSI score table

Condition	Weight (%)	Index (1/2/3/4)
Health criterion of the transformer	50	x1
Technological criterion	10	x2
Age criterion	20	x3
Operational criterion	20	X4
GTC		$\sum_i x_i$

Table 5.4-3 GTC score table

In the same way, the GTC calculation follows the model presented in Table 5.4-3:

The GTC is in fact an Asset Health Index of the transformer. This example shows that in reality the utility uses a combination of different factors: an aggregate health index.

The document [23] gives further explanations about the method to determinate the index value for each item. The representation of GSI cross to GTC is presented in Figure 5.4-3. As a matrix of risk management, the graph represents the critical situations where a remedial action is expected.

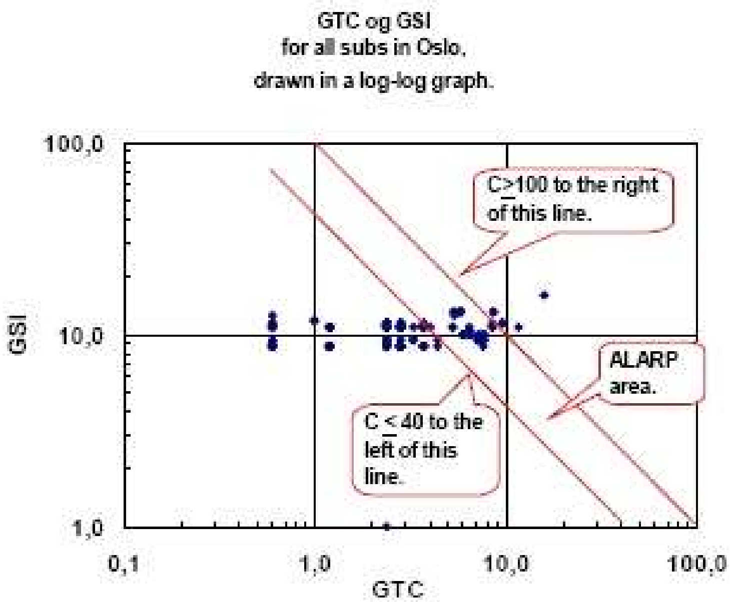


Figure 5.4-3 GSI and GTC graph

This example shows as the Health Indices model is implemented by the Asset Manager in order to take into account the asset condition for the risk assessment process.

5.5 Continual Improvement of Risk Indicators

Chapter 5, describes approaches related to operational asset management using several examples from the working group.

- Asset Data for business case analysis
- Risk of equipment performance
- Value at Risk
- Asset Health Indices

The collection of data to model the failure behavior of assets is a key responsibility for operational asset management. In the first section of this chapter a method is described to derive failure curves from sparse asset data. These failure curves are used by tactical asset managers in business case analysis.

Minor failures may lead to major failures. A minor failure may be a risk indicator with predictive value. A new approach, called "the m2M-model", based on heuristic knowledge (field experience and equipment know-how) was described and is still under optimization. It uses previous failure occurrences and inspected damage records (historic maintenance records) to simulate the progression of an inspected damage to a failure state. Hence, the operational risk due to higher failure occurrences and due to reduced asset life times, can be identified by using this new approach.

A few decades ago the concept Value at Risk was introduced in the financial world as a risk indicator for portfolios of financial assets. The concept can also be used to estimate the total risk of a power system. The advantage of the VaR methodology is to give deep insight into the risk structure of a system by analysis of its risk factors. Furthermore the development of a common basis for risk indicators can be effectively used for comparison of different systems; but in any case a substantial data base needs to be collected.

The Asset Health Index is another example of a risk indicator. The AHI is used by the Asset Manager as one of the qualitative inputs to a risk assessment. AHI represents the technical part of the input. In addition to the health indices, the Asset Manager uses information on the impact of a failure, the cost of the failure and the cost of mitigating measures.

Once the risk indicators are developed they must be continuously monitored, reviewed and improved for their predictive value of risks so that the asset manager has reliable input for his quantitative asset management decision making (tactical level asset risk management).

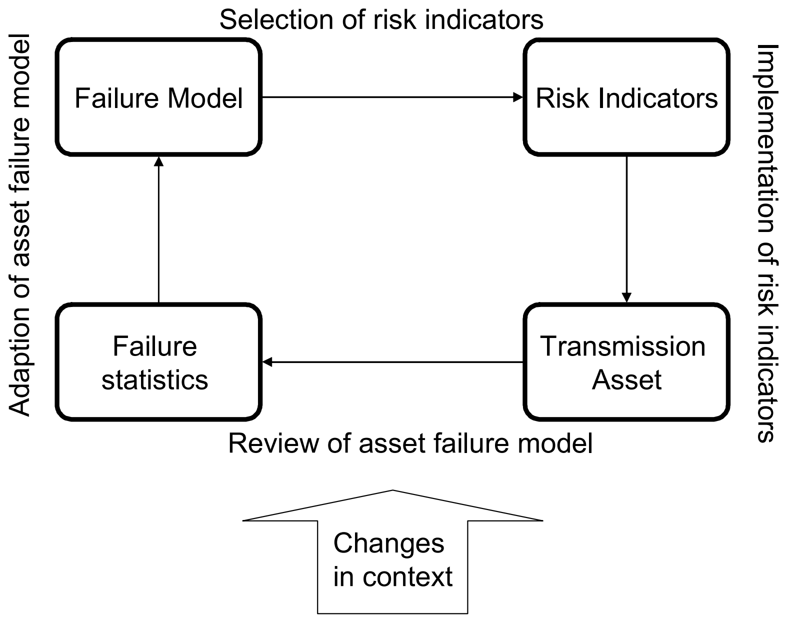


Figure 5.5-1 Continual improvement of risk indicators

6 TACTICAL ASSET MANAGEMENT – RISK MANAGEMENT ON TACTICAL LEVEL

In this chapter several approaches of risk management to help decision making on tactical asset management level are described.

6.1 Introduction

When the division into three level asset management is implemented the organization of the middle management arrangement problem comes to the fore in the tactical asset management level. The tactical layer of asset management is confronted with having to satisfy both strategic asset management and operational asset management needs, as well as manage the information and communications between the levels and justify the decisions made. The problem is how to decide on information from to the field with regard of the business as a whole. As explained in the previous chapters on strategic level the decision framework is set up and maintained on operational level work and the data from the field is delivered to the asset manager. On tactical level the asset manager uses the decision framework and the information from the field to decide on risks to be treated.

6.2 Risk register and Risk Management Cycle

6.2.1 APPLICATION OF DECISION FRAMEWORK – INVESTMENT DECISIONS

The asset manager makes use of the decision framework and the data from the field for his risk treatment decisions. This example from a utility in the Netherlands is about a transmission capacity issue and it illustrates the application of the decision framework for a specific risky event. [4] The risks identified are linked to the business values service quality and image.

A city in the Netherlands (from the MW-consumption it can be concluded by the formula mentioned that there are 40,000 customers) is supplied through a 50/10 kV substation, that is fed by two paper/oil cables, one of which is a cold standby. The failure rate of the feeding cable is once per year and the time to switch over is estimated to be 20 minutes. Such a cable failure is an outage with 0.8 Million Customer Minutes Lost, thus it is an event with a serious consequence.

Once per year gives a risk that is assessed as medium, which may motivate a decision to reduce the risk in the coming years. But, given the fact that this incident, which indeed is not regarded as being a high or very high risk, occurs every year in the same city, another business value has to be considered as well: image to the authorities. Interruptions of the power supply every year will lead to an escalation level that within a couple of years (if nothing is done to mitigate the situation) will likely result in conflict with the local authorities. Risk consequence: severe, risk frequency < 10 years, risk assessment: H. Therefore, the normal procedure leads to a proposal for mitigations being written and to recommend the decisions that have to be taken.

Per incident	Image “attention in press”	Regulator “corrections”	Environment “clean-up-costs”	Image “authorities”	Financial “Damage ”	Quality “1.5*kW*min ”	Safety “victims ”	Legal “penalty ”
Catastrophic	> 1 month national	structural clashes	> 10 M€	structural clashes	> 10 M €	> 10 Mmin	several deaths	loss of licence
Severe	week national, month regional	single conflict	1 – 10 M€	single conflict	1- 10 M €	1- 10 Mmin	1 death/heavy handicap	imprisonment
Serious	TV-program, national article, week regional	dozens of corrections	0.1 – 1 M€	dozens of corrections	0,1 - 1 M€	0,1 - 1 Mmin	1 disabled	heavy fine
Moderate	regional article, complaint in newspaper	< 10 corrections	< 100 k€	< 10 corrections	< 100 k €	< 100 kmin	longlasting absenteeism	condemnation

Probabilty/effect	# per year	Catastrophic	Severe	Serious	Moderate
Permanent	>1000	VH	VH	VH	H
Daily	>100	VH	VH	H	M
Monthly	>10	VH	VH	H	M
Yearly	>1	VH	H	M	L
Frequently	>0,1	VH	H	M	L
Probable	>0,01	H	M	L	N
Possible	>0,001	H	M	L	N
Not likely	>0,0001	M	L	N	N
Almost impossible	<0,0001	L	L	N	N

Figure 6.2-1 Decision Framework

6.2.2 Asset Condition and Business Value

The asset manager makes use of the decision framework and the data from the field for his risk treatment decisions. In this section the use of the decision framework to identify key assets for the company, to enable risk analysis and to prioritize maintenance and replacement is illustrated. The following examples are discussed.

In an example involving circuit breakers the decision is whether to maintain or to replace. In this example the decision solely depends on the condition of the asset. The asset importance indicator is used to decide on which CB maintenance or replacement should start. The decision to replace or refurbish is evaluated by calculating a “System Performance Index”. [7]

In an example relating to oil-pressurized cables the decision whether to maintain or replace depends on the condition (age, no. of oil additions/year) and the importance to business values (amount and rate of oil leakage) of the asset. The decision to replace depends on the magnitude of the overall business. [E]

A generic problem is described in the case from France: when the same failure happens twice it is time for analysis and possible treatment. Data from the operational level: failures. From the strategic level: safety for environment. From the tactical level: analysis and risk treatment measures. [A]

To perform a risk analysis as treated in Chapter 2 for asset management one needs to have a decision model to be able to identify the top events and their consequences for the business. Information is needed to find the causes and sources of the events. This is based on data from the field that has been transformed by operational asset management into useful information. So a close cooperation between experts and asset managers is needed to have a thorough and accepted risk analysis.

6.2.3 Risk Register

The decision framework needs to be used to prioritize risks and the risk treatment measures. A risk register can be set up as a ranking tool.

An overview of risks and risk assessments is not only helpful to allocate financial means and other restricted resources (e.g. expertise, materials available, information), but may also help to focus the asset managers themselves on the most urgent jobs (risks). The next figure shows a tool designed by a utility from the Netherlands to log risks from all sorts of information sources (service providers, failure data, load and capacity data, maintenance data, governmental plans, legal end regulator developments, specialized studies, consultants, company staff, operators, etc.), to give a risk ranking, to communicate and discuss this provisional ranking, to set priorities for the asset managers and to develop plans for the coming years. In a second step the risks with the highest priority have been assessed more accurately, giving detailed information to identify which risks have to be reduced with a very high priority (i.e. immediately) or with a high priority, thus leading to investment proposals (the first part of which is based on this accurate risk assessment). [4]

Figure 6.2-2 Example of Risk Register Record

6.2.4 Risk Management Cycle

An example of continual improvement of asset management decisions is the Risk Management Cycle used by a utility from The Netherlands where risks are identified, evaluated and treated. The interests of the company are laid down in the value model agreed between the Asset Owner and the Asset Manager. The objective of the Asset Manager is to optimize the return on all business values of all assets over their life cycle. To optimize the return, the asset manager is continually searching for improvement. The assets are regarded over their entire life cycle, so optimization takes place over a long term scope, as is appropriate for the assets. The core of the AM-process is the identification and assessment of risks and the decision to accept or reduce the risk.

- the analysis and assessment of the risks within and for the infrastructure along the business value model
- the decision to accept or reduce the risk
- the design and planning of the risk-reducing measures e.g. adaptation of maintenance plans, initiating investments in replacement or refurbishment
- the execution of the risk reducing measures e.g. execution of a replacement project

After this a new situation exists and the asset manager continues analyzing the risks in the adapted infrastructure.

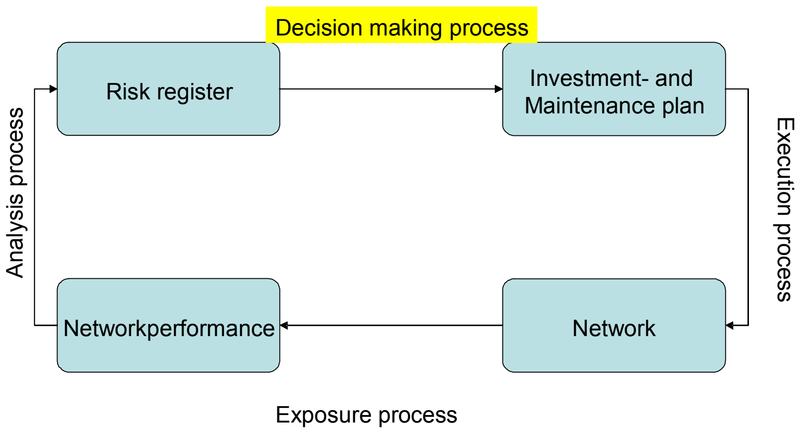


Figure 6.2-3 Risk Management Cycle, [4] and [53]

6.3 Life Cycle Costing

6.3.1 INTRODUCTION

In view of increasingly tight economic circumstances in the area of electrical power supply two terms are frequently discussed, which are used for the decision criteria of investments as well as for replacement strategies. These terms are the "Life Cycle Costs (LCC)" and the "Risk Analysis". The calculation of the life cycle cost is helpful in comparing of different variants or optional asset investments, for example if a new substations is being designed [24] comparison between an air insulated (AIS) and a gas insulated substation (GIS) may be needed. Furthermore the LCC calculation can be used to identify different parts of the overall cost analysis, e.g. the influence of the maintenance costs on the total present value.

The Risk Analysis for example should be performed if different maintenance strategies (no action, service, refurbishment or replacement) have to be compared. In this case not only the probable outage costs are compared with maintenance costs, but also the sociological aspects are taken into consideration.

An approach that could be seen as an expansion of the LCC concept is the Life Cycle Assessment approach (LCA). LCA is holistic approach accounting for all environmental impacts occurring from the system's "cradle" to the "grave", together with all related activities throughout the lifetime of the system. Hence, this approach accounts for environmental risks as a part the overall risk management.

The ISO 14040 standard series introduces some common guidelines for system boundary selection and presents a general LCA framework. The main ISO standards are listed below:

- ISO 14040 Environmental management -- Life cycle assessment -- Principles and framework [25]
- ISO 14041 Environmental management -- Life cycle assessment -- Goal and scope definition and inventory analysis [26]
- ISO 14042 Environmental management -- Life cycle assessment -- Life cycle impact assessment [27]
- ISO 14043 Environmental management -- Life cycle assessment -- Life cycle interpretation [28]
- ISO 14044 Environmental management -- Life cycle assessment -- Requirements and guidelines [29]

6.3.2 GENERAL CONSIDERATION AND DEFINITIONS

The calculation of the life cycle cost is performed according to IEC Standard 60300-3-3 "Dependability management; Part 3-3: Application guide – Life cycle costing" [30], with the exception that expenditure for operation and maintenance are treated separately. The various phases of life cycle costing are illustrated in Figure 6.3-1 below.

– concept/definition	– design/development	– manufacturing
– installation	– operation	– maintenance
– disposal.	–	–

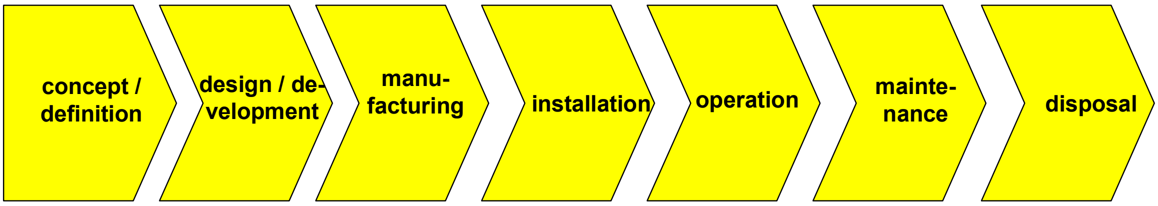


Figure 6.3-1 Life cycle phases according to IEC Standard 60300-3-3

Sometimes it makes sense to summarize different cost elements for:

- acquisition
- ownership
- disposal

The acquisition costs are known and can be estimated before the decision is made (concept/definition, design/development, manufacturing), whereas the ownership costs can not be easily predicted (operation, maintenance). The installation costs can be either counted as acquisition or ownership costs. The IEC-Standard [30] explains the different steps in general to calculate the life cycle costs, so that this procedure can be applied broadly. The activities in the different phases can be expressed as follows for a substation investment:

Concept/definition: Costs related to activities to ensure the feasibility of the substation, e.g. the time to prepare the specification and the concept.

Design/development: Costs attributed to activities to meet the substation requirements e.g. design engineering, documentation, vendor selection.

Manufacturing: The costs to manufacture the components of the substation as well as the marketing activities of the manufacturer belong to this phase.

Installation: All costs, which occur on site, have to be considered, for example for components these include transportation, civil works, installation of the earthing grid, tests, erection of the substation.

Operation: The expenditures to operate the complete substation have to be taken into consideration, for example power losses (transformers), labor costs to control the substation, consumables, initial training of the staff.

Maintenance: In general different maintenance strategies have to be taken into consideration, possible strategies are:

- corrective
- time based
- condition based.

A reliability centered strategy will not lead to a different assessment of maintenance expenditure, compared to the condition based maintenance. The difference is that only the priority of the maintained equipment is changed to due the importance of the equipment for the entire system. Depending on different maintenance strategies various parameters have to be used:

Corrective maintenance: The replacement of the equipment will taken place after failure. This means only "major" failures and their probable expenses per year (human as well as material resources) have to be considered. The consequence is that a service will not be applied.

Time based maintenance: All activities (incl. replacement) will be performed according to fixed time intervals, so that all expenditures for inspections and overhauls (depending on the time) have to be considered. In addition the probable human as well as material costs to repair the equipment due to the "minor" and "major" failure rate have to be taken into consideration.

Conditioned based maintenance: All activities (incl. replacement) will be performed according to the condition of the equipment. The implication is that expenditures for inspections and overhauls have to be considered. In addition the probable human as well as material costs to repair the equipment due to the "minor" and "major" failure rate have to be taken into consideration. Furthermore the expenses to apply the condition (e.g. investment costs for the monitoring system and the assessment of the results) have to be calculated.

In general different hazard rates for "major" and "minor" failures depending on the various maintenance strategies have to be considered as the yearly occurred outages of the equipment depend on the applied strategy. Furthermore, additional outage costs, which need to be financially assessed, have to be taken into consideration, e.g. possible damages of further components, lost revenue, assessment of the non delivered energy, penalty costs etc.

Disposal: This part includes the decommissioning and disposal of the old substation taken into account the environmental legislation for hazardous items. For example the following costs have to be considered: human, material and disposal cost. Recycling fees received on disposal have to be subtracted, e.g. copper windings of power transformers.

Additional input data: In order to calculate life cycle costs following data have to be considered beside the above mentioned values:

- interest rate
- usual life time
- inflation rate
- labor costs per hour

Under consideration of the stated or fixed usual life time of the complete substation, e.g. 50 years, various components have different life times, so that they have to be replaced according to their life time.

6.3.3 EXAMPLE: CALCULATION OF THE PRESENT VALUE

The calculation of the present value gives on overview of the payment depending on the different years. The following financial data are used:

- interest rate (discount rate) 6.5 %
- inflation rate 2 %
- useful life time (equipment) 40 years (except secondary equipment 25 years)
- depreciation time (equipment) 25 years
- calculation time 40 years

The data for outage and maintenance costs, including the maintenance intervals are listed in report [24]. Figure 6.3-2 shows the cost elements of the total present value (17.1 M€) of a complete substation related to the different substation components for an interest rate of 6.5 per cent. It is obvious that the substation as well as the power transformer costs have a part of 39 % resp. 34 % of the total present value, whereas the other components have a minor influence on the result.

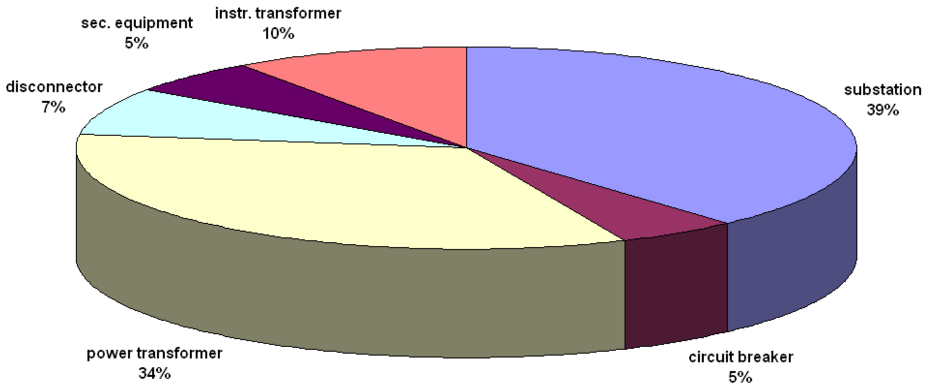


Figure 6.3-2 Present value of the 380 kV substation

Figure 6.3-3 and Figure 6.3-4 show the present values of two components (circuit-breakers and power transformers), which are treated by the time based maintenance, related to the various detailed costs. In case of the circuit-breakers the acquisition costs amounts to 84.7 % of the total value. Whereas inspection costs have less influence (0.2 %), the probable outage costs have a cost of 10.2 %.

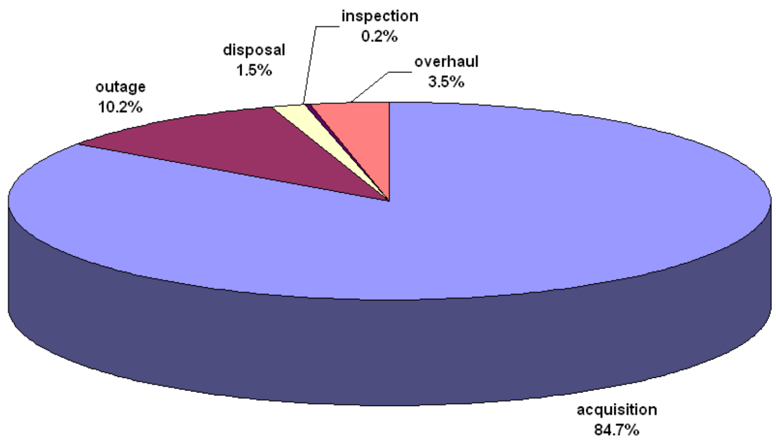


Figure 6.3-3 Present value of the circuit-breakers

In case of power transformers the operation costs have an important influence on the present value (41.5 %), whereas the acquisition costs have a portion of 56.7 % (Figure 6.3-4).

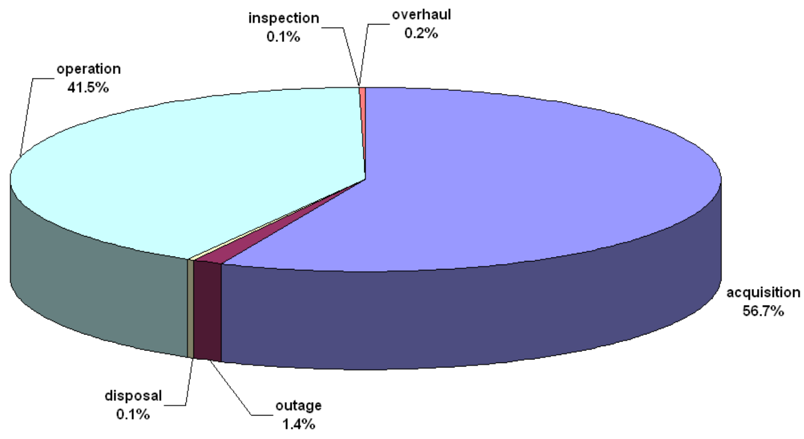


Figure 6.3-4 Present value of power transformers (interest rate 6.5 %)

6.4 Development of a long term asset strategy

6.4.1 Introduction

A possibility of measuring the effects of technical and financial boundary conditions exists in the view of the entire costs of a group of equipment under consideration of the unavailability at the system nodes [12]. With the help of this procedure it is possible to evaluate the effects concerning the maintenance and investment strategy, e.g. extension of the service cycles or useful life time of the equipment.

6.4.2 Development of a long-term strategy

6.4.2.1 General Procedure

The goal of this analysis is to develop a long-term plan for the maintenance and investment strategy of a system using suitable equipment models. These models should be able to simulate the equipment behavior over a time interval of 30 to 60 years for example, according to the service life time of the different components. Thus the following work procedures result in the case of a dynamic simulation:

- Condition assessment and failure behavior of the group of equipment,
- deduction of an aging model for the different equipment,
- reproduction of different functional chains by digital simulations with consideration of the personnel and financial boundary conditions,
- realization of dynamic simulations,
- analysis of the results for the decision making process.

6.4.2.2 Condition assessment of equipment

For condition assessment of equipment a procedure frequently cited in the recent years, which considers both the condition and the importance of the equipment for a complete system [7]. With this method the condition of equipment is determined with the help of different criteria, which can be assigned to different groups, for example:

- template data,
- operational data,
- technical data.
- age-dependent data,
- financial data,
-

The criterion classes specified above mean, that not only the technical condition of equipment is measured, but also additional values, which are of substantial importance for the decision-making process regarding the replacement of equipment for the asset manager. These different classes are subject to different aging procedures, which must be likewise considered in an aging model during the service lifetime of equipment.

6.4.2.3 Aging model

Simplifying, the failure rate of equipment can be represented as a function dependent on the life time of the equipment. Assuming an average value of the failure rate, several different classes are deduced in order to get a typical bath tub curve. The behavior of the failure rate is used for the simulation to fix the number of necessary condition classes of the Markov model according to Figure 6.4-1. An aging model can be developed on the basis of these considerations, which shows the change of the technical condition. As an example a condition model can be shown by different maintenance measures and the individual condition classes are simulated. Under consideration of different transition rates between the condition states and measures, the condition of equipment can be derived depending on the age.

The portions of a whole group of equipment, which are allotted to a condition state (excellent, good, poor, and bad), have to be considered via a condition assessment. The individual components go through the different states during their life time, whereby the maintenance measures can slow down or accelerate this process, which depends on the success of the maintenance measure and on their cycle. A substantial task in this work procedure is to assign all components to the different conditions and to specify the transition rates between the condition states.

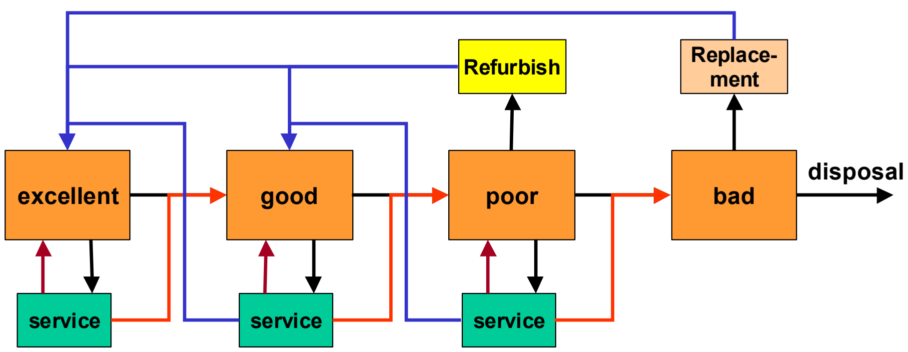


Figure 6.4-1 Aging and condition model of equipment (Markov model)

6.4.2.4 Functional chains

The effects of aging and the concluding measures (maintenance or replacement), can be determined by functional chains, which represents the causes and effects of several factors. Figure 6.4-2 shows an example of the connections between the areas: technology - staff - finance - customer - company. By making use of the aging model of the equipment, the necessary human and financial resources of a transmission system operator can be determined, regarding maintenance and replacement of the components. Simultaneously the condition of the equipment influences the total condition of the system which has an impact on the power quality, which affects again the consumption behavior of the clients.

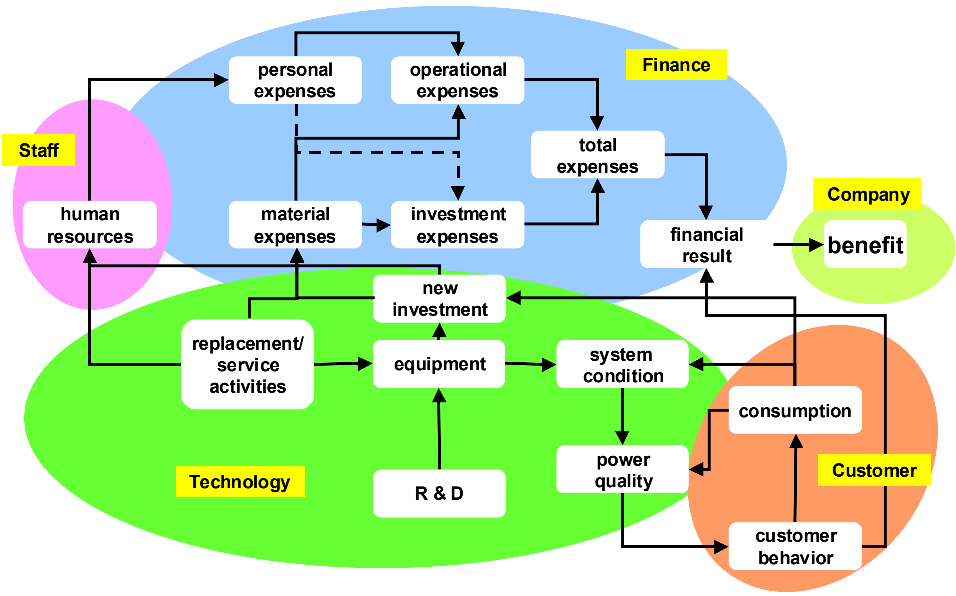


Figure 6.4-2 Functional chains of the asset management process

6.4.2.5 Result of the dynamic simulation

Based on knowing the different costs and having a projection of how many components per year must be maintained and removed, it is in principle possible to evaluate the total expenditures for a group of equipment and in consequence for the entire system during the complete period (e. g. 40 years). Beyond that it is possible using such a simulation to estimate the probable annual expenditures for repairs and outages on the basis of the failure rates, divided into "major" and "minor" failures. In this connection the following costs can be differentiated during the entire simulation period depending on the operational requirements:

- CAPEX: capital investment expenditure,
- OPEX: operational expenditure.

The summary of these two cost classes shows the expected financial expenditure for the fleet of equipment or of an entire system, so that different investment and maintenance strategies can be derived. Beyond that, further results of the simulation for the simulation period are possible:

- personnel requirements for maintenance and replacement activities,
- structure and age profile of the components,
- invested capital,
- not supplied energy, etc.

6.4.2.6 Input data

The asset simulation needs several different types of data which have to be collected by the utility, in order to carry out the calculation. The values can be grouped in several classes, for example:

General data:

- Type and age of equipment,
- maximum useful life time,
- condition assessment of the equipment group,
- simulation time (e. g. 40 – 50 years).

Outage data:

- Failure rate and outage time depending on the age of equipment (minor, major),
- consequence in case of a failure (non delivered energy, damage of other components),
- costs of repair (human, material).

Maintenance data:

- Costs for inspections (human, material),
- Costs for overhauls (human, material),
- Maintenance interval (inspection, overhaul).

Financial data:

- Investment costs for a single equipment,
- type of new equipment,
- power losses,
- Costs for non delivered energy,
- Number of new installations (extension or reduction of the system),
- Disposal costs,
- Inflation rate (if necessary).

6.4.3 EXAMPLE

This example deals with a simulation a population of 110 kV circuit-breakers. A condition evaluation provides a distribution depending on the different circuit-breaker types: Air blast, minimum oil and SF_6. With consideration of the failure data and expenditures for maintenance and repair for the installed circuit-breakers, a simulation can be performed over the given period. It is assumed during the simulation that a circuit-breaker, which is at the end of its useful life time, is replaced in each case by a new SF6 circuit-breaker. Beyond that new installations are assumed to be added at a rate of 1 % per year related to today's amount of assets (in this case 1000 circuit-breakers).

The results of the simulations are represented in Figure 6.4-3 and Figure 6.4-4. Figure 6.4-3 shows the total investment budget for new circuit-breakers under the constraint of a constant financial amount for each component during the time period. The investment peak arises in 2018 because in that year a number of minimum oil circuit-breakers are projected to be replaced.

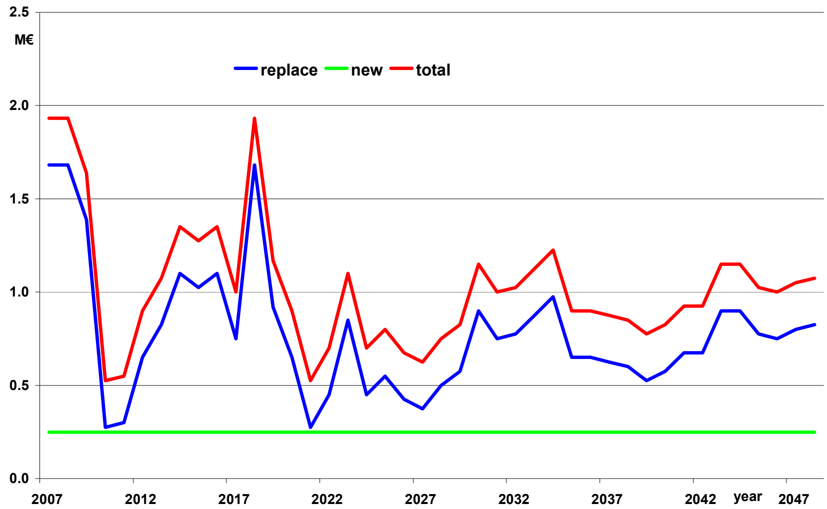


Figure 6.4-3 Investment budget per year (CAPEX)

On the basis of the number of circuit-breakers in the fleet, the annual, probable repair costs can be estimated due to the failure rates (minor and major) as well as the annual expenditures for inspections and overhauls. The results are represented in Figure 6.4-4. In the first few years the reduction of the costs for overhauls results is the consequence of the replacement of air blast and minimum oil circuit-breakers by new SF_6 types with lower operational costs.

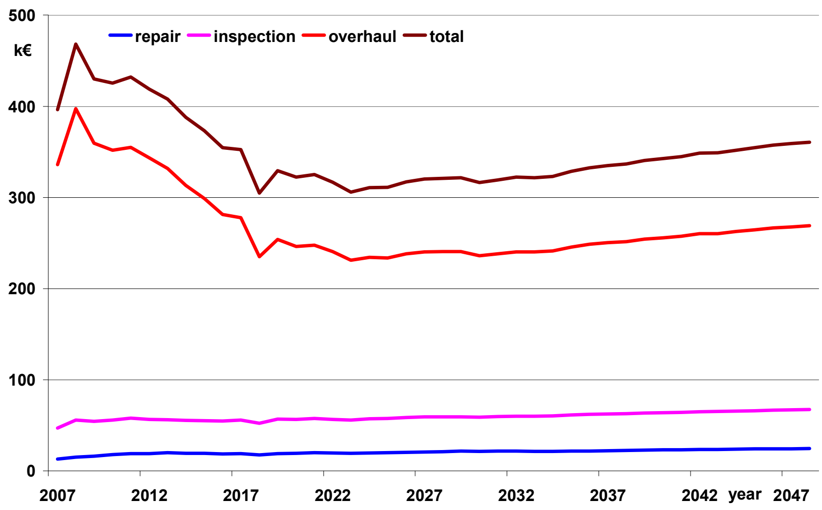


Figure 6.4-4 Financial expenditure for inspection/overhaul and outage costs (OPEX)

6.4.4 CONCLUSION

The investment and maintenance needs (OPEX and CAPEX) can be projected with the help of an asset simulation for different years based on current boundary conditions (failure rates, expenditure for maintenance etc.). Apart from the knowledge of the projected financial requirement based on the current maintenance and renewal strategy, the dynamic asset simulation provides the significant advantage of enabling evaluation of the influence of different strategies on the final results; e.g. deferment or advancement of renewals or more versus less maintenance activity.

6.5 Business Case Analysis Using a Risk-based Model

6.5.1 INTRODUCTION

Risk-based models by definition, involve the multiplication of the likelihood of events with the consequential costs should the events occur. This process is typically displayed as in Figure 2.1-5 in a matrix format to define the methodology, the likelihoods and the consequential factors and levels. Expanding on this concept, Figure 4.3-1, Figure 4.4-1 and Figure 4.4-2 provide examples of the definition of the consequential impacts and their classifications. These are expanded in the figure below. In the column on the left is a listing of the impact criteria. These are directly related to the corporate KPI's for the company. Across the table horizontally are definitions or descriptions of the ranges of impacts for each impact criteria, with category 1 being minor impacts ranging up to category 5 which are major or worst case impacts.

IMPACT CRITERIA		1	2	3	4	5
Safety		First aid injury/illness	Medical aid injury/illness	Lost time injury/ temporary disability	Permanent disability	Fatality (ies)
Financial		Impact totaling < $25,000	Impact totaling $25,000 - $100,000	Impact totaling $100,000 - $500,000	Impact totaling $500,000 - $1 Million	Impact exceeding $1 Million
Reliability		One of: < 5,000 customers hrs lost or <250 MWh of energy not delivered	One of: 5,000 to <10,000 customer hours lost or 250 to <500 MWh of energy not delivered	One of: 10,000 to <50,000 customer hours lost or 500 -<1000 MWh of energy not delivered	One of: 50,000 to <100,000 customer hours lost or 1000 MWh to <5000 MWh of energy not delivered	One of: 100,000 or more customer hours lost or > 5000 MWh of energy not delivered
Market Efficiency		Customers and rate payers lodge complaints to Company	Company customers and rate payers lodge complaint to Government or the Regulator	Government or Regulator enquiry conducted into Company practices and policies	Government or Regulator impose strategic and operational changes upon Company	Failure to deliver required level of service resulting in Governemnt or regulator imposed organizational changes and large corporate fines
Relationships		External opposition resulting in short-term delays or modifications to work plans	External opposition affecting Company's ability to implement its work plans is constrained and/or substantive modifications of its work plans are required.	External opposition resulting in increased regulatory oversight, some loss of shareholder value, increased shareholder scrutiny and/or restricted access to work sites.	External opposition resulting in increased regulatory/legislative/court actions or government intervention resulting in a loss of responsibilities impacting Company's corporate mandate and moderate loss of shareholder value	External opposition resulting in loss of licence, significant loss in shareholder value and/or corporate restructuring
Organization & People		Negligible impact on service delivery and staff	Impacts on efficiency or effectiveness of some services, but would be dealt with internally	Portions of organization experience unexpected attrition or reduced attraction factors	Ability to achieve corporate goals is threatened or there is a significant increase in the cost of service	Unexpected loss of multiple critical staff including senior leadership and the ability to deliver critical services
Environment		Non-reportable environmental incident	Reportable environmental incident with short term mitigation (<6 Months)	Reportable environmental incident with long-term mitigation (6 months or more)	Reportable environmental incident with regulatory fines and mitigation possible to achieve	Reportable environmental incident with regulatory prosecution an/or uncertain mitigation

Figure 6.5-1 Example of a matrix defining the range of impacts associated with organizational KPI-based impact criteria

Associated with ERM are corporately approved risk thresholds and actions that are approved and expected to be taken should risks within the risk threshold ranges be identified. A hypothetical example for such a table is shown in Figure 6.5-2.

CORPORATE SEVERITY CLASSIFICATION	APPROVED ACTIONS	RISK THRESHOLDS
EXTREME	Must be managed through a detailed plan by an executive	> $10 M
HIGH	Detailed study and planning required at senior management level and executive attention is required	< $ 10 M > $ 2 M
MODERATE	Management responsibility must be specified managed by specific monitoring procedures	< $ 2 M > $ 0.5 M
GUARDED	Managed by regular procedures - regular monitoring required	< $ 0.5 M >$ 0.25 M
LOW	Managed by routine procedures	< $ 0.250 M

Figure 6.5-2 An example of a corporately approved actions and associated business risk thresholds

Therefore should a risk having monetary impacts in the range of $1/2M to $2 M be identified, management responsibility for this risk must be specified and the risk monitored by specific monitoring procedures.

6.5.2 Risk Matrix Method for Asset Management

Such risk matrix methods are then used for specific asset management studies by quantifying the likelihood estimates and the consequential costs for the options being studied. The likelihood estimates can be determined through analysis of company data which quantifies the probability of specific events based on historic data relevant to the case at hand. Alternatively, industry data may be used if it is considered to be a good representation for the business case being analyzed. For example in the area of transformers, Figure 6.5-3 illustrates typical industry data that has been published by CIGRÉ and by Ofgem [16].

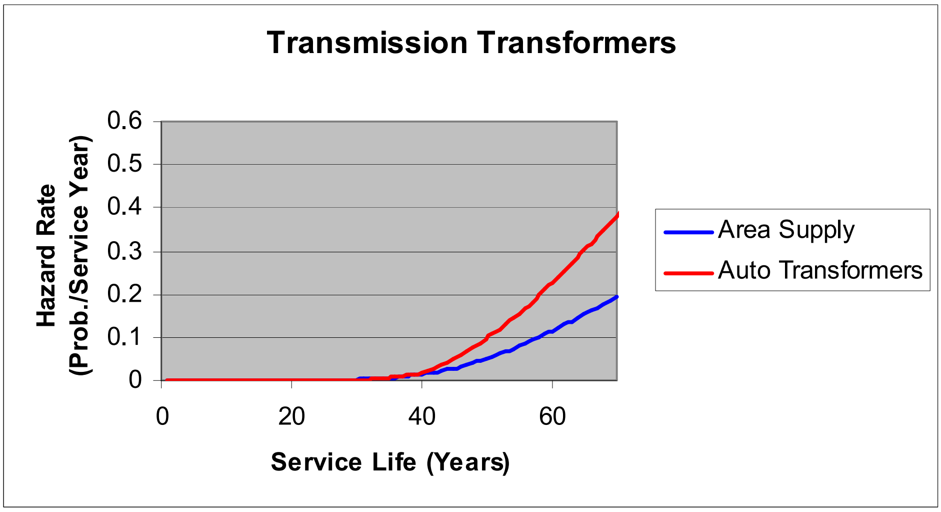


Figure 6.5-3 Industry data on transformer life expectancy

These hazard rate curves show the likelihood of failure for these types of transformers as a function of their service lives. Therefore for an auto transformer that has seen fifty years of service the likelihood of failure at age 50 is approximately 0.1. Therefore data from these curves can be applied in the likelihood column in the risk matrix. In a similar way, consequential costs for the various consequential classifications can be represented by statistical distributions, if the data are available, or by deterministic estimates based on historic experience. In this case the sensitivity of the end result needs to be assessed by carrying out studies using a range of consequential costs based on optimistic, most likely and worst case estimates.

6.5.3 Case: Analysis of the Value of Monitoring Systems on Transformers

An example of this process is shown below for a case study to analyze the value of applying transformer monitoring systems to transformers of various types and applications. In this case the effectiveness of the monitoring system has been set at 75%. In other words, the monitoring system will be effective in mitigating the risk of failure only 75% of the time.

Figure 6.5-4 below illustrates the risk matrix for a typical area supply transformer for three levels of service life. Values from the blue curve in Figure 6.5-3 are entered into the likelihood column for each of the respective service lives. Next the asset manager estimates the impacts in monetary terms for each of the impact criteria and for each of the asset management scenarios (that is for each of the combinations of with or without monitoring for each of the service lives). These values are entered into the lower part of the matrix and totalled in the bottom row. These totals are then multiplied by the likelihoods for each of the respective service ages.

The results are highlighted on the green boxes. The colour is green in this case because the risk levels are in the green range as defined in Figure 6.5-2. Lastly the differences between the "with monitoring" and "without monitoring" risks are calculated and displayed in the risk reduction column on the upper right side of the table.

Highlighted Quantities are the Business Risk Estimates for each Scenario ($M)

LIKELIHOOD OF OCCURRENCE ↓	Scenario ⟶ Service Life ↓	Transformer with a service life of 40 years - No Monitoring	Transformer with a service life of 40 years - With Monitoring	Transformer with a service life of 50 years - No Monitoring	Transformer with a service life of 50 years - With Monitoring	Transformer with a service life of 60 years - No Monitoring	Transformer with a service life of 60 years - With Monitoring	Risk Reduction (k$)
0.114	60					0.1598	0.1255	$34
0.051	50			0.0713	0.0560			$15
0.014	40	0.0194	0.0153					$4
IMPACT CRITERIA								
Safety		0	0	0	0	0	0	
Financial		1	1	1	1	1	1	
Reliability		0.1	0.025	0.1	0.025	0.1	0.025	
Market Efficiency		0.1	0.025	0.1	0.025	0.1	0.025	
Relationships		0.1	0.025	0.1	0.025	0.1	0.025	
Organization & People		0	0	0	0	0	0	
Environment		0.1	0.025	0.1	0.025	0.1	0.025	
Total Impact $ k		1.4	1.1	1.4	1.1	1.4	1.1	

Figure 6.5-4 Risk matrix for the application of monitoring at various levels of service life for a typical area supply transformer

As can be seen the amount of risk reduction gained by the use of monitoring in this type of application is relatively minor. This result improves somewhat if the transformer application is related to the supply of an important industrial customer. In this case the consequential costs are greater and the resulting risk levels and risk reductions are greater through the application of monitoring as shown in Figure 6.5-5. In this case the risk reductions are more significant and the application of monitoring for the transformer with a 60 year service life could support a decision to defer the replacement or other action to this transformer for several years.

LIKELIHOOD OF OCCURRENCE ↓	Scenario ⟶ Service Life ↓	Transformer with a service life of 40 years - No Monitoring	Transformer with a service life of 40 years - With Monitoring	Transformer with a service life of 50 years - No Monitoring	Transformer with a service life of 50 years - With Monitoring	Transformer with a service life of 60 years - No Monitoring	Transformer with a service life of 60 years - With Monitoring	Risk Reduction (k$)
0.114	60					0.5192	0.3010	$218
0.051	50			0.2317	0.1343			$97
0.014	40	0.0631	0.0366					$27
IMPACT CRITERIA								
Safety		0	0	0	0	0	0	
Financial		2	2	2	2	2	2	
Reliability		0.5	0.125	0.5	0.125	0.5	0.125	
Market Efficiency		0.5	0.125	0.5	0.125	0.5	0.125	
Relationships		1	0.25	1	0.25	1	0.25	
Organization & People		0.05	0.0125	0.05	0.0125	0.05	0.0125	
Environment		0.5	0.125	0.5	0.125	0.5	0.125	
Total Impact $ M		4.55	2.6375	4.55	2.6375	4.55	2.6375	

Figure 6.5-5 Risk matrix for the application of monitoring at various levels of service life for a transformer serving an important industrial load

Similarly, results for the case of an important autotransformer are shown in Figure 6.5-6 below. In this case the consequential costs include system disruption costs which could be very large, and this naturally results in significantly higher risk levels and risk reductions.

Highlighted Quantities are the Business Risk Estimates for each Scenario ($M)

LIKELIHOOD OF OCCURRENCE ↓	Scenario ⟶ Service Life ↓	Transformer with a service life of 40 years - No Monitoring	Transformer with a service life of 40 years - With Monitoring	Transformer with a service life of 50 years - No Monitoring	Transformer with a service life of 50 years - With Monitoring	Transformer with a service life of 60 years - No Monitoring	Transformer with a service life of 60 years - With Monitoring	Risk Reduction (k$)
0.240	**60**					**3.3565**	**1.3786**	$1,978
0.106	**50**			**1.4894**	**0.6117**			$878
0.024	**40**	**0.3369**	**0.1384**					$199
IMPACT CRITERIA								
Safety		0	0	0	0	0	0	
Financial		3	3	3	3	3	3	
Reliability		7	1.75	7	1.75	7	1.75	
Market Efficiency		1	0.25	1	0.25	1	0.25	
Relationships		2	0.5	2	0.5	2	0.5	
Organization & People		0.5	0.125	0.5	0.125	0.5	0.125	
Environment		0.5	0.125	0.5	0.125	0.5	0.125	
Total Impact $ M		14	5.75	14	5.75	14	5.75	

Figure 6.5-6 Risk matrix for the application of monitoring at various levels of service life for a system critical autotransformer

While these risk reductions are significant, they cannot be considered equivalent to cost savings. In other words most utilities or investors would not pay an amount equal or similar to the amount of risk reduction in order to obtain that amount of risk reduction for an event that may never happen.

6.5.4 RISK ATTITUDE

How much a utility might invest depends on the company's risk aversion/seeking policies; but from the perspective of the asset manager needing to justify an investment in risk reduction, that is exactly what needs to be quantified. Fortunately this issue has been the subject of much study and application in the insurance industry.

For our purposes in these examples it is useful to ask the question, how much would it cost on an actuarially neutral basis to insure against the calculated risk in Figure 6.5-6 of a 60 year old transformer failing without monitoring? The answer would be the risk amount $3.36 M multiplied by the probability of the event 0.24 giving a "risk premium" (or in other words the actuarial cost for accepting that risk) of $ 0.805 M. Then doing the same calculation for the transformer with monitoring we get a risk premium of $ 0.331 M. The net reduction or saving in risk premium based on adoption of monitoring is therefore $ 474 k.

This assumes that the utility's risk aversion/seeking policy is neutral, that is the utility would choose to be neither risk averse nor risk seeking. The overall results for these three case studies are tabulated below:

Application Service Life (Years)	Area Supply	Important Customer	System Critical
60	$ 4 k	$ 25 k	$474 k
50	$ 1 k	$ 5 k	$ 93 k
40	$ 0 k	$ 0 k	$ 5 k

Table 6.5-1 Reduction in risk premium for the current year in monitoring transformers of differing service lives and applications

As can be seen in these results, the extent to which it makes sense to invest in monitoring of transformers at various stages in their service lives depends strongly on the type of application. The important point here is not the numbers in this hypothetical example, but rather the method. Obviously this method would produce differing results if applied in differing utilities because the impacts would differ and the likelihood of failures may also vary depending on asset types and application.

6.5.5 CASE: IMPROVING LIFE EXPECTANCY OF THE TRANSFORMERS

Rather than applying this method at three specific levels of service life, business cases can be developed using this methodology at each year in an asset's life. For example, asset managers may be asked to justify the application of monitoring (or any other investment in an asset that might improve its life expectancy) when an asset first goes into service. Shown below are portions of the business case analyses for the cases of applying monitoring to new important customer transformers and to system critical transformers. Only the first seven years of the calculation are shown; but the net present value results are for a service life of 70 years.

The top portion of the spreadsheet lists the input data, the inflation rate and the discount rates are typically set by corporate standards which are revised periodically by finance specialists. The replacement cost for the transformer in this example was set at $ 2M. The impact costs in the event of failure with and without monitoring are taken from the table in Figure 6.5-5. In the case that monitoring is selected, this example assumes that the differential cost with a monitoring system in place is $100 per year to allow for the acquisition and analysis of the data and the maintenance of the monitoring system.

The first row in the calculation is the inflated impact costs for no monitoring (IC) going forward. These are calculated from the formula: $IC_{n+1}=IC_n(1+Inflation)$. The second row in the calculation is taken from the data which defines the area supply curve in Figure 6.5-3. The expected impact costs for no monitoring is the product of the entries in row 1 times the corresponding entries in row 2. The inflated impact costs with monitoring and the expected impact costs with monitoring are calculated in a similar way.

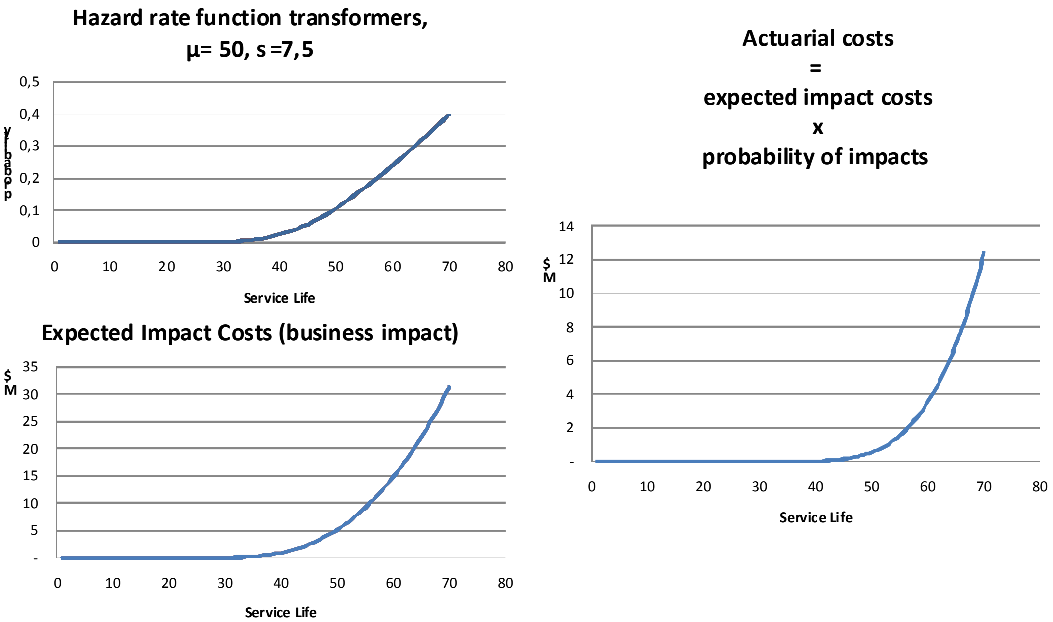


Figure 6.5-7 Graphs illustrating calculation of actuarial costs

The actuarially neutral (that is assuming that the company is neither a risk taker nor a risk seeker) costs with and without monitoring are determined by multiplying the respective impact costs by the probability of impacts. The annual cost savings is determined by subtracting the sum of the OPEX differential with monitoring and the actuarial cost with monitoring, from the actuarial cost without monitoring. The present value of the cost savings is calculated from:

PV_n = Cost in year n/(1+ discount rate)^n

The net present value of the cost savings is the sum of the present values over the 70 year period.

Inflation Rate %	0.025
Discount Rate %	0.0875
Replacement Cost at year 0 $M	2
Impact Costs with No Monitoring $ M	4.55
Impact costs With Monitoring $ M	2.64
OPEX Differential $M	0.0001

	Years Ahead	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Inflated Impact Costs no Monitoring		4.664E+00	4.780E+00	4.900E+00	5.022E+00	5.148E+00	5.277E+00	5.409E+00
Probability of Impacts		1.857E-08	3.171E-08	5.361E-08	8.972E-08	1.487E-07	2.439E-07	3.961E-07
Expected Impact Costs no monitoring		8.662E-08	1.516E-07	2.627E-07	4.506E-07	7.653E-07	1.287E-06	2.142E-06
Inflated Impact Costs with Monitoring		2.706E+00	2.774E+00	2.843E+00	2.914E+00	2.987E+00	3.062E+00	3.138E+00
Expected Impact Costs with monitoring		5.026E-08	8.796E-08	1.524E-07	2.615E-07	4.441E-07	7.467E-07	1.243E-06
Actuarial Cost No Monitoring		1.609E-15	4.808E-15	1.408E-14	4.043E-14	1.138E-13	3.139E-13	8.487E-13
Actuarial Cost with Monitoring		9.335E-16	2.790E-15	8.171E-15	2.346E-14	6.602E-14	1.821E-13	4.924E-13
OPEX with Monitoring		1.025E-04	1.051E-04	1.077E-04	1.104E-04	1.131E-04	1.160E-04	1.189E-04
Annual Cost Savings		-1.025E-04	-1.051E-04	-1.077E-04	-1.104E-04	-1.131E-04	-1.160E-04	-1.189E-04
PV of annual savings		-9.425E-05	-8.884E-05	-8.373E-05	-7.892E-05	-7.438E-05	-7.011E-05	-6.608E-05
NPV of Savings $ k	**$16**							

a) Transformers serving important customer loads

Inflation Rate %	0.025							
Discount Rate %	0.0825							
Replacement Cost at Year 0 $ M	2							
Impact Costs with No Monitoring $ M	14							
Impact Costs With Monitoring $ M	5.75							
OPEX Differential $ k	0.0001							
	Years Ahead	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Inflated Impact Costs no Monitoring		1.435E+01	1.471E+01	1.508E+01	1.545E+01	1.584E+01	1.624E+01	1.664E+01
Probability of Impacts		2.864E-11	6.784E-11	1.578E-10	3.608E-10	8.101E-10	1.787E-09	3.872E-09
Expected Impact Costs no monitoring		4.110E-10	9.979E-10	2.380E-09	5.575E-09	1.283E-08	2.901E-08	6.444E-08
Inflated Impact Costs with Monitoring		5.894E+00	6.041E+00	6.192E+00	6.347E+00	6.506E+00	6.668E+00	6.835E+00
Expected Impact Costs with monitoring		1.688E-10	4.098E-10	9.774E-10	2.290E-09	5.270E-09	1.192E-08	2.647E-08
Actuarial Cost No Monitoring		1.177E-20	6.770E-20	3.756E-19	2.012E-18	1.040E-17	5.185E-17	2.495E-16
Actuarial Cost with Monitoring		4.836E-21	2.780E-20	1.543E-19	8.262E-19	4.270E-18	2.129E-17	1.025E-16
OPEX with Monitoring		1.025E-04	1.051E-04	1.077E-04	1.104E-04	1.131E-04	1.160E-04	1.189E-04
Annual Cost Savings		-1.025E-04	-1.051E-04	-1.077E-04	-1.104E-04	-1.131E-04	-1.160E-04	-1.189E-04
PV of annual savings		-9.469E-05	-8.966E-05	-8.490E-05	-8.039E-05	-7.612E-05	-7.207E-05	-6.825E-05
NPV of Savings $ k	**$394**							

b) System Critical Transformers

Figure 6.5-8 Business case analysis to justify application of monitoring on new transformers

In these cases the NPV savings over the period is $16 k for the typical important customer transformer, and $394 k for the system critical transformer. The corresponding result for the typical area supply transformer is $ 2 k.

6.5.6 PLANNING FOR ASSET REPLACEMENT

The same form of business case analysis can be applied to the issue of determining asset end-of-life. Consider for example the question of when it may be appropriate to plan replacement for an aging transformer that serves an important customer load as in the previous examples. If such a transformer has no special monitoring applied, the relevant results are in the spread sheet lines titled Expected Impact Costs no Monitoring which is the business risk going forward, and Actuarial Cost No Monitoring which is the risk premium going forward.

These parameters are plotted over the transformer service life in the following graph, Figure 6.5-9. As can be seen the business risk escalates rapidly after about 40 years of service, while the yearly risk premium also increases noticeably after about 50 years of service. Plotted as well is the cumulative sum of the yearly risk premiums, labeled the aggregate risk premium.

For utilities that are self insuring, the risk premium is the yearly actuarial amount that needs to be prudently put aside to balance off the risk of a failure of a transformer of this type and application. For utilities that buy commercial insurance, the cost would be at least this amount plus margins for profit and the extent to which the insurer is risk averse. In either case these yearly risk premiums accumulate and escalate rapidly as shown after fifty years of service. Assuming that a replacement transformer can be installed at the projected inflated replacement cost and requires a lead time of three years for delivery, the question is, "When should a decision be made to plan for the replacement of such transformers?".

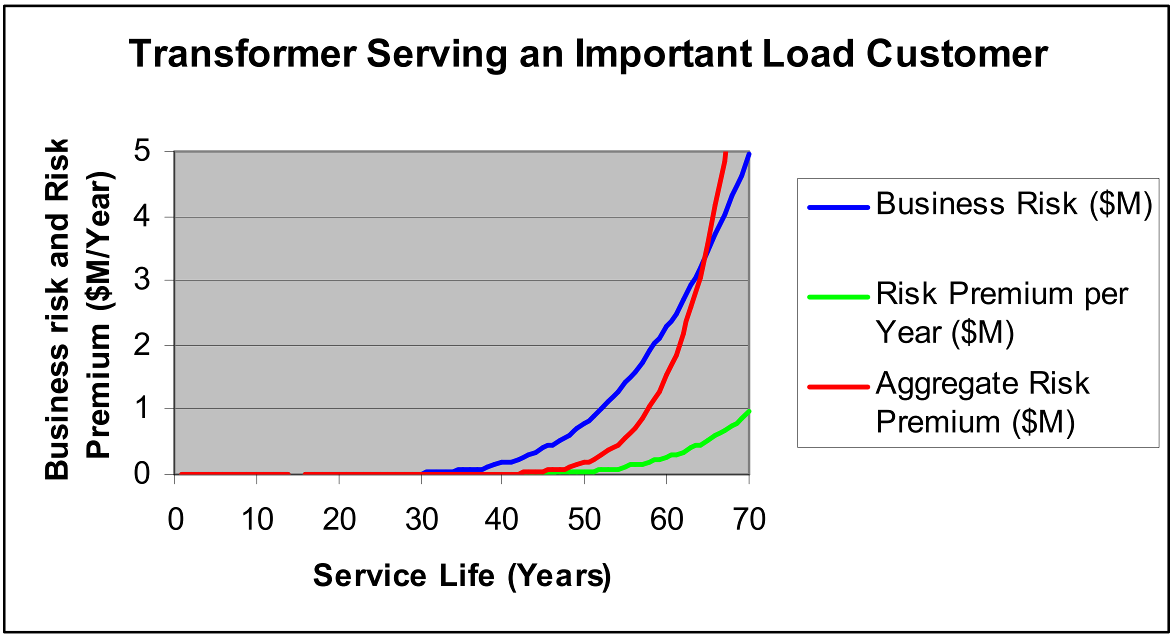


Figure 6.5-9 Replacement planning for transformers serving important customer loads

While the answer is not obvious from the graph, it can easily be determined from the spread sheet. If the criterion for replacement is that replacement should be planned such that the aggregate risk premium while waiting for delivery should be less than the replacement cost, then replacement should be planned at a service life of 66 years in this example.

6.5.7 Conclusion

Quantifying risks associated with optional asset management strategies is useful in comparing the effectiveness of the options. However, the issue of quantifying how much a utility would be prepared to invest in order to reduce the risk of asset failures should they occur over defined planning periods is a critical component of any business case analysis that is to be used to justify investments in assets.

6.6 Continual Improvement of AM-decision making

The asset manager assesses the risk by use of the risk indictors from operational level and the risk criteria from the strategic level and combines this on tactical level to asses the risk and to find the risk treatment options with the most risk return. In chapter 6 several options for risk treatment evaluation are described. First an example of a risk register as part of the risk management cycle is given. Then examples for evaluation methods of risk treatment options are given.

- Development of a risk register and the risk management cycle
- Life Cycle Assessment
- Development of a long term plan for asset management
- Business case analysis using a risk-based model

After assessing the risks, the next step of the asset manager in the risk management cycle is to find and decide on risk treatment options. To evaluate risk treatment options the asset manager has several methods. An example is discussed: "Life Cycle Costs (LCC)". An approach that could be seen as an expansion of the LCC concept is the Life Cycle Assessment approach (LCA). LCA is a holistic approach accounting for all environmental impacts occurring from the system's "cradle" to "grave", together with all related activities throughout the lifetime of the system. Hence, this approach accounts for environmental risks as a part the overall risk management.

In many cases, budgets for investment in maintenance, replacement and refurbishment are limited for certain reasons (financial or human resources etc.) to a certain amount. Electricity transmission companies are questioned by their regulators about maintaining the reliability of their networks. A possibility for measuring the effects of technical and financial boundary conditions exists in view of the entire costs of a group of equipment under consideration and of the cost of unavailability at the system nodes. The investment and maintenance needs (OPEX and CAPEX) can be projected with the help of an asset simulation for different years based on current boundary conditions (projected failure rates, expenditures for maintenance etc.). Apart from knowledge of the projected financial requirement based on the current maintenance and renewal strategy, dynamic asset simulation provides the significant advantage of enabling evaluation of the influence of different strategies on the final results; e.g. deferment or advancement of renewals or more versus less maintenance activity.

Risk-based models by definition, involve the multiplication of the likelihood of events with the consequential costs should the events occur. This process is typically displayed in a matrix format to define the methodology, the likelihoods and the consequential factors and levels. Quantifying risks associated with optional asset management strategies for risk treatment is useful in comparing the effectiveness of the options. However, the issue of quantifying how much a utility would be prepared to invest in order to reduce the risk of asset failures should they occur over defined planning periods (the risk attitude) is a critical component of any business case analysis that is to be used to justify investments in assets.

At the tactical level the Asset Manager strives for continual improvement of its decisions to treat business risks arising from the assets, thus creating value for the asset owner. Asset Management budgets are underpinned by risk treatment measures. The risk treatment measures are derived from risk analysis and prioritization of the risks. In some cases prioritization is made transparent by a risk register.

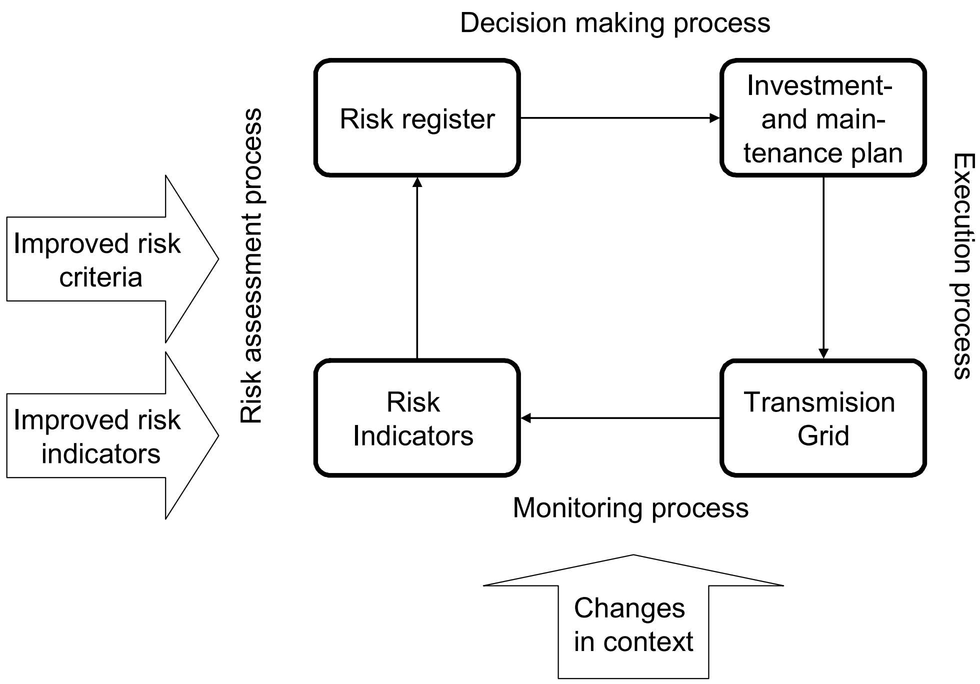


Figure 6.6-1 Continual Improvement of Asset Management Decisions on Risk Treatment

7 END OF LIFE

Many transmission networks contain assets that are approaching their design life. Some groups of assets may have increasing failure rates due to ageing and may have an adverse impact on supply reliability. Determination of failure rates, condition monitoring of assets and forecasting end-of-life have become key activities for network companies to enable timely decisions on measures to be taken such as condition-based maintenance, proactive replacement, refurbishment, spares planning etc.

Expenditure in a network through either CAPEX or OPEX to maintain or improve reliability performance is typically limited to some budgeted/regulated level and it is paramount for a network company to target this investment to achieve maximum benefit. The objective of this chapter WG is to provide an insight into the risks due to an ageing asset base and how these are managed.

7.1 Introduction

Asset management activities and practices attempt to optimally manage assets, and their associated performance, risks and expenditures over the lifecycle for the purpose of achieving the required level or quality of service in the most cost effective manner. [4]

In his process, the asset manager has to assess the budget for mid and long terms in relation with the needs for grid development and for replacement of assets. He has also to assess the time to replace the asset, due to obsolescence or other factors. Nowadays financial pressures and regulatory scrutiny are increasing and in consequence, the requirements for short and long term capital and operating budget forecasting are higher.

The use of advanced methods for quantitative analysis of forecast asset investment needs is essential in the development of asset management strategies to smooth and manage capital expenditure levels over the mid and long-terms. Utilities need more accuracy in projecting their expected needs, in particular in the case for asset replacement programs.

The replacement program includes mainly assets to be replaced that are considered to be at "end of life". Defining end of life and identifying the factors which affect it have been the subjects of much industry discussion, study and analysis. The purpose of this chapter is to present different methods used by utilities to integrate "end-of life" issue in respect to their needs for asset replacement. Even as the "End of life" issue is complex and even if the parameters that need to be taken into account before deciding to replace an asset are numerous, in mid and long term forecasting, the asset manager needs to quantify and justify the budget necessary to replace the assets considered to be at end of life. Mathematical models can be used to establish failure rate curves, in order to assess the length of service at which death of assets is commonly accepted. But these models need to be applied with care and attention.

This chapter points out also the need to include consideration of the condition of the assets, the loading histories and other operational and maintenance factors in the application of probabilistic approaches, in order to avoid mistakes or misunderstanding.

7.2 End of life definition

7.2.1 AGE AS CRITERIA FOR REPLACEMENT STRATEGY

Technical Brochure n°165 [35] and the document [36], report the results of enquiries inside utilities about justification and motivation for "end of life" operations. End of life criteria were ranked to what is considered as being the most important criteria and to the most frequently applied criteria. The results are presented in Figure 7.2-1. The factor ranked as most important is the safety criterion. The criterion ranked most frequently is reliability. It could be a surprise to see that age is not regarded as a relevant criterion, but it is used quite often as such, perhaps because of the convenience of its application.

Age alone, however, is not the only or an adequate parameter to determine the end-of-life, as some designs and applications require that assets are replaced at a relatively young age, while other designs and applications allow assets to be in service for very long time. By rigorously applying age as the criterion for replacement, one runs into a so-called "re-investment wall", where extrapolated from the original erection dates, one projects the need for an enormous investment after a fixed number of years. Load growth that leads to investment as well as a growth in revenues, is a pattern that every normal business would like to have. Economics is another trigger to replace equipment, which include: maintenance costs, costs of spare parts, costs of maintaining expertise, costs of unavailability, offering a better profit and so on. Safety, reliability and environmental issues usually imply the need for more investment; but these factors are triggered by a certain level of society welfare and therefore societal requirements.

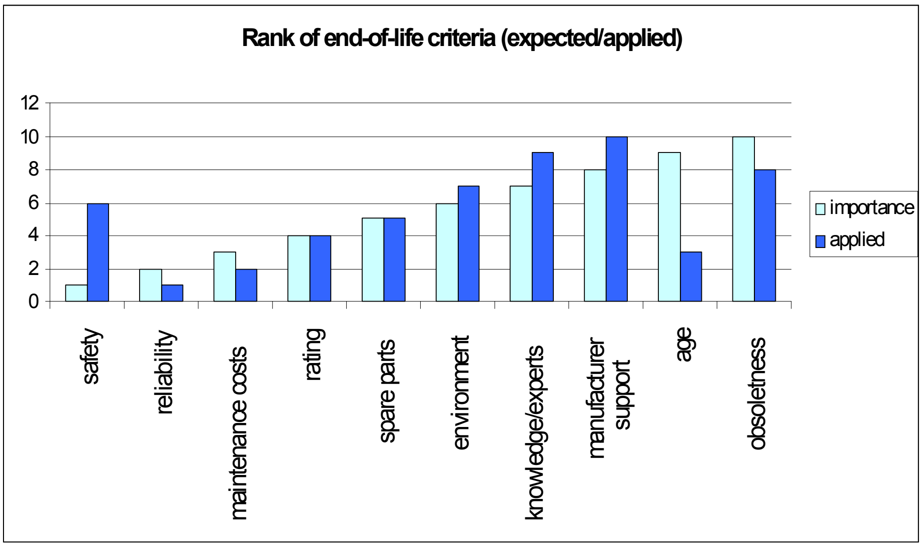


Figure 7.2-1 End of life criteria (extract from [3])

7.2.2 DEFINITION FOR "END OF LIFE"

The Cigré Technical Brochure 358 [46] proposes a definition for "end of life ": End of life is reached when an asset does not meet the requirements any more. Usually, it involves a combination of technical, economic and strategic requirements.

Then this brochure introduces three aspects of "end-of life":

- Technical "end of life": when repair does not seem to offer a reliable solution or the asset does not meet the technical specification.
- Economic "end of life": when it becomes too costly to maintain an asset in service in comparison to technical alternatives.
- Strategic "end of life": when the company values are not met any more.

The following sections present the "end-of life" approach for different domains.

7.2.3 EXAMPLE FROM THE TRANSFORMER DOMAIN

An article in Electra [37] gives a good description of end of life issue for transformers, which can also be applied for other assets. This document sums up the different criteria presented above. Indeed, there are three aspects for an end of life definition:

- Functional end of life,
- Economic end of life,
- Reliability end of life.

The "functional end of life" means that the asset must be replaced due its obsolescence. The possible reasons are:

- Short-circuit capability: the asset cannot withstand anymore the current stress.
- Service voltage: due to an increase in service voltage.
- Load withstand: due to an increase in current.

In the positive case, the end-of life is reached for the asset, even if the asset or parts of the asset are used for a "down-grade" operation (an asset could be obsolete for a grid and could be useful for a less stressed grid).

"Economic end of life" occurs when an asset must be replaced for more profitability. The possible reasons are:

- Maintenance costs: maintenance costs of assets typically increase with time. At some time it can be more profitable to replace the asset rather than to maintain it, especially when quality spare parts are not available at reasonable costs or when knowledge of the required maintenance is expensive to maintain.
- Operating costs: besides maintenance costs, costs of losses can justify replacement, especially for transformers.

Reliability end of life occurs when the asset is deemed unsuitable or unusable, that is to say when failures or risk of failures become unacceptable. The possible reasons are:

- Security or safety reasons: due to the position of the asset inside the network, it could be unacceptable to have a failure,
- Customer impact: due to poor reliability,

- Environmental reasons: as above,
- Public image of the company.

7.2.4 EXAMPLE FROM THE CABLE DOMAIN

Cigré Technical Brochure 358 [46] describes the approaches used in order to assess the remaining life time of power cables. The first approach is based on failure statistics. This approach needs a lot of data from similar cables. The second approach is based on ageing effect.

If the degradation mechanisms are known, it is possible to quantify in theory the extent of cable degradation. Unfortunately, TB 358 explains that these two approaches fail in practice. Data available are not considered to be adequate for statistical calculation. Cables operate in different conditions and the operating and maintenance histories of cables are different. Many degradation mechanisms work simultaneously and synergystically. Therefore with the current state of knowledge of aging mechanisms, it is difficult to summarize the degradation quantitatively by formulae.

As a result, the TB presents another approach more often used to assess "end of life" for cables, and therefore to estimate time to replace them.

This approach combines three criteria:

- Technical criteria,
- Strategic criteria,
- Economic criteria.

And the combination of these three criteria induces a score and forms the basis of the remaining life estimation (see Figure 7.2-2, extract from TB358 [46]).

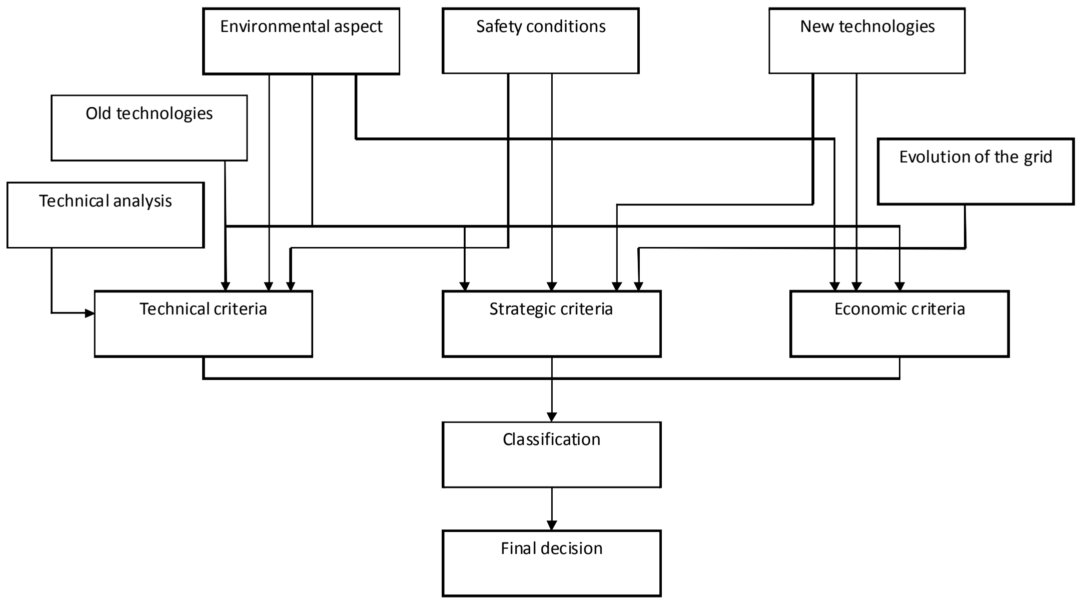


Figure 7.2-2 Approach presented in TB 358 [46]

The technical criteria includes: the history of each cable (including failures if any) and the age. A threshold of 40 years is fixed as the gate for ageing effect. The economic criteria include a cost calculation. The calculation of the total cost of maintaining and operating the old cable are compared with the cost of a new cable with potentially lower losses, lower maintenance and lower risk of non-delivered energy.

The strategic criteria include different parameters as technical obsolescence (higher nominal current, higher short circuit power), new strategy for the networks (upgrade of voltage levels), environmental impact, discontinued support from the supplier etc.. Finally the score, which is a combination of the 3 criteria, is used to rank the cable for the need to be replaced.

7.2.5 EXAMPLE FROM THE OVER-HEAD-LINE DOMAIN

Cigré Technical Brochure 353 [47] presents another economic approach for "end-of life" topic. The "economic end of life" of a long lived asset, such as an Over-head Line, is reached when the cumulative cost of the asset, including depreciation, maintenance, losses and risk costs, per year of service is a minimum.

The model used is based on a method applied by some American and Australian utilities [48],[49].

The aim of the method is to include all costs of an Over-Head line asset:

- the investment cost,
- the maintenance cost,
- the risk cost.

Of course, the risk cost is the most difficult one to assess. The method takes into account the probability of a failure and the economic impact of the failure. Therefore hazard rates are needed and also the expected life of the asset. In general, these factors are needed for the calculation of the optimum time to replace each asset.

7.2.6 SYNTHESIS

These examples show that "end of life" cannot be determined by the age criterion only. It is in reality a combination of several factors such as: obsolescence, economic and reliability. At the end of the process, a decision must be taken: is it or is it not profitable for the company to replace the asset from its present place?

But answering this question with a simple yes or no is not necessarily adequate for senior managers and regulators, who want to see a business case presented that tells them what the cost will be in the future if they do not replace the asset or if they do replace the asset now. This requires a projection ahead over the planning period of the asset management options that are practical.

Whatever the criteria used, obsolescence, economic, reliability, etc. the "end-of life" assessment process is ended by a value which is an age: the age to replace the asset. Therefore, the definition of "end of life" chosen for this chapter is the asset which can not be kept in service any more without a deep and non-profitable refurbishment.

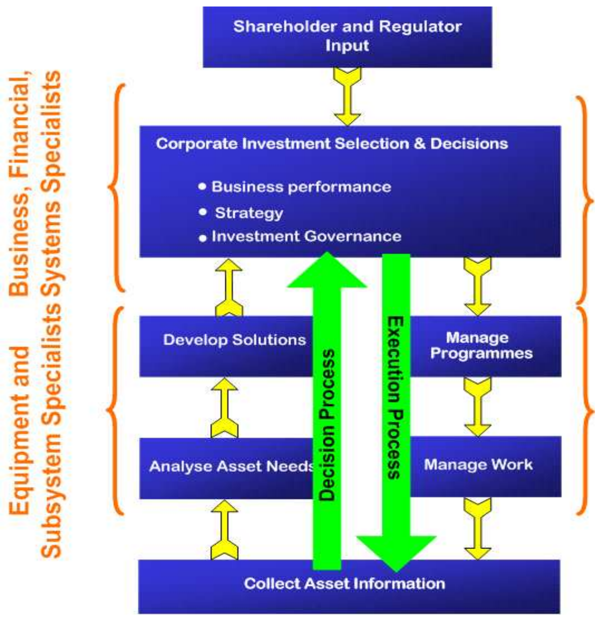
7.3 The issue of end of life for asset management

7.3.1 INTRODUCTION

The fundamental objective of life management can be defined simply as: 'to get the most value of an asset', by ensuring that actions are carried out to promote the longest possible service life or minimize the life-time operating cost, whichever is the most appropriate.

For large capital assets, like transformers, the direct capital cost of a replacement is usually by far the largest cost element, and for this reason it is often difficult to justify replacement before an obvious life ending failure. However, there are sometimes situations, usually when the indirect outage costs are very high, when a replacement can be justified before an end of life failure if the costs of keeping an unreliable asset in service are sufficiently high [38]. Clearly then, economic as well as technical and strategic factors determine the effective end of life of equipment.

In regards to the risk management model developed in the previous parts of the technical brochure and represented in the following Figure 7.3-1 and Figure 7.3-2, the "end of life " issue is processed with different objectives.



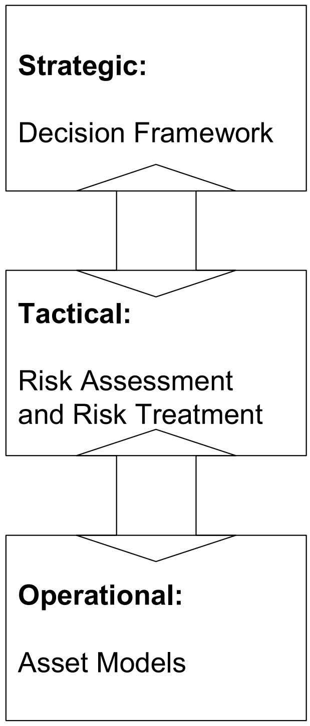


Figure 7.3-1 and Figure 7.3-2 The different levels of Asset Management

In the following sections the motivation for each level is developed, especially for the tactical level, as this level corresponds to the level of asset managers.

7.3.2 END OF LIFE ISSUE FOR THE STRATEGIC LEVEL

The strategic level determines the objectives and the general framework for the company, based on input coming from shareholder and from regulator (see Figure 7.3-1).

The financial resources useful for the assets are usually fixed at this level, which include financial resources for near, mid and far terms. Financial constraints are set on the company as a whole. Profit targets, projections of revenue based on known rates and the load forecast, provide a forecast for the cost side.

In regards to the "end-of life issue", the strategic level determines the financial resources allocated to the replacement of assets. Indeed these resources are established according information and data coming from tactical and operational levels, but the priorities, the arbitration and the decision are processed at this level. The strategic level may also establish tolerable risk levels for the organization which are used to set the priorities. Moreover, the strategic level makes decision about the development of the company. The areas concerned by new installations, by dismantling and by renovation are identified by strategic level decision.

As a consequence, the output of strategic level and concerning "end-of life issue" are:

- Global budget for near, mid and far terms to replace old assets,

- Localization of areas concerned by development or renovation in mid and far terms, and therefore identification of the time limit for assets located in these areas, if these assets are old.

At this level, the replacement budget can be global, without detailed cost for each category of assets. Age of assets, distributed according the different families of assets, is a useful indicator. This information can help the strategic level in the exchange with the shareholder and regulator to explain change in resources needs. In fact the mean value and standard deviation are sufficient indicators.

But these mean values must be compared to the expected life of assets. Therefore the strategic level also needs the "expected life" of the different categories of assets. This expected life is in fact the mean value of "end-of-life" for each category of assets.

7.3.3 END OF LIFE FOR THE OPERATIONAL LEVEL

For the operational level, the purpose is to assess the condition of each asset to support a decision to continue or to plan for replacement or other options. This assessment is a local approach. The operational level employs experts of asset technology and also operators who perform the maintenance. A lot of documents can be found in the literature to explain how to manage "end of life" at this level. [35], [36], [37], [38], [42], [44]. The output of operational level regarding the "end-of life" issue include:

- Data and information on each asset, useful for tactical level: characteristics, age, condition, etc…
- Time to scrap an asset: due to poor condition and the cost to keep in service (repair cost, refurbishment cost, renewal cost etc.).

All of these outputs are connected to the tactical level, as input for this level.

7.3.4 END OF LIFE ISSUE FOR THE TACTICAL LEVEL

The tactical level is generally managed by the Asset Managers. Tactical Asset Managers must determine the amount of assets to be installed and to be replaced. For this level, the inputs are coming from on, one hand from the strategic level, and on the other hand from the operational level. As described in section 3.5, the inputs coming from the strategic level are volume of money for replacement and localization of areas concerned by asset changes. As described in section 3.4, the inputs coming from the operational level are the technical data and information on the assets, data including characteristics, age, condition and so on. Thanks to these data and information, the asset manager can determine which part of the budget can be allocated for the replacement of assets; the replacement due to the "death" of assets because of obsolescence. In regards to the "end-of life" issue, the outputs of the tactical level process are:

- For each category of assets, the volume to be replaced in the near, in the mid and in the far terms,
- The localization of asset to be replaced in the mid and far terms due to grid evolution or due to age limit of asset.

The first part is quantitative: number of assets or amount of money for the next terms.

The second part is qualitative: the localization and the time for the asset to be replaced. But the time of replacement could be given without any high precision; only mid or far terms are needed. This information is useful for planning, engineering and purchases processes. Figure 7.3-3 sums up this process:

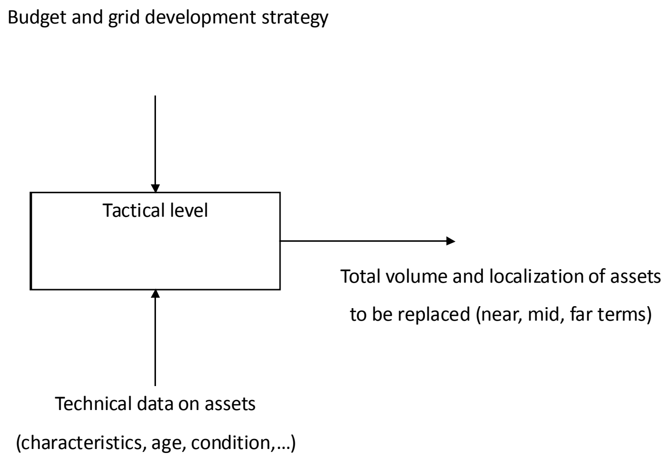


Figure 7.3-3 Input and output for tactical level in regards to "end-of-life" process

For the financial analysis, the results are expressed in monetary terms for ease of comparison with the budget allowed by the strategic level. Ideally asset managers would like to have a detailed and quantitative understanding of the ageing curves in order to support the several types of decisions that they might make to justify investing in maintenance, refurbishment or replacement programs for populations of assets.

An approach currently in use by utilities, for the purpose of forecasting costs associated with replacing ageing infrastructure, is the use of probabilistic failure curves for the various asset groups which are convolved with projected asset demographic information. The approach is based on utilizing probabilistic representations of asset life for major classes of delivery assets and applying these to the related demographic information for each asset group. Sometimes regulators have required utilities to provide this type of information for the purpose of ensuring that their sustaining related investment levels are keeping pace with their ageing systems, thereby avoiding unexpected increases in capital investment in the future.

As shown in the following Figure 7.3-4 taken from the Cigré TB 309 [4], the approach involves utilizing demographic information for either a specific asset group or an appropriate combination of asset groups. This demographic information year by year is convolved with the failure rate year by year, based on the hazard rate function, for the particular asset group or groups for each year ahead in the planning period to obtain a forecast of the expected numbers of failures for the population going forward in time. To obtain an estimate of the forecasted Capital expenditures, a per unit replacement and consequential failure cost is established and applied to the forecast of unit replacements, at each time interval. In a sense, this basic method consists of the crossing of the ages of asset population with the failure rate curve or hazard function.

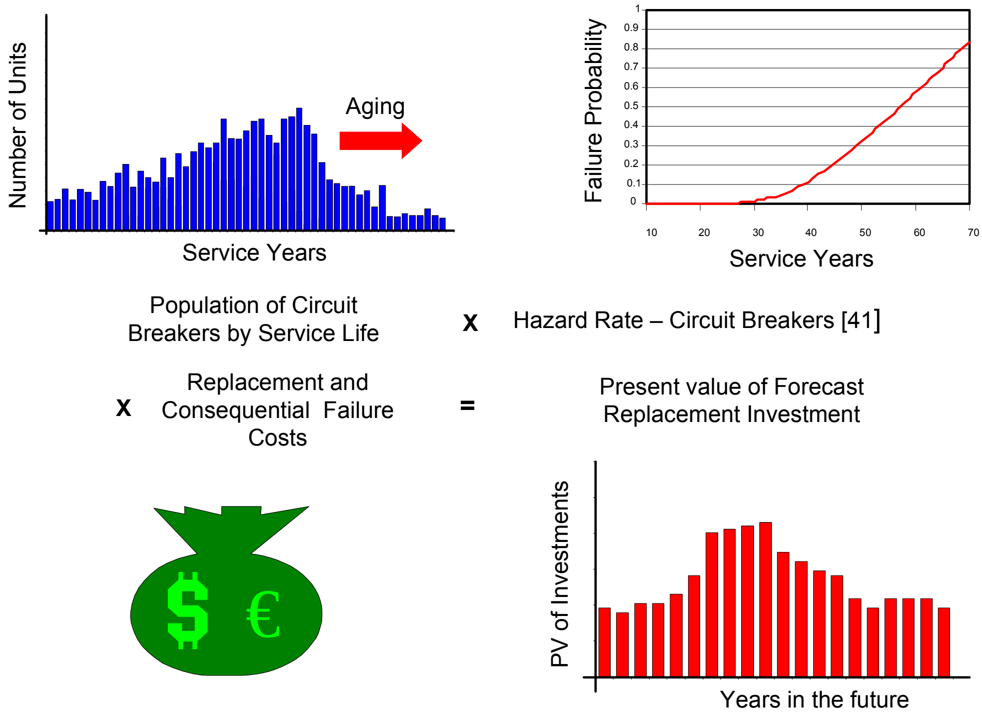


Figure 7.3-4 Circuit-breakers population for end of life assessment in term of budget [4]

This process requires the failure rate curves, or the hazard rate curves, for the whole period of life. But as discussed in section 5.1 on data analysis, depending on the availability and quality of the data, it is not always possible to obtain a useful estimate for the hazard rate function. For this reason some utilities use another method, more simple, and based on age limits, or also called life expectancy. In this case, utilities [39], [40] cross the age of asset population with the age limit of the assets.

Nevertheless, the age limit is useful for the qualitative part of the process: the localization of the obsolescent asset. For this exercise, the asset manager needs to know the expected life for each asset category. Then according the evolution of the grid, the characteristics of the assets, and also the age of asset, he can assess the time to replace each asset. This exercise is a planning exercise, without high precision for the time of replacement: Therefore an age limit is enough to determine "end of life" of each asset in each localization. In the next section, the useful models for asset manager are presented.

7.4 Models applied by asset managers

Apart from the model described in section 6.4 asset managers use the following models for end-of-life replacement.

7.4.1 OBJECTIVE

As indicated in 7.3, the asset managers expect to assess two types of study:

- A quantitative study: for each term, near, mid and far, the number of assets in end of life.
- A qualitative study: for each asset place, the time to replace it due to obsolescence or to "end-of life".

The qualitative study is fairly easy to perform. For this exercise, the asset manager needs only a figure, the expected age, for each type of asset. Naturally, this figure must be reliable and must correspond to the mean value of the life duration, from a statistical point of view. The quantitative study is more complex. Only a figure, age limit, is not enough as all assets will not die at the same age. A statistical model is useful for this quantitative study. The following sections present and explain the different methods.

The problem to be solved by the asset manager can be presented as below: Considering an asset population at the year Y, the question is to know how many assets will be in operation in year Y+N and in consequence how many assets must be replaced each year from Y to Y+N.

The following figure gives an illustration of the problem for Asset Managers. Taking into account the asset age distribution of 2325 units in Figure 7.4-1, what could be the number of assets to be replaced each year.

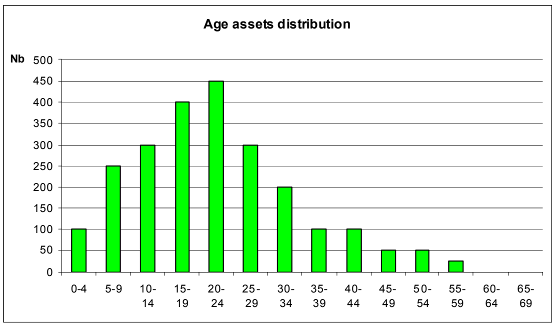


Figure 7.4-1 Example of asset age distribution

The most common used models are:

- Model based on boundary limits,

– Model based on statistics,

– Model based on failure rate model.

These models are presented below.

7.4.2 MODEL BASED ON BOUNDARY LIMIT

For this model, what is needed is the age limit for a type of assets. A type is a homogeneous population of assets, for example 400 kV transformers, or 225 kV circuit-breakers.

In most of the cases, the limit is a couple of values, minimum-maximum. The objective is to get for each family of assets a limit or an interval of limits with the following boundaries:

– Minimum value: Life guaranteed; if the age of the asset is less than this limit, then asset replacement must not be planned,

– Maximum value: Technical life limit; this limit gives the age maximum anticipated for an asset. Above this value, the replacement is required.

The Figure 7.4-2 illustrates this definition. The data are based on expert opinion.

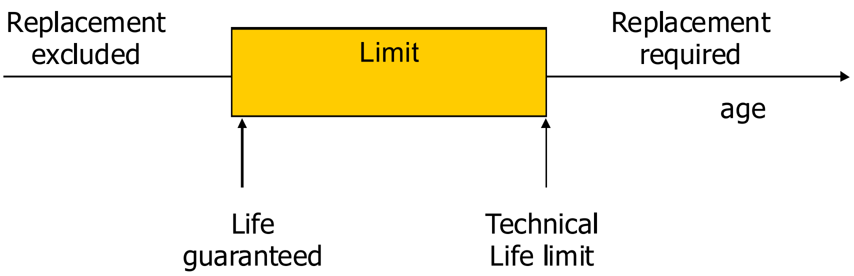


Figure 7.4-2 Boundary limit model

An example of the application of this method is given below. Referring back the sample presented in Figure 7.4-1, Figure 7.4-3 presents an example of a homogeneous assets population.

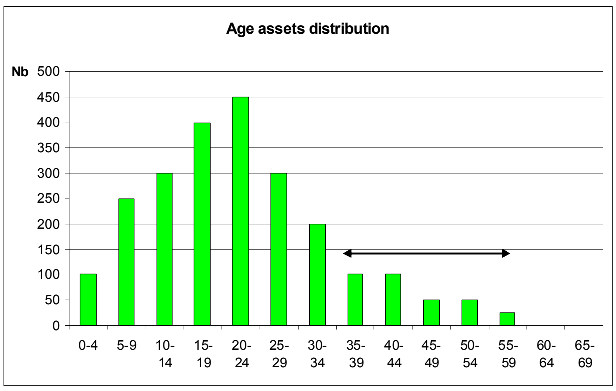


Figure 7.4-3 Assets to replace for the next 5 years

The age distribution is given in Figure 7.4-3.

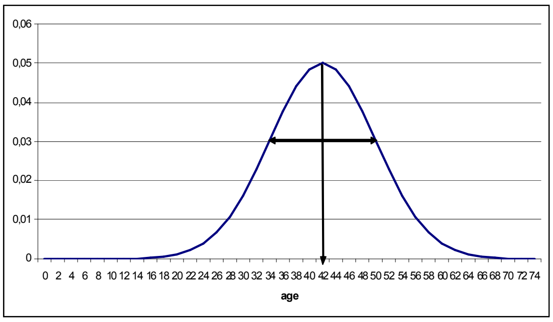
Taken into account the hypothesis of a range limit [35y – 55y], the maximum number of assets to plan to replace in the next 5 years would be all assets aged more than 30 years, as they will reach the limit of 35 years in the next 5 next years. In total, there are: 200+100+100+50+50 +25= 525 units. The minimum would be: 75 units (age > 55y). Taking into account a margin of error, the Asset Manager will probably plan to replace a volume between the minimum and maximum, for example: 300 units.

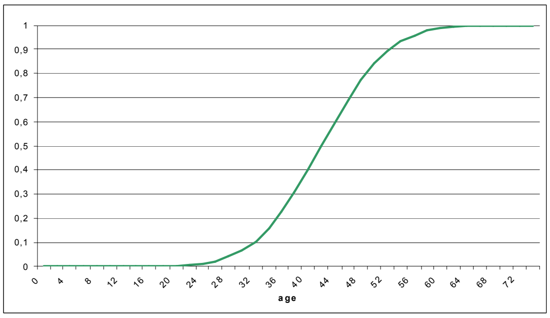
7.4.3 MODEL BASED ON STATISTIC LIMIT

The next method uses a statistical approach. More details about the possible statistical models are presented in appendix H. The method assumes that the age of "end of life" follows a normal distribution. The hypothesis is that a small percentage of assets will fail during the early life cycle, a few beyond the average expected life span and the majority will fail within their mean life [39].

In this case, the model applied considers that the lifetime distribution follows a normal distribution, and the objective is to assess the hazard function, to get the failure rates according age. The hazard rate function is obtained by dividing the density function by 1-cumulative function for each service life year.

Then this hazard function is crossed with the assets age population. The following Figure 7.4-4 and Figure 7.4-5 show this method. Figure 7.4-4 represents the normal distribution for "end-of life" value, where the mean is 42 years and with a standard deviation of 8 years. This result can come from the own feedback experience of the utility or from survey performed by experts. In this example, it comes from TB176 data for transformers [41].

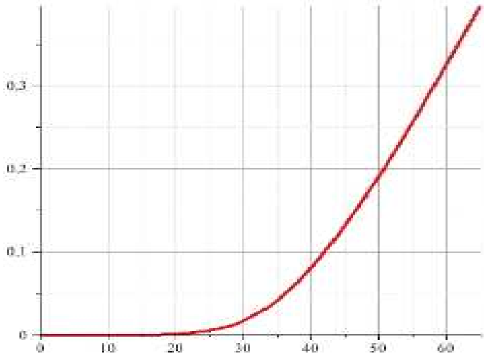




mean value = 42y, standard deviation = 8y

Figure 7.4-4 normal distribution and Figure 7.4-5 normal cumulative distribution

Figure 7.4-5, represents the normal cumulative distribution associated. Figure 7.4-6 represents the hazard function for this normal distribution with the parameters 42 years as mean value and 8 years as standard deviation.



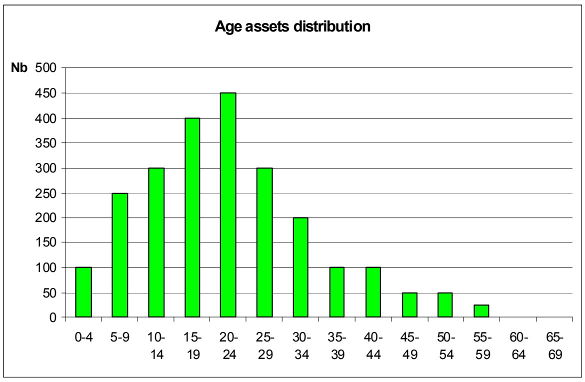


Figure 7.4-6 and Figure 7.4-7

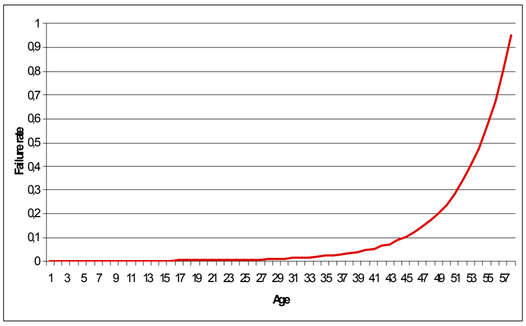
With the example of ages distribution of Figure 7.4-1, the convolution of Figure 7.4-6 and Figure 7.4-7 (Figure 7.4-1 also) is then processed. The convolution is the sum of assets in each age multiplied by the value of the hazard function for that specific age [44]. The result of this convolution is: 230 units to replace for the next 5 years.

7.4.4 MODEL BASED ON RELIABILITY CURVE

This method also requires the failure curve, or the hazard function, for the whole age range. If only average failure rates can be found in the literature, it is more difficult to find failure rates for each age or rank of age. Nevertheless, the document [42], indicates the model chosen by an insurance company, as risk model law for the failures. In the case of transformers, the law used is:

$$f(t) = 0.005 + a * e^{b*t} \quad (1)$$

where f(t) is the instantaneous failure rate, a is a constant, b is a time constant and t is the time in years. Figure 7.4-8 presents the corresponding exponential curve for a 20% failure rate at the age of 50 years.



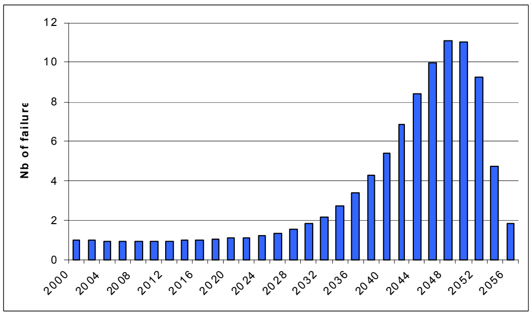


Figure 7.4-8 and Figure 7.4-9

In the case of a population of 100 assets put in service in 2000, with a failure rate of f(t), the predicted number of failures for the following next years are represented in Figure 7.4-9.

Note than the greatest number of failures will be in the year of 2048; in that year 11 will fail. After this year, the rate of failures is increasing very fast, but due to the declining population, the actual number of failures becomes smaller each year.

Although, this model assumes that earlier failures are not replaced, the model seems to be very interesting as it gives directly the failure rates for each age. When we compare this model to the previous one, of 7.4.3, the failure rate values are similar from age 0 until age 50 years. For 50 years, the failure rate is exactly the same: 0.2. But after 50 years, the failure rate values are different between the two models. With this last model, the failure rate is 1 (100%) at 60 years, when it is around 0.3. At the end, of course, the number of assets will be very different with this model and should be more pessimistic, as none assets should survive after 60 years, and we know that is not the case.

As the risk model law for failures proposed (1) for hazard function seems to be incorrect, the question now is to know if it is possible to build a more reliable function. It is the objective of the following paragraph.

7.4.5 CONSTRUCTION OF A MODEL FROM AVAILABLE FAILURE RATE

Until now, it is difficult to find in the literature failure rates according ages for transmission assets. Failure rates can be found for different kinds of assets, but in many of the cases, it is an average value, not the failure rate according the different ages. The document [43] gives several failure rates for transformer according age range. An extract is given in the following table.

Table 7.4-1

Age range	<15y	15-24y	25-34y	35-50y	>50y
Failure rate	0,5%	1,0%	1,5%	2,0%	3,0%

The question is to know if it possible to complete this table for the total range of ages by the use of mathematical tools, and if yes until which limit. In regards to the limit: Considering a population of N assets. After one year, 0,5% failed, and the new population is : N – Nx0,5%.

Using the same method, the population at end of 55 years will be:

$$N' = N.(1-0{,}005)^{15} * (1-0{,}01)^{10} * (1-0{,}015)^{10} * (1-0{,}02)^{15} * (1-0{,}03)^{5}$$

N'/N = 0,45

So, after 55 years, the residual population will be 45% of the initial population.

In the hypothesis of a failure rate which doubles every 5 years after 55 years, that is to say it will be respectively: 6%, 12%, 24%…for the following age range [55-59], [60-64], [65-69]…, the residual population at 70 years will be:

$$N'' = N.0{,}45.(1-0{,}06)^{5} * (1-0{,}12)^{5} * (1-0{,}24)^{5}$$

N''/N = 0,04

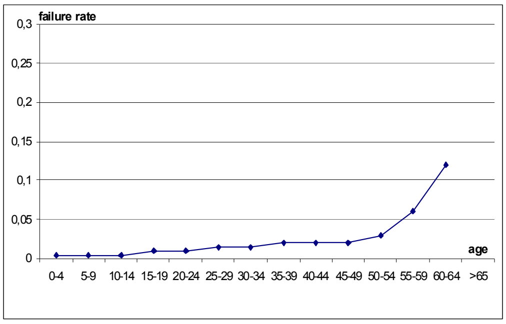
So, at 70 years, the residual population will be 4%, without having reached the failure rate of 100%.

Hereafter is the table corresponding to the evaluation :

Table 7.4-2

Age range	<15y	15-24y	25-34y	35-49y	50-54y	55-59y	60-64y	65-70y
Failure rate	0,5%	1,0%	1,5%	2,0%	3%	6%	12%	
Population (at the end of range)	93%	85%	72%	53%	45%	33%	17%	4%

This example shows that it is not useful to get the failure rates for all the ages. The collection of data can be ended when the failure rate is high enough (20% for example).



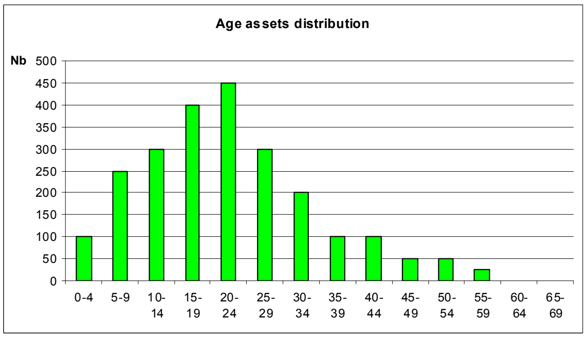


Figure 7.4-10 and Figure 7.4-11

The result of this convolution is: 140 units to replace for the next 5 years. This result is much smaller than the result obtained in 7.4.3. In fact the hazard functions are different, and therefore the results are different.

7.4.6 SYNTHESIS OF THE DIFFERENT MODELS

Among these three models for calculation of the volume of assets at or beyond "end-of life" for the next periods, the most reliable is the third one. But it is also the most difficult to get, as it needs to know the hazard function, that is to say the failure rate according each range of age. Fortunately, the knowledge of failure rates is not attended for all ages, but can stop when the failure rates is around 10 or 20%. Then, the population of aged assets is decreasing very fast.

When the hazard function is not directly available, it can be assessed by calculation. But in this case, it is necessary to know the mean value and the standard deviation of "end-of life" for the type of asset concerned.

When statistical data are unavailable, a qualitative approach can be used. But this model gives very rough results and care must be taken for the use of these results.

7.5 Data useful for asset managers

7.5.1 DATA EXPECTED

As presented in 3.5, the expected life of a population of homogeneous assets is needed by the strategic level for global analysis. A good approximation of this expected life is given by the mean value of "end-of life". With the knowledge of the standard deviation, the asset manager can assess the hazard function, as presented in 3.4 and 7.4. With the hazard function, which gives the "death rate" according age, the asset manager can assess all the data that he needs. Therefore, the data expected are:

- The mean value of asset life,
- The standard deviation,
- The hazard function.

With the possibility to assess the hazard function by calculation, if the death rates are not directly known.

7.5.2 DATA AVAILABLE

In 2000, the Cigré WG 37-27 performed a survey about lifetime for different kind of assets. The results contain the following data :

- Mean of asset life,
- Range of asset life,
- Standard deviation.

These data were given for bays equipment, transformers, GIS, protection, Over Head Lines and cables. The WG calculated the average of each value: mean, range and standard deviation. The total results are in the Technical brochure n°176, and hereafter a table of data extracted [41].

Table 7.5-1 Extract from TB 176

Asset	**Voltage (kV)**	**Mean of asset life estimates (years)**	**Range of asset life estimates (years)**	**Standard deviation (years)**
Transformer	≥ 110	42	32-55	8
Towers	≥ 110	63	35-100	21
GIS	≥ 110	42	30-50	8

As explained in 7.4.3, the asset managers can use the TB176 for getting information about the mean value of asset life, and thanks to the knowledge of the standard deviation, the hazard function can be assess with the hypothesis of a normal distribution for "end-of-life" value. For the calculation of the hazard function, method and advices must be communicated. There is, indeed, a risk of error as sometimes the cumulative distribution function is used instead of the hazard function.

7.6 Conclusion

The financial pressure is increasing and as a consequence, the requirement for budget forecasting is higher. The use of methodology for forecasting needs quantitative analysis of asset management strategies to smooth out the forecasted Capital expenditure levels over the mid and long-term. In this context, Asset Management involves the central key decision making for the network business to maximize long term profits, whilst delivering high service levels to customers, with acceptable and manageable risks. One of the main issues that the asset manager has to face, is the "end of life" issue. Even if the "End of life" issue is a complex process and even if the parameters to take into account before deciding to replace an asset are numerous, in the mid and long term forecasting, the assets managers need to assess the budget necessary to replace assets reaching their end of life.

Cigré documentation gives a lot of useful data on reliability for the different kind of assets. And "end of life" assessment has been performed by different Cigré committees. In this way, the Technical Brochure n°176 [41] gives useful data for all categories of asset for transmission grid. But the methods used by the different committees for the calculation are not always known. Moreover no indication or advice is given on the method to assess the hazard function.

The best solution is to get directly the hazard function, or also called the failure rate per age, for each category of assets. A more accessible method needs to get the average value of "end-of life". Then in the hypothesis of a normal distribution, the advanced mathematical tool can now be used to build the hazard function. The use of statistical methods to make equipment is entrenched in many industries. But these mathematical concepts are not always easy to understand and to use. Nevertheless advanced methods need to be used to establish failure rate curves, in order to assess the age of death for assets.

Uncertainty is an inherent characteristic for asset end of life. A probabilistic forecasting approach represents the range of possibilities in future asset failures and can simulate alternative scenarios useful for TSO in regards to the planned budget [40]. A better use of mathematical models in asset management for TSO can permit the introduction of more advanced financial method as the value at risk method, more popular in financial world [45].

In a certain sense, the use of advanced models can contribute for more innovation and a better efficiency of the asset management process. A co-operation between asset managers and experts must be encouraged to use common models and methods for getting the data useful for "end-of life" issue.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Asset Management involves the central key decision making for the network business to maximize long term profits, whilst delivering high service levels to customers, with acceptable and manageable risks.

Risk management has been implemented in many in Electricity Transmission Companies as a key process for asset management decision making. Cases and examples contributed by the companies participating in C1.16 demonstrate the use of a range of risk management techniques, although the techniques may not always be referred to as risk management. The development of international standards on risk management emphasizes the international trend that risk management is becoming a formalized process for informed decision making in business all over the world. This Technical Brochure uses the general principles and definitions included in the international standards of Risk Management for application in electrical transmission business.

Risk management is applied at every organizational level. The role of an asset manager is to link the notions of business risk and asset risk together to make the right decisions for the assets and the company as a whole. Risk management consists of several steps: risk assessment, risk treatment and risk monitoring and review. These steps are made in an improvement cycle namely: the risk management cycle. The asset manager uses risk assessment matrices to derive the risk criteria for his decisions. Risk indicators are developed to monitor the electricity transmission assets for risks.

Risk management by the asset manager is divided in three levels of asset management decision making supported by risk management: strategic, tactical and operational asset management. Cases and examples contributed by the companies participating in C1.16 support these concepts. Operational asset management is the development of information needed by the asset manager to be able to effectively manage the work by the service provider. Strategic asset management is the development of information the asset manager needs to make asset management decisions conform the organization's risk attitude and key performance indicators. Tactical asset management refers to quantitative analysis of optional asset management tactics to support and justify decision making.

Fundamental to asset management is the concept of continual improvement. The overriding process of the asset manager is continual improvement of his quantitative asset management decision making according to the risk management cycle for asset management. The basis for strategic and operational asset management is continual improvement of the criteria and indicators for risk assessment.

The development of a decision framework facilitates the asset management process by defining risk criteria from company's key performance indicators and business values. Risk indicators are developed from failure models and condition and performance indicators. Once the risk indicators are developed they must be continuously monitored, reviewed and improved for their predictive value for risks so that the asset manager has reliable input for quantitative asset management decision making.

The asset manager assesses the risk through the use of risk indictors from operational level and the risk criteria from the strategic level and combines this on tactical level to quantify the risk and to find the risk treatment options with the most risk return. At the tactical level the Asset Manager strives for continual improvement of decisions to treat business risks from the assets, thus creating value for the asset owner. Asset Management budgets are underpinned by the risk treatment measures.

One of the common issues that asset managers face is the "end of life" issue. Uncertainty is inherent to the definition of end of life of an asset. A probabilistic forecasting approach represents the range of possibilities in future asset failures and can simulate alternative scenarios useful for a TSO with regard to budgets over a planning period. Use of mathematical models in asset management for TSO can permit the introduction of more advanced financial method such as the value at risk method. The use of advanced models may contribute to more innovation and a more effective asset management process. Co-operation between asset managers and asset experts to use common models and methods for collecting useful data for the "end-of life" issue is encouraged.

8.2 Recommendations

Many transmission networks contain assets that are approaching their design life. Some groups of assets may have increasing failure rates due to ageing which may have an adverse impact on supply reliability. Determination of failure rates, condition monitoring of assets and forecasting end-of-life have become key activities for network companies. In this Brochure a structure for Transmission Asset Risk Management is proposed to improve insight into the application of risk management in electricity transmission companies, to evaluate risks due to an ageing asset base and to illustrate how these are managed.

Working Group C1.16 makes several recommendations for further investigations in the field of Transmission Asset Risk Management which are intended to aid asset managers in handling the issue of ageing infrastructure (the "end of life" – issue) and to promote the further development of the Risk Management Structure as proposed in this Brochure.

8.2.1 Further Development of Strategic Asset Risk management

In the risk management structure the meaning of the block 'strategic" is the development of information the asset manager needs to make the right asset management decisions for the organization taking into account the business values and the overall strategy of the company.

With this structure in mind, Working Group C1.16 recommends to further investigate:

1. The development of a methodology for including the carbon footprint in asset risk management
2. How do utilities quantify the monetary consequences for events impacting business values that are not directly measured in financial terms

(1) In the present context, sustainability approaches, and especially carbon consumption, develop a new conscience on the impact of industrial activity for the environment. This conscience concerns all people, and therefore sustainability becomes a value for more and more Companies. One of the components of the sustainability programs for the Transmission System Operators is the carbon footprint. The asset managers will have to introduce this new issue, the carbon footprint, in the Risk Management process for the choice of the best decision with regard to the values defined by the Company.

(2) In the electricity transmission companies participating in working group C1.16, transmission asset risk management was introduced as a qualitative process. This developed to a more quantitative approach using impact and risk categories. Now development of more financial evaluations of risks is evident. Examples from financial risk modeling should be studied and made applicable to physical assets.

8.2.2 FURTHER DEVELOPMENT OF OPERATIONAL ASSET RISK MANAGEMENT

In the risk management structure the meaning of the block "operational" is the development of information needed by the asset manager to be able to effectively manage the operation, in other words: to implement operational asset management.

With this structure in mind, Working Group C1.16 recommends further investigation of:

1. The development of failure statistics of transmission assets
2. The development of failure models of transmission assets
3. The development of Risk Indicators for transmission assets and the transmission system

(1) The Working Group emphasizes the need for statistical data for relevant equipment and subsystems of transmission grid to manage the "end-of-life" issue. High data quality is costly (common in many organizations and sectors) but bad data is a risk in itself. Further investigation on data is recommended:

  - What data is needed for asset risk management?
  - How to motivate companies for sharing data?
  - How to develop reliable data?
  - How labor intensive?
  - Which degrees of freedom to enter data?

(2) Development of failure models will give direction as to what data is to be collected for risk management purposes. The working group recommends development of data and risk models for different types of assets.

(3) To enable the asset manager to make the right risk assessment and determine the risk treatment options, the asset manager needs to have data available: asset data, data on internal and external developments like asset condition and operational factors such as the loading and maintenance history. From all of the considerable amount of data, the goal is to find those parameters, which indicate potential risks for the assets of the company. Therefore risk indicators need to be developed. A survey is proposed to find:.

- Risk indicators: which risk indicators are used by utilities and how do utilities develop and use them?
- An overview of the methods adopted for classifying and establishing asset condition
- Identification of the key indicators used for classifying and establishing asset condition

8.2.3 FURTHER DEVELOPMENT OF TACTICAL ASSET RISK MANAGEMENT

In the risk management structure the meaning of the block "tactical" refers to quantitative asset management decision making. With this structure in mind Working Group C1.16 recommends further investigation of:

1. Replacement due to asset aging for like–for-like or for future requirements
2. Implementation of risk management for assets / system

(1) The challenge for the Asset Manager is to use the synergy between system development and asset management. Replacement due to aging may be done like–for-like, but taking into account system development issues is an advantage for the company. Asset replacements should meet future requirements and the Asset Manager has to include new challenges, for example the development of renewable energy etc.

(2) In the electricity transmission companies participating in working group C1.16 transmission tactical asset risk management was implemented; but in none of the companies is it a fully mature process. However, there are implementation issues to be investigated, for example:

- The development of risk registers
- The development of quantitative evaluation of risk treatment options ("return on risk reduction")
- Investigation of utility practices in determining how much can be justified to invest in reducing or mitigating a risk by a defined amount
- How to implement the risk management process?
- What is the influence of the quality of the asset risk management process on Enterprise Risk Management and/or company rating?

9 REFERENCES

1. ISO Guide 73 Risk Management Vocabulary
2. Draft ISO 31000 Risk Management – Principles and Guidelines on Implementation
3. Draft ISO 31010 Risk Management – Risk Assessment Techniques
4. Cigré Working Group C1.1, "Asset Management of Transmission Systems and associated Cigré activities", Cigré Technical Brochure 309, 2006
5. Bartlett, S., "Asset Management in a Deregulated Environment", Paper 23-303 Cigré General Session 2002
6. Wester, Ph. et al., "Information Strategy to support Utility Asset Management", Electra April 2003
7. Balzer, G. et al, "Selection of an Optimal Maintenance and Replacement Strategy of H.V. Equipment by a Risk Assessment Process", Paper B3-103 Cigré General Session 2006
8. S. Federlein, A. Gaul, A. Schnettler. "Estimation of Failure Frequency of a 123 kV Circuit Breaker in Case of Deferred Maintenance Intervals" (International VDE-Congress, ETG-P1, Munich 2008)
9. Hamoud, G. et al., "Methodology for Assessing Safety Risk from Failure of Transmission Station Equipment", IEEE Transactions on Power Delivery Vol.22 No.3 July 2007
10. British Columbia Transmission Corporation (BCTC) Transmission System Capital Plan F2009 to F2018
11. British Columbia Government, "Enterprise Risk Management Guideline", 2006
12. Balzer, G.; Asgarieh, L.; Neumann, C.; Gaul, A.;Bakic, K.; Schorn, C. "Planning of Long Term Transmission Investment of Power Systems" C1-113 CIGRÉ 2008
13. Ford, G. et al, "Advanced Models for Transformer Life" PS2-24 CIGRÉ SC A2/D1 Colloquium Bruges October 2007
14. Nelson, W "Applied Life Data Analysis" John Wiley & Sons, ISBN 0471094587
15. NIST The Engineering Statistics Handbook. Available on the web at http://www.itl.nist.gov/div898/handbook/eda/section3/eda362.htm
16. KEMA "Review of the Electric Transmission Asset Management Policies and Processes as adopted by National Grid Electricity Transmission (NGET) within England and Wales, and Assessment of Implications for Capex for 2007/08-2011/12 DRAFT Final Report PR1078D4_NG_001 Re. 3.0
17. G. Balzer, D. Drescher, F. Heil, P. Kirchesch, R. Meister, C. Neumann. "Evaluation of Failure Data of HV Circuit Breakers for Condition Based Maintenance" (Cigré Session, A3-305, Paris 2004)
18. "Risk management in the electricity industry", Eurelectric, Ref.: 2007-030-0137.
19. A. Gaul, J. Hogräfer, C. Neumann, J. Schneider, A. Schnettler, M. Schwan, W. Wellßow. "Asset Management Techniques" (ScienceDirect, Journal of Electrical Power & Energy Systems 28 (2006) 643-654)
20. C. Neumann, G. Balzer, S. Federlein, B. Rusek, J. Schneider, A. Schnettler, C. Schorn, U. Zickler. "Strategy for End of Life Assessment for High Voltage Circuit Breakers" (Cigré Session, A3-101, Paris 2008)

21. S. Federlein, J. Schneider, A. Schnettler, U. Zickler. "Asset Management Processes for Future Substation Technologies" (Cigré SC B3 Colloquium, PS1-101, Berlin 2007)
22. G. Balzer et.al. "Life cycle assessment of substations: a procedure for an optimized asset management" (Cigré Session, 23-302, Paris 2002)
23. K.Ryen, "Risk evaluation and management of a transformer population", EuroDoble 2007
24. Balzer, G.; Schorn, C.: Life Cycle Costs Analysis of a Complete Air Insulated Substation. CIGRÉ SC B3 Berlin 2007, report 104b
25. ISO 14040 Environmental management -- Life cycle assessment -- Principles and framework
26. ISO 14041 Environmental management -- Life cycle assessment -- Goal and scope definition and inventory analysis
27. ISO 14042 Environmental management -- Life cycle assessment -- Life cycle impact assessment
28. ISO 14043 Environmental management -- Life cycle assessment -- Life cycle interpretation
29. ISO 14044 Environmental management -- Life cycle assessment -- Requirements and guidelines
30. IEC Standard 60300-3-3 "Dependability management; Part 3-3: Application guide – Life cycle costing"
31. Balzer, G.; Schreiner, A.; Gößmann, T.; Schorn, C.: Assessment of Outage Costs Using Value at Risk Methodology. CEPSI-Conference, Macau SAR, China, 2008, rep. 1047
32. Glyn A. Holton: "Value at Risk, theory and practice", Academic Press, Amsterdam 2003.
33. http://www.riskglossary.com/articles/var_measure.htm> 02.07.2006.
34. Balzer, G.; Schorn, C.: Risk assessment of high voltage equipment. CEPSI 2004, Shanghai, 102, M3.
35. "Life management of circuit-breakers", Cigré TB165, Cigré WG 13.08, 2000,
36. "Life cycle management of Switchgear-Review of Cigré WG 13-08 TB165", A.Janssen, G.Sanchis, D.Peelo, D.Markareinis, A.Carvalho, A3-104, Cigré 2008,
37. "Lifetime evaluation of transformers", J.Aubin…Cigré WG 12.09, 1992.
38. "Life management techniques for power transformers" TB 227, V.Sokolov…Cigré 2003
39. "Investing in life-cycle – A new methodology", L.Haffner, BCTC, Cigré 2006
40. "The asset retirement model", J.Toneguzzo May 2005,
41. "Ageing of the system impact on planning", TB176, Cigré WG 37-27, 2000,
42. "Life cycle management of utility transformer assets", W.Bartley, October 2002,
43. "Guide on economics of transformer management", TB248, Cigré WG A2-20, 2004
44. "Managing aged transformers" G.Ford, co., Transmission and Distribution world. July 2005,
45. "Value at Risk method for asset management of power transmission systems", G.Balzer, A.Schreiner, 2006.
46. "Remaining life management of existing AC underground lines", TB358, Cigré WG B1.09, 2008,

47. “Management of existing transmission lines”, TB353, Cigré WGB2.13, 2008,
48. “Management of existing Overhead transmission lines”, TB175, Cigré SC22 WG 22.13, 2000,
49. ”The Replacement Decision for Linear Assets” P.Buckland & N.Hastings, ICOMS 2001,
50. Sand, K. et. al. “Current Risk Exposure in the Distribution Sector – Initial Study”, Technical Report Sintef, ISBN 978-82-594-3310-7
51. Technical report no. TR A6787 “Risk indicators for distribution system asset management”, Kjell Sand, SINTEF Energy Research February 2009
52. Method for the development of technical risk indicators, SINTEF Report STF38 A98434, SINTEF Technology Management , Safety and Reliability ,1999 (in Norwegian)
53. Y.C. Wynia, “Risk Management for Grid Operators”, TU Delft, faculty of TBM, 2004
54. Twijnstra&Gudde & Nuon Asset Management, “Asset Management Course”, 2003
55. CapGemini & Nuon Asset Management, “CapGemini Best Practice Model”, 2004

A GENERIC FAILURE IN GIS SUBSTATIONS – FRANCE

A.1 Introduction of the case

This case concerns a generic failure in Gas Insulated Substation (GIS) and is an example of experts and asset managers setting up asset strategy. First some explanations are presented how the question of a generic failure is managed.

A.1.1 MANAGEMENT OF GENERIC FAILURE

When a failure occurs on an asset, it is not always easy for the owner to know if it is a single case or if the event can occur again on other assets. Even if the failure analysis involved experts, there is often a reserve about the probability that the same failure can be found later on other assets. The difficulties are due to the fact that, in many of the cases, the population of assets is not large enough from a statistical point of view to qualify a failure as a generic failure. But when the same failure occurs for the second time, under the same conditions, there is no doubt and a deep analysis is required by the asset-manager to build a strategy.

The asset manager moves forward step by step to build a strategy. The first step is to know all technical characteristics of the asset involved by the problem: technology, manufacturer, age,…. and also the stress applied. In consequence, the failure mode can be described and the problem explained. Nowadays, thanks to the share of experience through international organizations, like for example Cigré, the different failure modes of assets are better known. It is a good help for the asset-managers in their analysis.

When the asset manager knows that the probability of a failure mode exists, the next question is to evaluate the risk that the failure occurs during the 'normal life' of the assets and the consequence. Most of the time the risk depends on the condition of each asset. Diagnosis methods can be useful tools to evaluate the status of the assets. Then, according the results, the preventive correction can be performed only on assets concerned.

Diagnosis methods do not exist for all failure modes. Sometimes, the only solution to detect signals of a failure is a deep inspection leading to the dismantle of the asset. In that case, the cost of inspection can be very high and be a deterrent.

A.1.2 CASE DESCRIPTION

The assets involved in this case are all 400 kV GIS substations installed before mid-nineties by the same manufacturer. The reason to start a risk analysis was the same failure happening twice on different specimens but same type of 400 kV GIS installations.

The failure under consideration is a flashover inside a compartment due to metal particles moving in the electrical field leading to an unplanned outage of the GIS during the repair time of several weeks. Due to temperature variation the busbar moves. This induces friction in the contacts: contact of male connector against contact of female connector. Metal particles originate from the wear of the contacts.

Normally the contacts are greased to avoid wear. In the case concerned, the maintenance procedures of the installation did not mention contact greasing. Some of the maintenance personnel did grease the contacts and some did not.

At this moment it is not clear what maintenance was performed on each specific GIS of this generation. A complete generation of GIS is suspected to have this system failure. After the mid-nineties, the process was changed and all contacts were greased.

Especially long busbars move a relatively large distance, because of the temperature changes and generate a relatively large amount of metal particles. The GIS-installations having busbars longer than 5 meters are critical.

A.2 Operational Asset Risk Management

Experts within the Electricity Transmission Company analyzed the failures. Because an intrusive diagnosis method, taking the GIS out of operation and opening the compartments is too complicated a non-intrusive method is choosen to analyse the failure mechanism. Off all diagnosis methods known for GIS [x], not one is applied to investigate the present failure mechanism. Ultra-ray inspection is not accurate enough for detecting little particles. Partial Discharge measurement is not reliable enough.

The failure mechanism was analysed for all GIS-installations with the same design. A failure model was developed by experts. This model of the failure mechanism takes into account the following parameters:

- The length of bus bar
- The range of temperature during the year
- The age of the busbar (This models part of the degradation process)
- The position of the bus-bar compared with the position of the nearest circuit-breaker (The circuit-breaker is a source of mechanical vibration. The operation of the circuit-breaker increases the vibration and the risk of particles moving in the GIS.)

From these parameters, the failure model determines in what year the quantity of particles is such that a flashover may occur in the GIS. The failure model was verified with the previous flashovers. The failure model confirmed the existence of a high risk of flashover before they occurred. Also preventive maintenance was performed to confirm the wear mechanism.

In the last 4 years, 4 failures occurred, an average of one per year. According to the development of the degradation, it is derived that the failure rate is between 0.02 and 0.03 failure/equipment*year.

When taking into account the whole population of the assets, the number of failures per year can be calculated including the repairs on the failed GIS each time. The development of the number of possible failures is shown in the following figure.

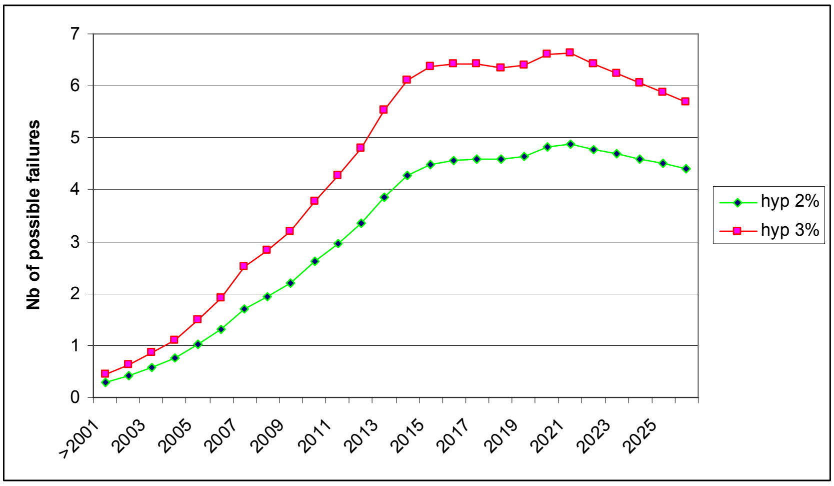


Figure A-1 Prognosis of the Development of Failures

The development is indicated for two hypotheses of the failure rate: 0.02 and 0.03 failure/equipment*year.

A.3 Strategic Asset Risk Management

The Electricity Transmission Company Service Quality, the (social and natural) environment and a sound financial situation, but has not derived a decision framework for enterprise risks yet. The impact and risk levels are assessed for this case specifically.

Business Value Impact	**Moderate**	**Serious**	**Severe**	**Catastrophic**
Service Quality 1	< 20 min	20 min – 4 h	4 h – 2 days	> 2 days
Service Quality 2	< 1 week	1 wk - 4 wk	1 month – 6 months	> 6 months
Environment & Social	Low impact	Local pollution	Huge pollution	Injury
Finance	< 10 k€	10 - 100 k€	100 k€– 1 M€	> 1 M€

Figure A-2 Business Impact Matrix

A.4 Tactical Asset Risk Management

The reason to start risk analysis is the expectation that a of a generic/systematic failure in the GIS installations exists.

A.4.1 RISK IDENTIFICATION

From the information in A.2 and A.3 the main risk for the 400 kV GIS switchgear can be described and analyzed. On operational level a failure mechanism has been designed and verified.

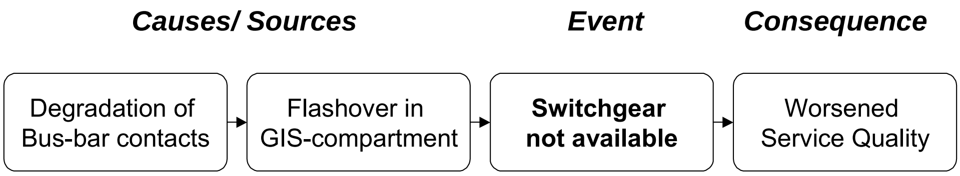


Figure A-3 Risk description

A.4.2 RISK ASSESSMENT

The consequences of the event are assessed according to the framework in A.3.

- Service quality : the duration of outage is around 2 or 3 weeks, without any preparation to repair. According consequence matrix, the consequence is Catastrophic for service quality 1 and Serious for service quality 2.
- Environmental and social : normally a flashover inside a GIS does not induce any explosion. So there is no injury risk for personal and no pollution risk for environmental. Moreover, care must be taken for the repair by operators. The consequence is Moderate in that case.
- Finance impact : the total cost includes repair or preventive cost and the outage cost when it is concerned. In the present case, there is no difference between preventive and corrective maintenance. In both cases, the bus bar must be changed. The cost of each repair is severe.

Due to the present failure rate of 0.01 to 0.1 failure/equipment*year and the consequence on Service Quality in the category Catastrophic. The risk of this event for the business is High, which implies that risk treatment measures need to be taken.

A.4.3 IDENTIFICATION OF RISK TREATMENT MEASURES

Without any information on the status of the asset, concerning the failure mode involved, the asset manager is in front of two strategies :

- To perform preventive maintenance, on all assets
- To perform corrective maintenance, only after a failure.

To perform preventive maintenance means dismantle and repair all the assets by changing components involved by the failure mode concerned, or refurbish the assets. This operation is similar to the repair. Sometimes the whole asset is replaced. To perform corrective maintenance means to wait for the failure and then to repair.

In the present case, two technical scenarios, preventive and corrective maintenance are analysed.

Scenario 1 : Preventive maintenance

The preventive solution consists on changing the bus-bar used damaged connector and on assembling the new ones with the adapted process, with grease.

But the number of compartment involved is very large, several hundreds of compartments. The site operation takes long time, more or less 10 days per compartment involved. And the cost is high, between one and two hundred euros per compartment.

In consequence, the total cost of the preventive maintenance could be several millions euros.

Scenario 2 : Corrective maintenance

The repair solution consists on replacing the bus-bar after a failure. In that case the corrective maintenance and preventive maintenance are identical for each bus bar corrected.

For preventive and corrective maintenance, the duration of repair is similar, when operators are well trained and when spare part are available. The cost is also the same, excepted the outage cost.

A.4.4 EVALUATION OF RISK TREATMENT MEASURES

In this case, the asset manager built the three following solutions :

1. preventive maintenance for all the assets involved,
2. corrective maintenance, which means wait for the failure,
3. few operations of preventive, just to settle the repair organization and then corrective maintenance.

Solution n°1 : The objective is to avoid unexpected outage. Some failures could occur, as the time to correct all GIS will be long. This solution limits the unexpected outage. The cost is the highest one.

Solution n°2 : in this solution, nothing is done to prevent failures.

Solution n°3 : this solution is a compromise between the two previous ones. The critical cases, the strategic GIS, are preventively repaired, GIS without any redundancy. The purpose is to reduce risk for service quality 1. The repair organization, present in the company, ensures the availability of operators, in a short time. In this way, there is quite none difference on the delay to prevent or to repair. The only conditions are to get well trained people and to get spare parts very fast. In consequence, few operations are necessary, on the one hand to treat the critical cases, on the other hand to train operators in charge of emergency repair.

The strategy chosen by the asset manager was the third one. This strategy shows to be the most cost efficient for reducing risk on service quality 1.

A.5 Conclusion

This case points out the advantages of a risk analysis including all impacts. When a failure mode is well known, the first tendency is to apply preventive action rather than waiting for a possible failure.

But even when a failure mode is well known, it is not so easy to confirm that the failure will occur during the time life of an asset.

In a financial point of view, it can be worth to do preventive maintenance.

Also a risk analysis, including all the impacts, is useful to focus the asset manager on the priorities. The priorities are to release service applied by the client, in respect of rules and environmental impact and for the best cost.

Of course strategy can be changed if the hypothesis change. In the present case the failure rate could be a key indicator to check the validity of the choice.

B. App. B TU Darmstadt: EXAMPLE OF A RISK ASSESSMENT

1. RISK ASSESSMENT PROCEDURE

1.1 Workflow

The fundamental proceedings and thus the processes for the evaluation of the outage risk of an equipment and installation are represented in Figure 1 [1]. Basis of the evaluation is the determination of the outage probability of the equipment. For this reason it is necessary to determine the failure frequency of an equipment in dependence on the time after the commissioning or the last maintenance activity. In parallel, a calculation of the non-delivered energy, which is caused by the outage of the equipment, has to be performed by a reliability calculation. During the consideration of both procedures the different requirements of the company regarding the equipment (e.g. technique) and the system (e.g. availability of energy), have to be taken into consideration. In the next step the probable outage costs are determined and compared with the expenses regarding the possible maintenance scenarios. It has to be differentiated between the following maintenance strategies [2]:

- Extension of the life-time by service, e.g. more intensive service in order to shift the investment.
- Renewal by replacement: all components of an asset are replaced and the system remains unchanged.
- Renewal by refurbishment: some components of an asset are exchanged, so that the installation can be regarded as "new"; the system remains unchanged.
- Upgrading or renewal: the system is enhanced in some way, e.g. by increasing the current capacity or short-circuit strength.
- Redesign of the system: re-configuration of a part of a system, e.g. change of the nominal voltage or the configuration of a substation.

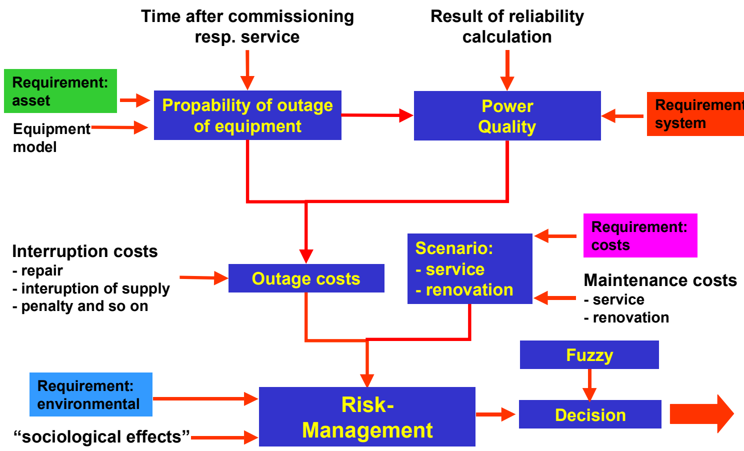


Figure 1: Procedure of Risk-Assessment

Finally there should be an assessment under consideration of the "sociological effects" (e.g. social consequences, public image of the company, frequency of outage etc.). Also, in the two last cases requirements of the company regarding finances and the environment are to be included during the consideration. If a decision is finalized, considerations are necessary regarding the realization of the maintenance measures. Thereby decision techniques utilized by Fuzzy logic are very helpful if complete substations are evaluated [3]. A maintenance makes sense if these costs are lower than the probable outage costs.

1.2 Outage costs

The outage costs cover all financial expenses which occur in case of an outage and are necessary to restore the original situation. The probable costs, which result from the outage of the equipment, can be calculated according to the failure rate of the equipment (minor as well as major). Additionally, the costs due to the non-delivered energy and the expenses, which are caused by contracts with customers or requirements of the regulator, have also to be considered. The following informations should be available:

- repair costs of the faulted equipment
- possible damages of further components
- costs and amount of non-delivered energy
- liability costs due to third party damages
- failure rate of equipment (minor, major)
- customer contracts, requirements of the regulator

In case of outage costs calculation, in general, it has to be differentiated between two failure scenarios which lead to a various financial assessment:

- major failure: instantaneous unplanned outage of the equipment with and without energy interruption (e.g. flashover inside the circuit-breaker due to lightning strike),
- minor failure: failure which can be repaired by a planned maintenance and does not lead to an outage of the supply.

1.3 Maintenance and replacement costs

As a consequence of different maintenance scenarios the expenses for these scenarios can be estimated and compared with the probable outage costs in case of a fault. The following informations are important for an evaluation:

- maintenance measure
- investment costs for a new equipment
- depreciation method and interest rate
- maintenance costs and time interval
- usual life-time
- disposal costs.

1.4 Environmental and social impact

The environmental and social influences have to be considered for the final decision. However, these effects are generally not financially assessable and they depend on public and company requirements. Among other, following informations are of interest:

- personal injuries in case of an outage
- pollution
- land use
- social aspects of the customer
- damages of the property in case of an outage
- public image of the company
- electric and magnetic fields
- right of ways.

2. EAMPLE

2.1 Data base

In the following 14 circuit-breakers of different types for the high voltage level are considered and for the calculation of the present values the following data are taken into consideration:

- intensive service to extend the replacement: 6 years
- life time 25 years
- interest rate 6.5 %/a

Considering a replacement of a circuit-breaker, the installation of a modern SF_6 type c.b. with the same voltage rating is assumed and its investment costs are estimated to:

- 123 kV 25 k€
- 245 kV 75 k€
- 420 kV 220 k€

2.2 Evaluation

2.2.1 Outage costs

The failure frequency of the circuit-breakers has a substantial influence on the calculation of the possible outage costs. According to the outage statistic in Germany over the years 1991 - 2000 the following hazard rate λ (major failures) can be derived depending on the type and rated voltage of the circuit-breakers, Table 1.

type	110 kV	220 kV	380 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

Table 1: Hazard rate λ p.a. for major failures of h.v. circuit-breakers

The relationship between minor (mf) and major (MF) faults is derived from [4] and is assumed to:

- 123 kV: 7.0 mf/MF
- 245 kV: 8.6 mf/MF
- 420 kV: 6.4 mf/MF

The data of Table 1 are used to calculate the probable annual outage costs to which the repair costs as well as the costs for the non-delivered energy belong to. If the repair costs for major failures are assumed to 25 % of the financial expense of a new circuit-breaker the probable repair costs per year can be calculated according to the hazard rate λ. The same is possible for the assumption of the repair costs for minor faults, if an amount of 1.0 k€ is taken into consideration independent on the type of circuit-breaker. Generally the calculation of the non-delivered energy is performed by reliability calculations, so that the effects of an outage of a certain circuit-breaker can be evaluated at different nodes. The result is that the amount of the non-delivered energy at the system nodes depends mainly on the topology of the system and its redundancy (radial - meshed). For simplification the energy E which is interrupted by the faulted circuit-breaker is calculated to $E = P \cdot T_s \cdot \lambda$; with P: interrupted active power; T_s: switching-over time (20 min); λ: hazard rate of the equipment. The financial assessment of the non-delivered energy amounts to 5 €/kWh. In addition to the above mentioned costs possible damages of further components are taken into consideration with an amount of 15 % of the investment costs of a new circuit-breaker.

The complete outage costs for different parameters are listed in Figure 2. This figure shows that the costs for non-delivered energy have the main impact on the outage costs (curve 3), if a value of 5 €/kWh is assumed, whereas the repair costs of the circuit-breakers are nearly negligible, even if 420 kV c.b.'s are considered (no. 3 and 6) with the current average hazard rate.

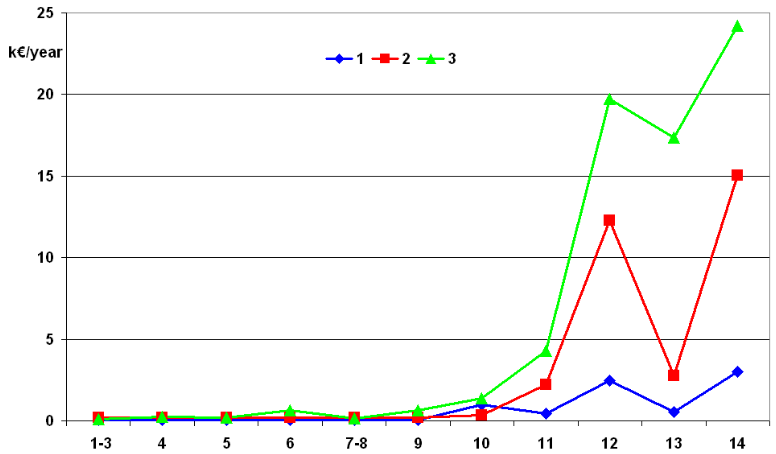


Figure 2: Expected value of annual outage costs for different circuit-breakers (1-14)
1: hazard rate acc. Table 1, costs of non-delivered energy not included
2: five times the hazard rate acc. Table 1, costs of non-delivered energy not included
3: hazard rate acc. Table 1, costs of non-delivered energy included

2.2.2 Maintenance costs

Three different maintenance scenarios are taken into consideration, in this case:

- corrective maintenance ("wait and see"),
- refurbishment/overhaul of the equipment to shift the replacement,
- and immediate replacement of the equipment.

The expenses of an intensive maintenance work of different circuit-breakers are listed in Table 2. Furthermore it is assumed, regarding the calculation of the total present value, that a modern SF_6 circuit-breaker needs a service after 12 years (maintenance costs: 123 kV: 2.5 k€; 245 kV: 4 k€; 420 kV: 5 k€) and an inspection (~ 800 €) after six years.

type	123 kV	245 kV	420 kV
air blast	15	25	50
minimum oil	10	15	30
SF_6	5	10	20

Table 2: Overhaul costs (per k€) of different circuit-breakers (exemplary)

Figure 3 shows the maintenance costs for the considered circuit-breakers for a time range of six years. The replacement costs (line 2) for the 420 kV circuit-breakers are calculated to about 18.5 k€ due to the high investment costs of a new equipment.

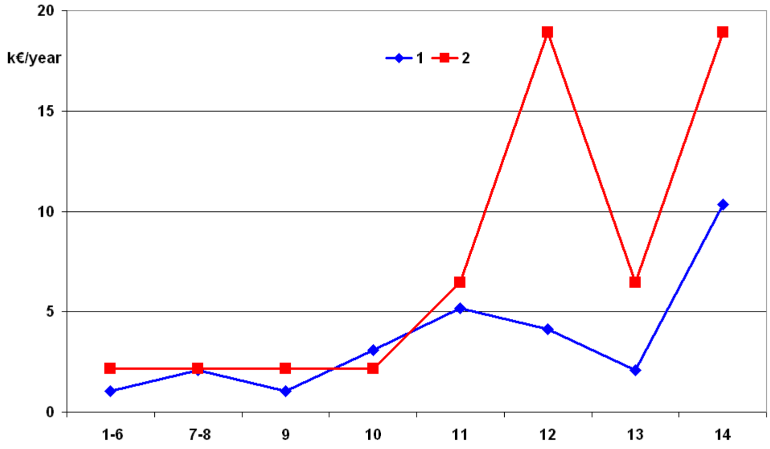


Figure 3: Annual maintenance costs of the different circuit-breakers (1-14)
1: overhaul 2: replacement

2.2.3 Assessment of the result

Finally the costs (outage, maintenance) have to be compared and the results are presented in Figure 4 and 5. The different columns present the financial expenses according to Figures 2 and 3 as well as the "risk" which is evaluated from the difference. The following combinations have been considered:

- variant a: outage costs (curve 2, Fig. 2) vs. overhaul costs (curve 1, Fig. 3)
- variant b: outage costs (curve 3, Fig. 2) vs. replacement costs (curve 2, Fig. 3)

The figures show the final results of the costs-assessment depending on the defined parameters. The calculation emphasizes that the result extremely depends on the amount of the non-delivered energy, which is the result of the topology and the protection scheme of the system as well as of the financial assessment of the energy. Furthermore penalties due to the interruption of the energy supply are not taken into consideration. But in general the evaluation of the possible outage costs is very difficult especially in high voltage systems.

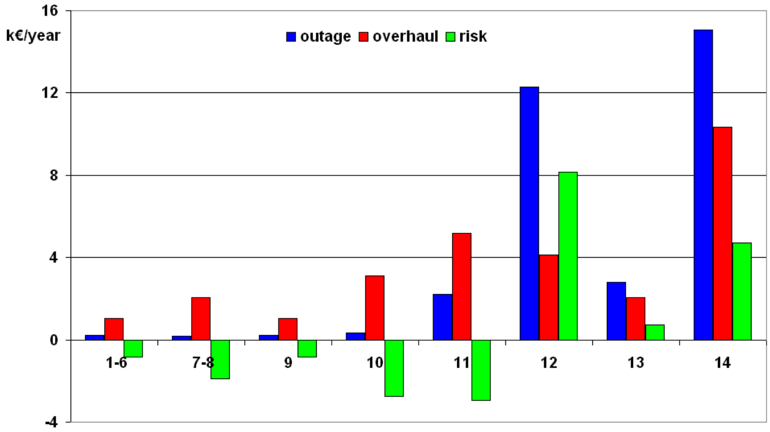


Figure 4: Result of the risk assessment depending on variant a

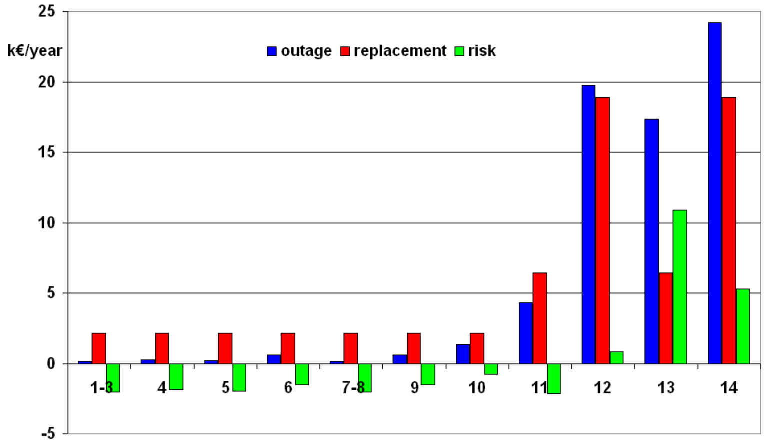


Figure 5: Result of the risk assessment depending on variant b

3. BIBLIOGRAPHY

[1] Balzer, G.; Bakic, K.; Haubrich, H.-J.; Neumann, C.; Schorn, C.: Selection of an Optimal Maintenance Strategy of H.V. Equipment by a Risk Assessment Process. CIGRE 2006, Paris 2004, B3-103

[2] Ageing of the System-Impact on Planning. WG 37-27, Cigre Brochure 176, December 2000

[3] Balzer, G.; Degen, W.; Laskowski, K.; Halfmann, M.; Hartkopf, T.; Neumann, C.: Strategies for optimizing the use of substations assets. Paris 2004, B3-102

[4] Final report of the 2nd enquiry on HV circuit-breaker failures and defects in service. SC13, Brochure 83(1994)

C APPENDIX:

Transformer Failure Probability and Impact Analysis

- Canada -

Through the analysis of various data it is possible to draw a relative comparison of the probability and impact of a transformer failure. This enables Asset Management to direct the appropriate response and resources to transformers indicating the highest probability of failure and greatest impact to the system.

This pro-active approach provides Asset Management with a means of maintaining all transformers within an acceptable risk of failure (probability/impact).

Application of the Asset Management Process

The Asset Worker provides most of the data for the probability/impact analysis and is responsible for implementing the transformer preventative maintenance program or any required corrective work.

The Asset Manager monitors and analyzes the probability/impact data and decides if any action is required, e.g. further confirmatory data, corrective maintenance, change in preventive maintenance schedule, etc.

The Asset Manager will recommend any major action items, e.g. transformer replacement, additional transformer position, etc. to the Senior Asset Manager.

Probability/Impact Analysis Data

Most of the data required for the probability/impact process originates in the field. Some of the data was provided to the company database during the original equipment installation, e.g. nameplate values. The Asset Worker provides additional data on an ongoing basis through the preventative maintenance program. Remaining items are found within the Asset Management organization.

The required data is as follows:

Equipment Ratings									
Station	Equipment	Voltage	MVA	Date	Phases				
Gas in Oil									
Station	Equipment	C_2H_2	C_2H_4	C_2H_6	CH_4	CO	CO_2	H_2	Date
Furans									
Station	Equipment	Furfural	Furalcohol	Date					
Peak Load									
Station	Equipment	Load MVA							
Station Rank*									
Station	Ranking								
Contingency**									
Station	Equipment	Contingency							
Spares***									
Station	Equipment								

* An Asset Management tool used for risk management of system stations. Each station is designated a ranking number based on the estimated risk to the system due to equipment failure.

** An Asset Management list of first and second contingencies for each system transformer.

*** An Asset Management list of spare transformers and the in-service transformers that each spare is designated for.

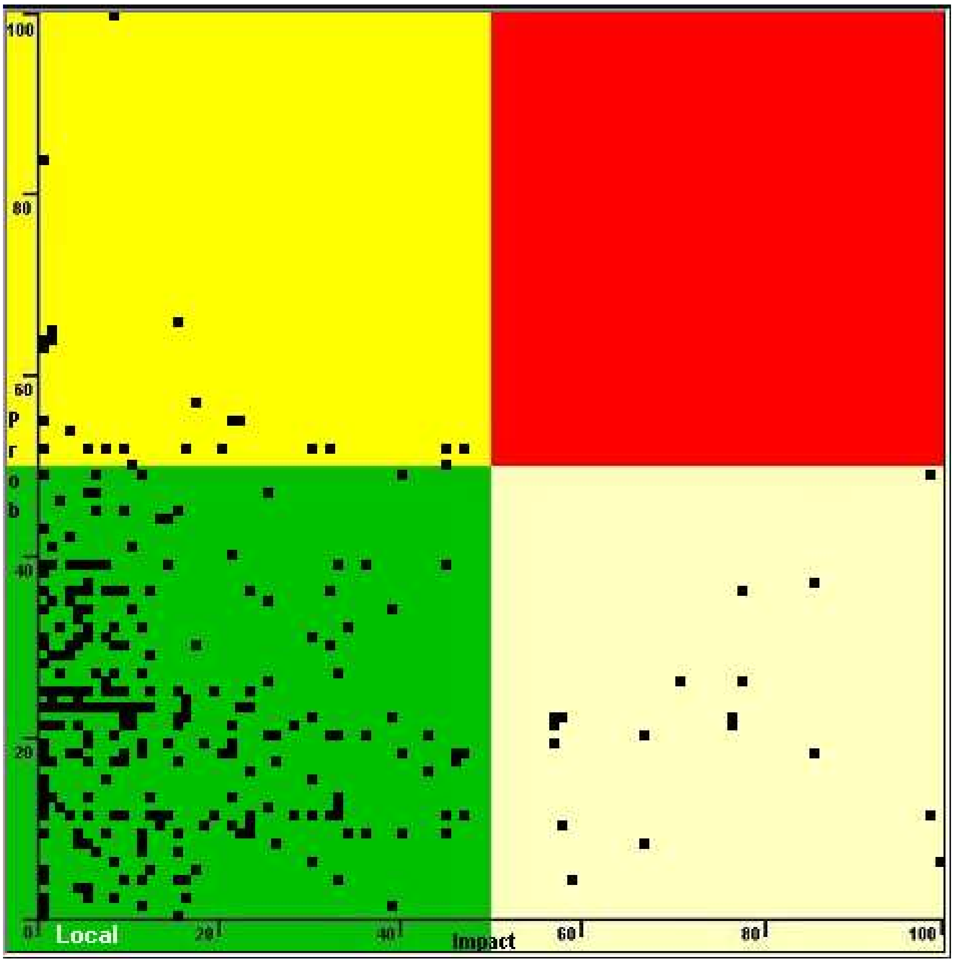
Probability/Impact Analysis

The probability/impact program produces a scatter chart showing the relative probability (Y axis) and impact (X axis) for each transformer. The probability (P) and impact (I) have values from 0 to 100.

Tables show the data used to calculate the P and I and display the points on the scatter chart.

The background of the chart is split into four quadrants.

Green: P and I <= 50.
Light Yellow: P <= 50, I > 50.
Yellow: P > 50, I <= 50.
Red: P and I > 50.



Probability/Impact Scatter Chart

Probability

Probability of failure is the normalized value (0 to 100) of (G + F) x A

G = the gas in oil index, F = the furans index and A = the age in years of the transformer.

Gas In Oil Index

The gas in oil index is calculated from the differences of gas content between the last two sample readings.

An initial index is derived for each gas based on the sample reading differences and then multiplied by the specific gas weighting. The indices are based on historical data and equipment experience.

The final gas in oil index is the average of the initial seven indices divided by the time period between the two samples.

The following table shows the initial index for specific quantities (ppm) of each gas.

Gas/Index	1	2	3	4	5	6	Weight
H2	<=100	<=200	<=300	<=500	<=700	>700	2
CH4	<=120	<=150	<=200	<=400	<=600	>600	3
C2H6	<=50	<=100	<=150	<=250	<=500	>500	3
C2H4	<=65	<=100	<=150	<=250	<=500	>500	3
C2H2	<=3	<=10	<=50	<=100	<=200	>200	5
CO	<=700	<=800	<=900	<=1100	<=1300	>1300	1
CO2	<=3000	<=3500	<=4000	<=4500	<=5000	>5000	1

Example GIO Index calculation:

	H2	CH4	C2H6	C2H4	C2H2	CO	CO2
01/15/2006	12	23	6	11	0.1	600	2500
05/15/2007	122	250	306	87	101	650	2750
Difference	110	227	300	76	101	50	250
Initial Index	2	4	4	2	5	1	1
Index x Weight	4	12	12	6	25	1	1

Total weighted initial index: 61
Average initial index: 61/7 = 8.7

Time period: 485 days/365 = 1.3 years (01/15/2006 to 05/15/2007)

Final GIO index: 8.7/1.3 = 6.7

Furans Index

Several different furans are generated by the aging paper insulation in transformers. Furans therefore give a good indication of the condition of a transformer's insulation. As the insulation degrades over time so more furans are generated. The two furans selected for initial indication are Furfural and Furalcohol.

The furans index is calculated from the highest historical value for each of the two furans. An initial index is derived for each furan, the final furan index being the average of the initial two indices. As with the gas in oil indices, the furan indices are based on historical data and equipment experience.

The following table shows the indices for furfural and furalcohol furans.

Furfural	Index	Furalcohol	Index
< 0.5	1	< 0.1	1
< 1	3	< 0.15	3

< 2	5	< 0.2	5
< 3	7	< 0.3	7
>= 3	9	>= 0.3	9

Example furans calculation:

Highest historical furfural reading: 2.7 Index = 7
Highest historical furalcohol reading: 0.32 Index = 9

$$\text{Furans index} = \frac{7 + 9}{2} = 8$$

Transformer Age

The age of a transformer is considered to be the number of in service years from the initial commissioning date to the present.

Impact

Impact of failure is the normalized value (0 to 100) of VA * SR * C * S

VA = peak loading in MVA for previous year
SR = station ranking
C = contingency index
S = spare transformer index.

Contingency Index

1 Installed redundancy.
2. Spare or mobile transformer.
3. No contingency.

Spare Transformer Index

1 Spare available.
2. No spare available.

The probability/impact scatter chart is currently a work in progress and will probably be enhanced and refined as the process matures. It is envisaged that all the required data will eventually be derived from a single database that is updated periodically.

The probability/impact chart shows the relative rating of individual transformers. It is planned to incorporate this information and similar information on other equipment into the overall power system and station ranking project.

D TRANSFORMER CONDITION – FRANCE

D.1 Introduction

In transmission business, the transformer gets a large part : due to the cost and also due to the impact of the failures for the clients.

The very high voltage transmission network started its development more than fifty years ago. The large groups of transformers installed during high growth periods are quite reached now the end of their life.

What is the end of life for a transformer ?

The end of life is a complex process and it is impossible to fix a limit available for all asset. However, according the experts and also utilities experience [WG37-27], the mean age limit for transformers is around 42 years with a standard deviation of 8 years.

Often, the larger is the transformer, the lowest is its age limit. This can be explained that for the same technology, when the transformer is large, it includes more components. In this way, the risk of failure is bigger.

Furthermore, the market for the furniture of transformers has changed. It becomes more stressed. And the time for delivery brand new transformer, or for reparation is increasing. More than two years are required nowadays.

Due to the long time for the delivery or for the time to repair, anticipated action is obviously necessary from the asset manager.

The present case presents the Life Cycle Transformer Management program from an European utility, strategy including all these new factors.

D.2 Background :

The objective of the asset manager is to get the most of each asset, but with the optimization of cost.

In the present case, the Life Cycle Transformer Management approach, similar to the strategies developed in other utilities [x] consists in three-step process :

- The risk assessment of transformer fleet,
- The condition assessment of individual transformer,
- The life cycle decisions : retire, refurbish, replace or relocate.

The objective for the first step is to get information about the age of the fleet and evaluate the risk to loose units in the future.

The second step is to precise the expected life of the transformer thanks to the results of diagnosis tests and then to calculate the cost of the useful preventive maintenance.

At last, in the third step, a decision is taken.

D.3 1st step : Risk Assessment of transformer fleet

The present feed-back experience on transformers is quite similar to international results [].

For the first thirty years, the failure rate seems to be stable, around 0.2% per year and per transformer for major failure.

Then this failure rate is continuously increasing. It reaches 1% at forty years and much more after.

But some transformers in service are more than fifty years.

These results are similar to those indicated in a Cigre brochure [ ] concerning transformers for substations : 2% for the population 35 – 50 years and 3% over 50 years.

So the age limit of 50 years can be a reliable data to be used as age limit for planned replacement strategy.

According the voltage range, the age limit taken into account in the present case are presented in the table below.

Primary voltage of Transfo	Expected life
400 kV	45 years
225 kV	50 years
< 225 kV	60 years

Table :

The purpose is to evaluate the condition of each transformer during the period in which the evolution of the failure rate is large. The tests must be performed not too soon in the life of transformer, rather in the third last part, when the failure rate is significant.

In the present case, a time of ten years before the "expected life" has been chosen.

Therefore diagnosis are performed on a 400 kV transformer when it is around 35 years old, and 40 years for 225 kV transformers.

D.4 2nd step : Condition assessment of each transformer

A lot of useful documents explained the diagnosis methods for transformers [227], [298] in relation with the failure modes known.

The methods aim to evaluate the condition of the following parts of the transformer :

- electromagnetic circuit,
- current carrying circuit,
- dielectric system,
- mechanical structure,
- cooling system,
- bushings,
- On Load Tap Changer (OLTC),
- oil preservation and expansion system,

– protection and monitoring.

The diagnosis methods applied are :

– Oil analysis (DGA, particles, furans, withstand, water contend,….),
– Electrical tests (insulation, resistance value, etc…),
– Visual check (without deep dismantle),
– Thermography tests.

These methods are efficient for some parts of the transformers, but not for all. In the present case, the diagnosis methods applied are useful for the part indicated in the table n°

	Diagnosis method			
Part of transformer	Oil analysis	Electrical tests	Visual check	Thermography
electromagnetic circuit	X			X
current carrying circuit	X	X		X
dielectric system	X			
mechanical structure	X	X		
cooling system			X	
Bushings	X	X	X	X
On Load Tap Changer (OLTC)		X	X	
Oil preserve and expansion system	X		X	
Protection and monitoring		X	X	

Table n°

In most of the cases, the methods give information on the condition but the diagnosis is not total, and crossed analysis are useful for building a total diagnosis.

Furthermore, the methods presented are applied for preventive maintenance. Other methods, like for example partial discharge method (electrical test for dielectric system) are not included because they are not applied as assessment method.

The main part of transformer is composed with : electromagnetic circuit (core), current carrying circuit (windings), dielectric system and internal mechanical structure. The refurbishment of this part is complicated and often expensive.

For the other parts, cooling system, bushing, OLTC and accessories, the refurbishment cost is lower and could be profitable.

The objective of the diagnosis is to evaluate the remaining life of each part.

If the remaining life of one or more of the other parts is lower than the remaining life of the main part, then refurbishment can be decided according the process described in the third step.

D.5 3rd step : Decision

As indicated above, the question of refurbishment is asked only when the remaining life of the main part is greater than for the other parts.

Then the decision to refurbish or not the transformer will depend on the result of the economical comparison of the two following strategies :

The transformer is not refurbished and the transformer must be replaced when it will fail, probably around the remaining life of the other part,

The transformer is refurbished and the expected end of life is at least the remaining life of the main part.

For the first strategy, the economical estimation can be done by the use of commonly known method [ ] It gives an average annual discounted cost referred to the reference, the cost of a brand new transformer and including 'I' interest rate of money. It represents capital expense during an assumed period of 'r' years from the moment of decision until the estimated end of life of the transformer.

Cost "without refurbishment" = $C_{new} / (1 + i)^r$

The second strategy take into account the cost for refurbishment and 'a' years, the extension of life for the transformer thanks to the refurbishment. The cost for refurbishment depends on each diagnosis. It can be evaluated as a percentage of a brand new unit. Often it is between 10% and 20%.

Cost "with refurbishment" = $C_{refurbis} + C_{new} / (1 + i)^{r + a}$

Symbols :

C_{new} = cost of a brand new transformer.

i = interest rate of money,

r = the remaining life of the transformer (= the minimum of the remaining life of its parts),

$C_{refurbis}$ = cost of the refurbishment.

a = the extension of life thanks to the refurbishment.

To take into account some uncertainties, a margin is including and the refurbishment is decided only if :

Cost "with refurbishment" $\leq$ 0,8 x Cost "without refurbishment"

Numerical examples are presented below.

Example 1 :

C_{new} = 1400 k€.

i = 6%,

r = 10 years,

$C_{refurbis}$ = 10% of C_{new} = 140 k€.

a = 10 years

$C1$ = Cost "without refurbishment" = 1400 k€ / $(1,06)^{10}$

$C2$ = Cost "with refurbishment" = 140 k€ + 1400 k€ / $(1,06)^{20}$

$C1$ = 780 k€ and $0,8xC1$ = 624 k€

$C2$ = 140 k€ + 435 k€ ≈ 575 k€

As $C2 \leq 0,8 \times C1$, then refurbishment is profitable.

Example 2 :

C_{new} = 1400 k€.

i = 6%,

r = 10 years,

$C_{refurbis}$ = 15% of C_{new} = 210 k€.

a = 10 years

$C1$ = Cost "without refurbishment" = 1400 k€ / $(1,06)^{10}$

$C2$ = Cost "with refurbishment" = 210 k€ + 1400 k€ / $(1,06)^{20}$

$0.8.C1$ = 624 k€

$C2$ = 210 k€ + 435 k€ ≈ 650 k€

As $C2 \geq 0,8 \times C1$, then refurbishment is not profitable.

Example 3 :

C_{new} = 1400 k€.

i = 6%,

r = 10 years,

$C_{refurbis}$ = 15% of C_{new} = 210 k€.

a = 15 years

$C1$ = Cost "without refurbishment" = 1400 k€ / $(1,06)^{10}$

$C2$ = Cost "with refurbishment" = 210 k€ + 1400 k€ / $(1,06)^{25}$

$0.8.C1$ = 624 k€

$C2$ = 210 k€ + 325 k€ ≈ 535 k€

As $C2 \leq 0,8 \times C1$, then refurbishment is profitable.

These numerical examples point out the influence of the different parameters. The profitability of the refurbishment is often reached when the extension of life (a) is large and when the remaining life of the transformer is not so large (r). Also when the refurbishment cost is not so large compared with the cost of a brand new transformer.

D.6 Conclusion

This case presents an approach of management for an old fleet of the transformers.

It shows the profitability of deep preventive maintenance when the life of transformer can be extended.

The method consists on estimate the end of life of each asset. Then according the diagnosis results, the remaining life of the different parts of the transformers and the cost of refurbishment, a decision can be taken after the comparison of two strategies : with and without refurbishment.

Nevertheless, when the remaining life of the main part of the transformer is small, the refurbishment is generally not profitable. In this case, on-line monitoring brings useful information to keep in service the transformer until deterioration of indicators and before a failure.

D.7 Bibliography

1. Balzer.G, Bakic.K, Haubrich.H-J, Neumann.C, Schorn.C : Selection of an Optimal Maintenance and Replacement Strategy of H.V. Equipment by a Risk Assessment Process. Cigré 2006, B3-103.
2. Cigré Brochure n°227, Working Group A2.18 : Life management techniques for power transformer.
3. Cigré Brochure n°298, Working Group A2.23 : Guide on transformer lifetime data management.
4. Cigré Brochure n°248, Working Group A2.20 : Economics of transformer management.
5. J.C Burgos, E.Pagan, B.Garcia, J.I. Anguas, A.Ramos, D.Montavez, E.Perez : Experiences in managing transformers trough maintenance operations and monitoring systems, Cigré 2004, A2-206.
6. Cigré Brochure n°176, Working Group 37.27 : Ageing of the system. Impact on planning.
7. William H:Bartley : Life Cycle Management of Utility Transformer Assets, Breakthrough asset management for the restructured power industry, October 2002.

E OIL- PRESSURIZED CABLES – THE NETHERLANDS

E.1 Introduction case

In 2002 this Transmission Company introduced the Asset manager – Service Provider organization model. One of the main reasons was to gain more control of the expenditures in relation to the quality of the infrastructure and its environment. The sustainability policy from 2003, stated that all components, which brought to much damage to the environment, should be removed or replaced. One of the spearheads of the sustainability policy was that for oil-pressure cables the leakages should be as much in control and prevented as possible.

E.2 Norms in the Value model

The first step is to find how the sustainability policy relates to the value model and find norms to assess the effect of the supposed incidents.

The first column shows the environmental impact of an incident, but in order to compare several environmental issues (e.g. oil leakage, noise, SF6-gas leakage, natural gas leakage, losses, contamination) and to combine them in one parameter, the clean-up costs have been chosen as the most relevant indicator, despite the fact that a severe impact on the environment could lead to relatively low clean-up costs. For the sake of simplicity, "clean-up costs" are applied.

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	week 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

Figure E-1 Soil cleaning costs as measure for oil leakage incidents

E.3 Quick risk analysis

The reason for the company to focus on oil leakages was the supposed worsened condition of the cables. Considering the total amount of oil refill each year and the associated clean-up costs the impact on business values of this issue fell in the impact category: catastrophic. These incidents happen each year, so from the risk assessment matrix it can be derived that the risk for the business caused by these incidents is: Very High.

The infrastructure has 1130 km of oil pressure cable in the 50 kV-grid and 270 km of oil pressure cable in the 110/150 kV-grid with a total value of 550 Million Euro. With a yearly total expenditure of 100 Million Euro on the complete Transmission Infrastructure, of which 1/5th is available for expenditures on connections a complete replacement of oil-pressure cables was not a realistic option.

It was clear this had to be taken very serious and it was decided to analyze the issue of oil pressure cables and the oil leakages in more details.

E.4 Detailed risk analysis

The succeeding investigation was aimed at the top 10 of oil pressure cables, which were responsible for the largest amount of oil-leakage. The failure mechanisms of and stress factors on the oil pressure cables were investigated. Therefore it was necessary to know of which types of oil pressure cables the population of oil pressure cables in the infrastructure was built up from.

The collection of data is of main interest to come to a right assessment of the size of the problem and the level of risk. A distinction is made in static and dynamic asset data. To the static data belong for example the data on the installation of the asset like name of the circuit, year of installation, cable type. To the dynamic data belong for example the data on the usage and maintenance of the asset, like the amount of oil per cable that needs to be added to keep the oil pressure on the right level.

E.4.1 Static asset data: Oil pressure cables type and year of manufacture

The desired data of the oil pressure cables were not directly available for various reasons.

Due to many merges of the electricity companies and resulting movement or disbanding of offices many archives were lost

Due to many merges in the electricity business responsible departments have been downsized in such a way that the process of data management stopped

Due to ill managed digitalization projects of archives data was lost.

For these reasons the collection of asset data is a time consuming and sometimes impossible process. After a workload of three months during one year the project team succeeded to collect the following data. See Figure E-2.

A list was drawn up of oil pressure cables, identified by their circuit name and the data: length and installation date. It appears that when length and installation date are drawn in a histogram, that these data follow the familiar pattern of growth in the electricity grid. A stage of growth, increasing by the end of the 50's, continuing during the 60's and decreases by the beginning of the 70's, followed by a peak of growth from the end of the 80's until the beginning of the 90's. This image of the ages and installed lengths of the oil pressure cables is recognizable and explainable. Of 1,6 % of the oil pressure cables the installation date could not be found out.

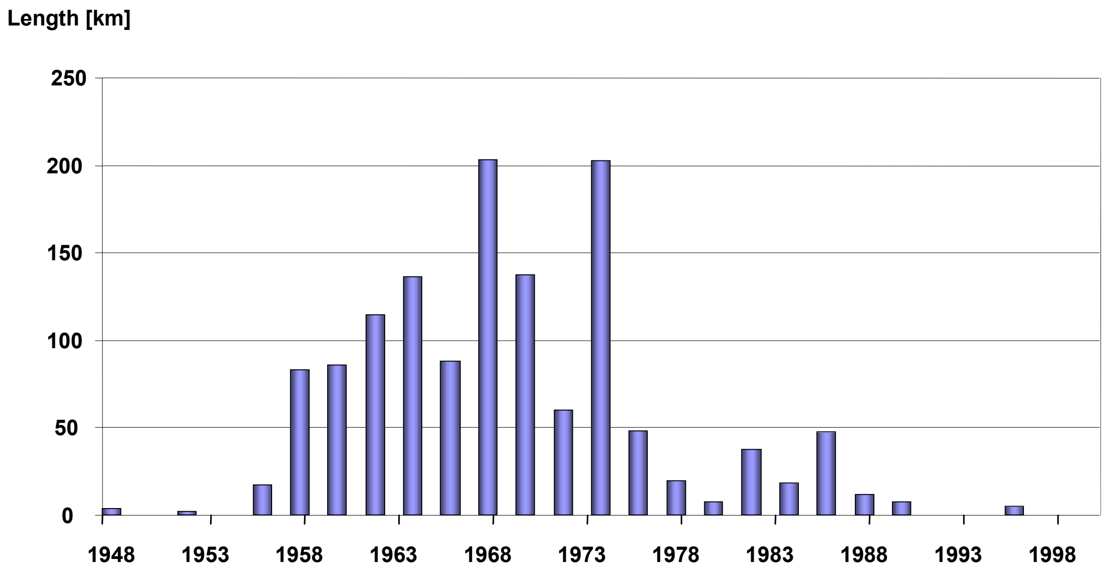


Figure E-2 Installation of oil pressure cables

The construction of the oil pressure cable consists of conductors, wrapped in paper and oil, contained by a lead sheath, pressurized by oil. From a first analysis the mechanic load and aging of the lead are the major causes of the leakages.

The structure of the lead and the lead sheath improved during the years of application of oil pressure cables, due to development of the production processes. Knowing this the age of the oil pressure cable is identified as a risk indicator. The risk indicator has two measuring points related to a modification in the production process.

The development of the production processes:

Before 1953 a lead sheath made out of pure lead was applied, produced in a discontinuous process. In this production process a welding seam appears along the cable, which is sensitive of mechanical pressure

Between 1953 and 1963 a lead sheath made out of pure lead was applied, produced in a continuous process. The welding seam no longer occurred but the pure lead of the sheath was still very soft en sensitive to mechanical pressure

Since 1963 a lead sheath made out of a lead alloy is applied and the cable sheaths are produced in a continuous process. By these improvements the two problems were prevented.

Knowing this about the production processes it was assumed that oil pressure cables dated before 1963 have an increased chance on leakage. The chance of leakage for oil pressure cables dated before 1953 are even higher because of the discontinuous production process.

It was concluded that of a total length of oil pressure cables (1400 km) 27 % has an increased chance on leakage and 0.4 % has an extra high chance on leakage, 71 % has only a small chance on leakage.

E.4.2 Dynamic asset data: data of oil refill

To track the oil leakages per cable a derived variable is used, due to the leakages that may appear on random affected points on the cable. The data on the oil added to keep the right level of oil pressure per cable is used. When a leakage increases, the oil pressure in the cable decreases. The maintenance personnel will after assessment of the situation add oil or detect the leakage. These data are reported to the asset manager. The amount of oil added is a measure for the oil leakage.

E.4.3 Risk Assessment

With these data on oil addition a risk analysis is performed. The risk is defined as probability times effect. The risk of leakage of an oil pressure cable becomes: de probability of a leakage times the effect of the leakage on the environment.

	Variables that impact prob. Or effect	Categories	Score
Probability	Year of installation	<1953	2
		1953-1963	1
		>1963	0
	+		
	Number of oil additions per year	>2x / year	2
		1-2x / year	1
		0x / year	0
X			
Effect	Amount of oil leakage	Large	3
		Medium	2
		Low	1
		None	0
	+		
	Rate of oil leakage	Slow	2
		Fast	1
		None	0

There are no absolute values for failure probabilities known for the several types of oil pressure cable. The assumption here is that the probability of an oil pressure cable mainly depends on its condition and the mechanical stress because of digging or ground changes. The key parameters, giving a measure for the oil leakage and for which data are available (after analysis of the failure mechanism) are the year of installation and the frequency of oil addition.

An oil pressure cable, which needs a small oil addition twice each year will have an small and difficult to locate point of leakage. Considering an old cable these points towards a bad condition of the lead sheath, when considering a younger cable it may point towards a minor damage. The addition of a large amount of oil points towards a large leakage point, probably caused by a excavating machine, ground drill or a pile.

Because of the lack of absolute values for probabilities on leakage a scoring technique is applied. The oil pressure cable types before 1953 have, because the production process and the applied materials, the largest probability of leakage, therefore a high score relative to the types is given.

The effect is measured by the amount of oil leakage. Two parameters are of interest. The amount of oil leakage and the flow rate of oil leakage. When a leakage appears with a sudden large flow of oil, the leakage point will be located by the maintenance personnel more quickly than when a small flow is involved. This speed in the actions limits the effect on the environment. The oil is only in small area in the soil and can be cleaned easily.

With the risk calculation matrix above using static and dynamic data on oil pressure cables the risk of the involved oil pressure cables can be determined. Further, the cables can be prioritized according to their risk assessment.

5	0	0	1	0	0
4	0	2	4	3	0
3	0	22	20	1	0
2	0	3	2	1	0
1	0	5	2	0	0
0	105	30	2	0	0
Effect / Probability	0	1	2	3	4

After the risk assessment in 2003, it was concluded that of 203 oil pressure cables in total only 66 had leakage of which 9 severe.

E.5 Risk reducing measures

De measures consist of:

- repair after leakage: by locating the point of leakage, repairing the cable and clearing of the soil
- prevention of leakage by replacing the oil pressure cable by another type of HV-cable: XLPE
- next to the measures considering the asset itself measures can be taken considering the organization around the asset: the asset management system.

It is of great interest that an organization is set up to manage the data to control the oil leakage on the short term and to be able to take measures for the longer term.

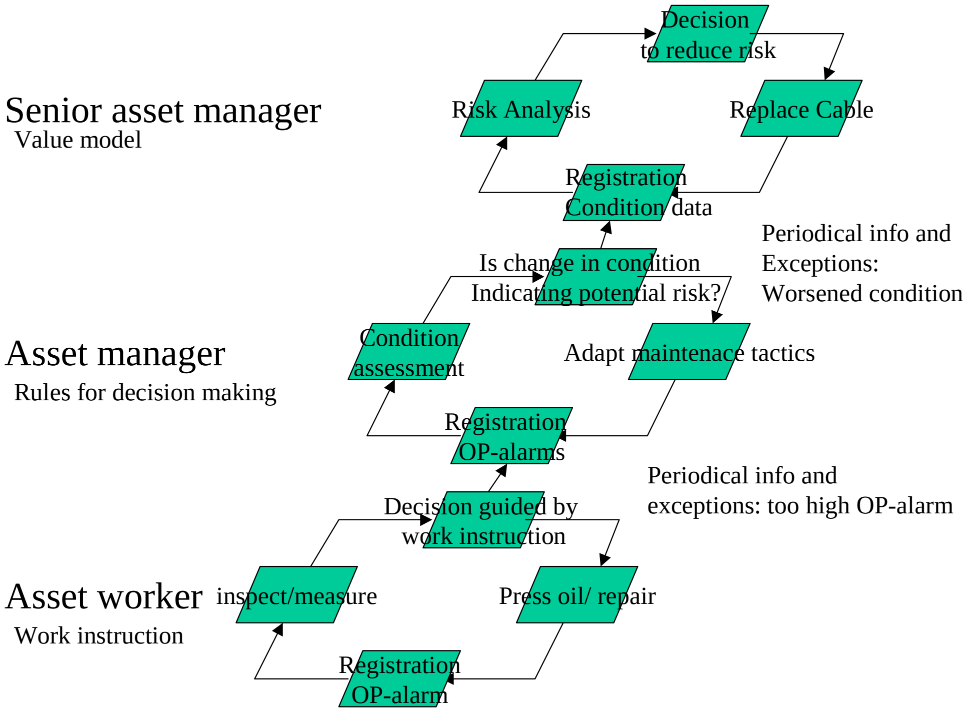


Figure E-3 Aggregation levels in the asset management system

E.6 Conclusion and decision making

The total amount of oil leakage in 2003 caused by oil pressure cables was reduced with 35 % by intensified maintenance. Of the remaining amount of oil leakage 46 % was caused by a Top 10 of oil pressure cables in an assumed bad condition. The rest (20%) was caused by several small leakages.

A combination of risk reducing measures was chosen as described above. Next to the replacement of oil pressure cables, which were responsible for the largest amount of oil leakage, the asset management system (organization) was improved in such a way that there is:

- adequate data management of static and dynamic data
- an efficient maintenance service for repair of leakages
- an improved program for finding the smaller, difficult to locate leakages

F 50 KV OIL-IMMERSED SWITCHGEAR – THE NETHERLANDS

In this case, about risk treatment of 50 kV oil-immersed switchgear in the Netherlands, the risk management steps are shown: define objective – identify risks – select risks – identify risk treatment measures.

Figure F-1 50 kV Coq oil immersed switchgear

F.1 Introduction

In the Netherlands 68 50 kV oil-immersed switchgear installations have been erected since 1956 with the largest growth in installations in the load growth period in the mid-70s. The overall number of bays is 467. The original equipment manufacturer of these legacy installations has reported that maintenance and spare parts will no longer be available. Furthermore the age and the large consequences of a catastrophic failure of this type of switchgear was reason for the company to perform a risk analysis on this type of equipment.

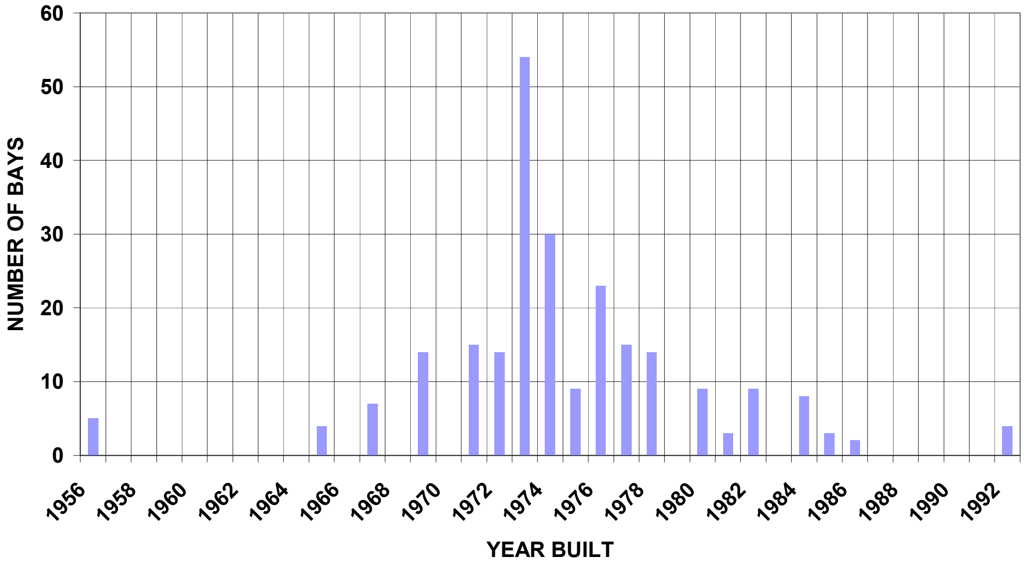


Figure F-2 Age distribution of 50 kV oil immersed switchgear

The scope of the risk analysis was limited to the possible events, in relation with the 50 kV oil-immersed switchgear, which would have consequences for the business as a whole. Therefore consequences needed to be linked to the business values.

F.2 Risk Identification

Several brainstorm sessions were set up including experts on maintenance and engineering of the 50 kV oil-immersed switchgear, asset managers and risk analysis facilitators. From these sessions the following risk description became clear.

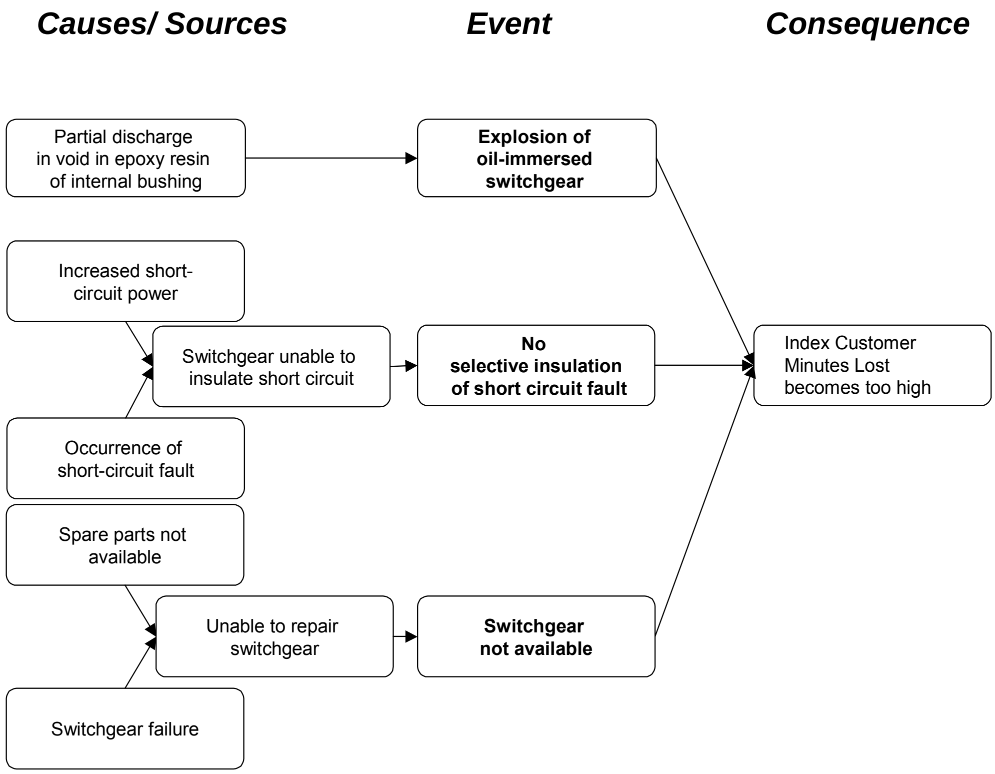


Figure F-3 Faulttree 50 kV oil-immersed switchgear

The events all lead to the same consequence for Service Quality. Because of the location of the substations and the cellars for cable connection underneath the installation the impact on Safety is regarded to be less severe than on Service Quality.

In the sessions many other events have been brought up, but for clarity reasons in this appendix only the main events that lead to high risk are reported.

F.3 Risk Selection

With the decision framework the risks identified are assessed.

Per incident	Financial "Damage"	Quality "1.5*kW*min"	Safety "victims"	Legal "penalty"
Fatal	> 10 M€	> 10 Mmin	several deaths	loss of licence
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

Figure F-4 Matrix of Impact Assessment

Probabilty/effect	# per year	Catastrophic	Severe	Serious	Moderate
Permanent	>1000	VH	VH	VH	H
Daily	>100	VH	VH	H	M
Monthly	>10	VH	VH	H	M
Yearly	>1	VH	H	M	L
Frequently	>0,1	VH	H	M	L
Probable	>0,01	H	M	L	N
Possible	>0,001	H	M	L	N
Not likely	>0,0001	M	L	N	N
Almost impossible	<0,0001	L	L	N	N

Figure F-5 Matrix of Risk Assessment

F.3.1 Partial Discharges in Internal Bushing leading to Explosion of Switchgear

If a partial discharge in an internal epoxy resin bushing leads to an explosion of the bay and eventually to fire of the whole installation the consequence will be that the whole installation will be lost and that it will take at least 24 hours to install an emergency switchgear installation. The consequences are in the impact category " Fatal/Catastrophic" .

From statistical analysis of the oil-immersed switchgear in the Netherlands it appears that even minor partial discharges below the norm, may result in failure of the bushing. The probability of this event is regarded: Probable.

This leads to the risk assessment: High Risk.

F.3.2 Short-circuit withstand ability

If a short-circuit fault takes place and the short-circuit power in that area of the network has risen in the past years the full switchgear installation may be lost. It will take at least 24 hours to install an emergency switchgear installation. The consequences are in the impact category " Fatal/Catastrophic" .

There has been an increase in short circuit power in the past decades. Calculations show that in two cases short circuit power is 7% over the nominal short circuit power of the switchgear installation. The estimate of probability shows that a short circuit in the next 10 years exceeding the nominal short-circuit power of the installation is possible. So probability: Frequently.

This leads to the risk assessment: High Risk.

F.3.3 Lack of Spare Parts

The time to repair is not clear and the quality of the repair is poor because the spare parts are not preserved in a well conditioned environment. The consequences are expected to be in the impact category " Fatal/Catastrophic" .

The spare parts expected to be available are not well kept and conditioned and therefore not usable. There is no storage system and no policy about the crucial spare parts and possible alternative materials. It is estimated that twice a year due to failures the switchgear need to be repaired but the right material is not available. So probability: Frequently.

This leads to the risk assessment: High Risk.

Figure F-6 Bushing

F.4 Identification of Risk Treatment Measures

There are several options to treat the risks assessed in the previous section.

- Risk treatment by technical solution: replacement of the oil-immersed switchgear
- Risk reduction: preventive measures to prevent the causes to lead to the risky event
- Risk mitigation: corrective measures to prevent the risky event to lead to large consequences for the business

These options will be investigated for the assets and components connected with he risks in the previous section.

F.4.1 REPLACEMENT OF THE OIL-IMMERSED SWITCHGEAR INSTALLATION

Replace switchgear installation: preventive replacement based on experience and statistical analysis (reliability curves). This measure for all 68 installations will incur replacement costs of 100 M€ over the next 15 years. Therefore other risk treatment measures are investigated making use of the risk description in the previous section.

F.4.2 PARTIAL DISCHARGES IN INTERNAL BUSHING LEADING TO EXPLOSION OF SWITCHGEAR

The preventive measure available is the replacement of the bushings, but this option has high cost and may introduce new risks when the old bushing were OK but replaced and new bushings are not installed properly.

A better option is to replace the bushings selectively: only the bushings that form a risk for the complete installation. But to do that the technology for in-service PD-measurement needs to be improved or alternatives need to be found. The available equipment is not sensitive enough.

Mitigation of fire in a part of the installation due to explosion of the bushing can be found in the following corrective measures. The cable cellar is sectionalized by fire resisting walls. The switchgear installation room may be better sectionalized from the from cable cellar by closing the cable opening with fire resisting material. In room sections fire extinguishing installation may be installed.

Note that the measures taken for prevention and corrective actions in case of fire are not meant in the first place for safety reasons but to prevent loosing the complete installation through fire and thus having a high risk on service quality.

F.4.3 SHORT CIRCUIT WITHSTAND ABILITY

The switchgear is in place to limit the consequences of a short circuit. When the switchgear is not capable of withstanding the short circuit in the network the consequences will be high. To be able to take measures on time the short circuit power in the network shall be monitored by calculations, especially when network configuration is about to change. Short circuit power must stay below norm for short circuit withstand of the switchgear installation.

To maintain the withstand ability of the switchgear the condition in the switchgear room may be improved by installing air dryers.

F.4.4 LACK OF SPARE PARTS

Improve organization for storage of spare parts and create awareness to store the spare parts in the correct way. Increase availability of spare parts through alliance with other companies with this type of switchgear in place: exchange of spare parts and exchange of knowledge.

F.4.5 STRATEGIC OPTIONS FOR LIFE CYCLE MANAGEMENT OF 50 KV OIL-IMMERSED SWITCHGEAR

Continue with the existing strategy means accepting a run-to-fail strategy. The risks as identified and assessed in the previous section are not treated then. Since the risk level is assessed High this is not an acceptable strategy. As already mentioned in subsection F.4.1 preventive replacement on short term of all 68 installations is not realistic because costs and availability of suppliers. Therefore a combination of selective preventive replacement of the 50 kV-oil-immersed switchgear installations and the other risk mitigation measures mentioned in sections F.4.2 to F.4.4 is most suitable.

Selective replacement takes place when the risk for a specific installation is considered too high and the other measures are not expected to mitigate the risk sufficiently, for example when the short circuit power in the network has become too high or when the level of partial discharges in the bushings has become too high. To facilitate selective replacement a ranking of installations is made considering the condition and importance of the installation.

In this ranking the following parameters are considered:

- Number of direct customers (importance)
- Number of adjacent bays (condition)
- Single or double rail (condition)
- Margin for dynamic short circuit current (condition)
- Expected year of reaching short circuit with stand limitations (condition)

In the figure below an example ranking is shown.

Substation	**rail**	**No. of bays**	**No. of large customers**	**Delta Idyn [80%]**	**Total score**
SS01	double	18	2+TF	-57	13
SS02	double	7	0	-44	6
SS03	double	16	TF	18	4
SS04	double	8	1	8	4
SS05	double	8	2	63	3
SS06	double	7	2	52	3
SS07	double	14	TF	41	3
SS08	double	7	0	23	3
SS09	double	7	0	39	3
SS10	double	8	1	15	3
SS11	double	9	0	7	3

Figure F-7 Prioritizing on Risk

F.5 Conclusion

In this case, about risk treatment of 50 kV oil-immersed switchgear in the Netherlands, the risk management steps was shown: define objective – identify risks – select risks – identify risk treatment measures.

APPENDIX

G TRANSFORMER LIFE ASSESSMENT – UNITED KINGDOM

G.1 Introduction

The case concerns the strategy chosen by the English TSO for life assessment of the transformers population.

Due to the start development of 275 and 400 kV in the 60's period, nowadays the main part of the transformers are between 30 and 40 years old. The failure rates observed seem to be constant, about 0,3% per year, with a failure defined as requiring replacement or back to works repair.

But whatever the reliability observed now, there must come a time when the probability of a failure starts to increase as materials and components approach their end of life.

Therefore, the company has an obligation to assess the impact of increasing failure rates in the future as transformers approach their end of life.

According the experience of this TSO, up to 35 years, there is no detectable increase in failure rate with age.

The objective pursues by the company is to build a replacement strategy for the transformers population in relation with his business values.

G.2 The different possible strategies

The three strategies analyzed are :

- 1: replace all units at a designed age; in this case, no reduction in reliability must occur,
- 2: replace on failure;
- 3: arrange a planned replacement when the condition of a transformer is such that it no longer meets the system reliability requirement.

The business values involved are mainly :

- finance,
- quality of service (or reliability),

G.3 The risks analysis

The first strategy ensures that no reduction on reliability occur, but the cost is extreme.

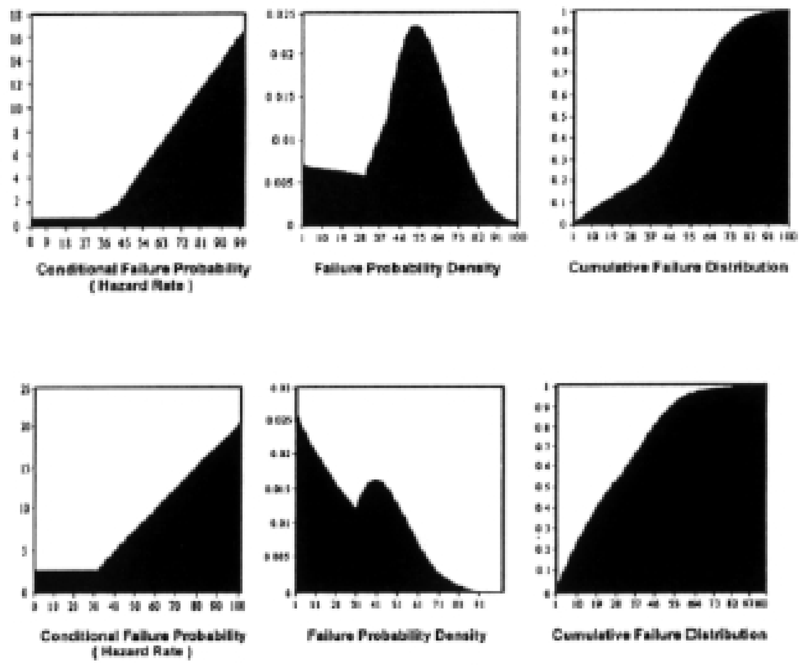
The second strategy seems to be a low capital cost strategy as units keep in service the maximum time, until failure. But the maximizing of the utilization of capital assets is apparent, because this solution induces a high level of redundancy to withstand the impact of an unexpected failure. Therefore the impact of this strategy is high for reliability or for financial.

The third strategy represents a better compromise between reliability and financial values. This solution is able to manage system reliability, compensations for replacing transformers before eventual failure. Therefore, the TSO gets the ability to plan the replacement programme, to smooth any "assets wall" and take advantage of lower prices for planned purchases.

G.4 Model used

The key parameter is the age which reliability begins to be reduced and also an estimate of mean life of asset population.

In relation with technical experts, and by that way involving risk management at the operational level, the asset managers have collected data and have drawn the patterns for reliability according age.



The document [1] presents the investigations of the technical experts, the condition tests performed on transformers and the organization process applied to follow the strategy for risk management.

G.5 Synthesis

This example shows an application of risk management for transformers, direct in relation with the concepts presented in this TB.

The asset managers have chosen the strategy to apply. Among different possible strategies, the strategy chosen represent the lower risk for the business values involved : financial and reliability.

Thanks to data on the transformer condition, data coming from the operational level, the asset managers get the hazard functions for the transformers population. They can therefore assess the age to replace transformers. This global approach is used for planning the volume of transformers to buy in the mid-term.

At the operational level, the real condition of transformers gives the priority order for the replacement program.

G.6 Reference

[1]"Life assessment of 275 & 400 kV transmission transformers", P.Jarman, J.Lapworth, A.Wilson, NGC, 12-210 Cigré 1998

APPENDIX

H.1 Models used for end of life assessment

H.1.1 THE MAIN PARAMETERS

Statistical models are used in demographic domain for "end of life" calculation. In demography, the term of "survival" is more often used rather than "end of life".

The theory of survival uses mathematical tools which are easier now to handle thanks to efficient software and mathematical tools for statistical calculation.

Survival analysis attempts to answer the questions such as : what is the fraction of a population which will survive past a certain time ? Of those that survive, at what rate will they die or fail ?

The main functions and parameters used in survival studies are :

- The survival function,
- The lifetime distribution (or the cumulative distribution function),
- The density distribution function,
- The hazard function.

These notions and terms are explained below [8].

H.1.2 THE SURVIVAL FUNCTION

The survival function, conventionally denoted S, is defined as :

$$S(t) = Pr(T>t)$$

Where t is time, T is a random variable denoting the time of death.

Pr(T>t) is the probability that the time of death, T, is later than a specified time t.

The survival function is usually assumed to approach zero as age increases.

H.1.3 THE LIFETIME DISTRIBUTION

The lifetime distribution function, conventionally denoted F, is defined as the complement of the survival function.

$$F(t) = Pr(T \leq t) = 1 - S(t)$$

H.1.4 THE DENSITY DISTRIBUTION FUNCTION

The derivative of F, also called the density function of the lifetime distribution, is conventionally denoted f,

$$f(t) = \frac{d}{dt} F(t)$$

Then F(t) can be assessed by this calculation :

$$F(t) = \int_0^t f(u)du$$

F(t) is also called the cumulative distribution function.

H.1.5 The hazard function

The hazard function, conventionally denoted λ, is defined as the event rate at time t conditional on survival until time t or later.

$$\lambda(t)dt = \frac{f(t)}{S(t)}dt = -\frac{S'(t)}{S(t)}dt = \frac{f(t)}{1-F(t)}dt$$

The hazard function may be increasing or decreasing but never negative.

An example of hazard function is the bath-curve, which is large for small value of t, decreasing to some minimum, and thereafter increasing again. This model the property of some mechanical systems to either failure soon after operation, or much later, as the system ages.

The hazard function is also the death rate at a specific age (t), or also failure rate at a specific age (t).

H.1.6 Expression for the main parameters

In consequence, the survival evolution of each population can be described by the use of the following parameters :

- The density function of lifetime f(t), or also called density function of "end-of life",
- The cumulative distribution function F(t)= $\int_0^t f(u)du$,
- The survival function S(t) = 1 – F(t),
- The hazard function λ(t) = $\frac{f(t)}{S(t)}$, or also called failure rate according age.

H.2 Examples of survival distribution

H.2.1 Introduction

Survival models are constructed by choosing a specific probability distribution for the survival function.

In the following part, some typical examples of survival distributions are given [9].

The simplest one, the uniform distribution, make easy the understanding of these different parameters.

The two next examples, normal distribution and Weibull distribution, are more often used in reliability studies.

H.2.2 Uniform distribution

The general formula for the density function of the uniform distribution is :

$$f(t) = \frac{1}{B-A} \qquad \text{for } A \leq t \leq B$$

where B-A is the scale parameter. Take the case where A = 0 and B = 100, as an example for the graphic representation. Therefore :

$$f(t) = \frac{1}{100} \qquad \text{for } 0 \leq t \leq 100$$

The formula for the cumulative distribution function of the uniform distribution is :

$$F(t) = \int_0^t f(u)du = \frac{t}{100}$$

The followings figures n°1&2 represent the uniform probability density function and of the uniform cumulative distribution function.

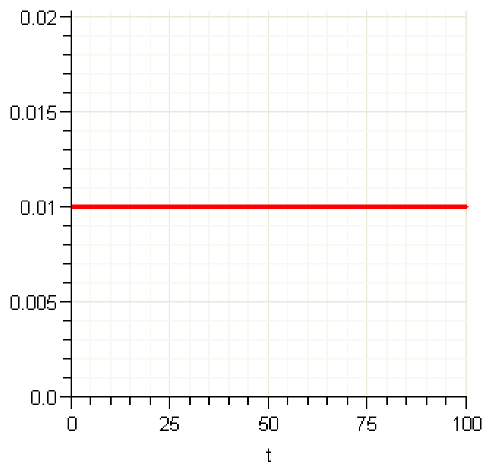


Figure n°1: uniform probability density function

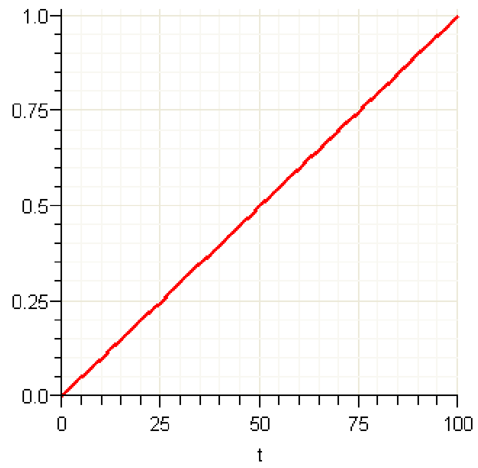
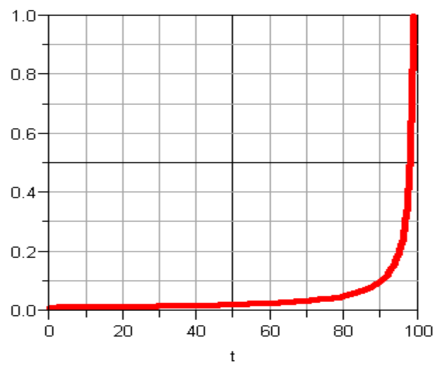


Figure n°2 : uniform cumulative distribution function

The formula for the hazard function of the uniform distribution is

$$\lambda(t) = \frac{1}{100-t}$$

The following figure n°3 represents the uniform hazard function.



A flat density function, as in figure n°6, means that the „end-of life" is not correlated to the age.

The straight line for the cumulative distribution function, figure n°2, means that the probability to fail is increasing linearly with time.

The exponential evolution of the hazard function, figure n°3, means that the failure rate is relatively flat at the beginning but increase very fast closed to the limit of "end-of life".

Figure n°3 : uniform hazard function

H.2.3 NORMAL DISTRIBUTION

The general formula for the density function of the normal distribution is :

$$f(t) = \frac{e^{-(t-\mu)^2/2\sigma^2}}{\sigma.\sqrt{2\pi}}$$

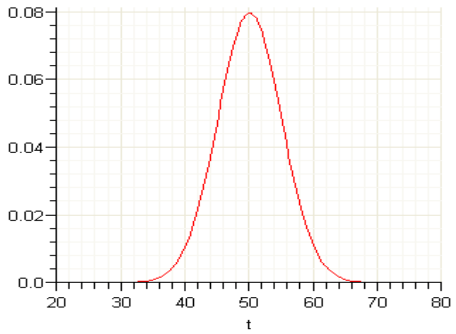
where μ is the mean value and σ is the standard deviation.

For the following drawings, the values : μ = 50, and σ =5 are taken.

$$f(t) = \frac{e^{-(t-50)^2/2\cdot 25}}{5.\sqrt{2\pi}}$$

The formula for the cumulative distribution function of the normal distribution does not exist in a simple formula. It is computed numerically.

The following figures n°4&5 represent the plot of the standard normal probability density function and the normal cumulative distribution function.



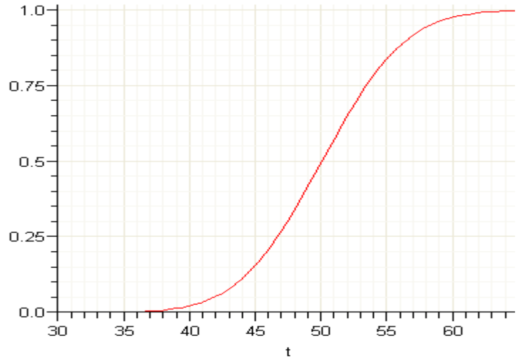


Figure n°4: standard normal probability density function *Figure n°5 : normal cumulative distribution function*

Also the hazard function of the normal distribution are not easy to determine by a formula :

The computer and calculation are very useful for a graphic representation.

The following figure, n°6, represents the normal hazard function.

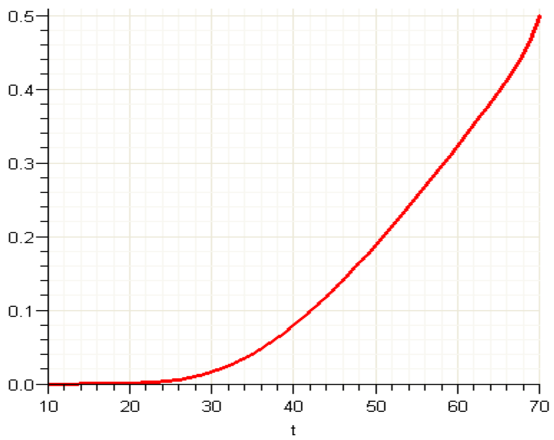


Figure n°6 : normal hazard function

The figure n°4 means that the higher probability for "end-of life is the mean value (50 in the example).

The figures n°4&5 mean that the probability to be failed, or to reach "end-of life", at a specific age follows a normal distribution.

The figure n°6 means that the increase of failure rate is very flat at the beginning then strongly increases after the mean value of end of life (50 in the example).

H.2.4 WEIBULL DISTRIBUTION

The formula for the probability density function of the general Weibull distribution is

$$f(x) = \tfrac{\gamma}{\alpha} \cdot (\tfrac{x-\mu}{\alpha})^{(\gamma-1)} \cdot \exp(-((x-\mu)/\alpha)^{\gamma}) \qquad x \geq \mu; \gamma, \alpha > 0$$

Where γ is the shape parameter , μ is the mean parameter and α is the scale parameter. The case where μ= 0 and α = 1 is called the standard Weibull distribution. The case where μ = 0 is called the 2-parameter Weibull distribution. The equation for the standard Weibull distribution reduces to

$$f(x) = \gamma \cdot x^{(\gamma-1)} \cdot \exp(-(x)^{\gamma}) \qquad x \geq 0; \gamma > 0$$

Since the general form of probability functions can be expressed in terms of the standard distribution, all subsequent formulas in this section are given for the standard form of the function.

The formula for the cumulative distribution function of the Weibull distribution is :

$$F(x) = 1 - e^{-x^{\gamma}} \qquad x \geq 0; \gamma > 0$$

The following figures n°7&8 represent the plot of the Weibull probability density function and the plot of the Weibull cumulative distribution function with the same values of γ as the pdf plots above.

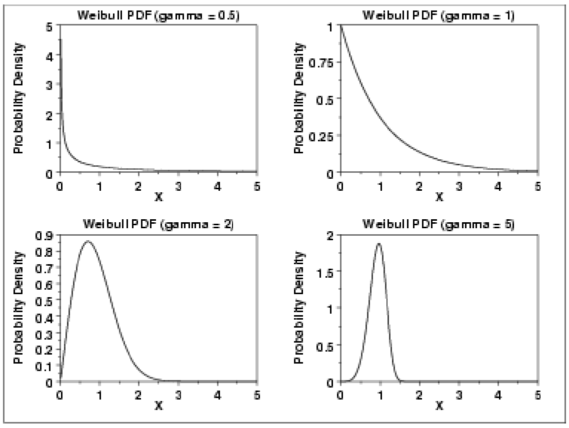


Figure n°7: Weibull probability density function

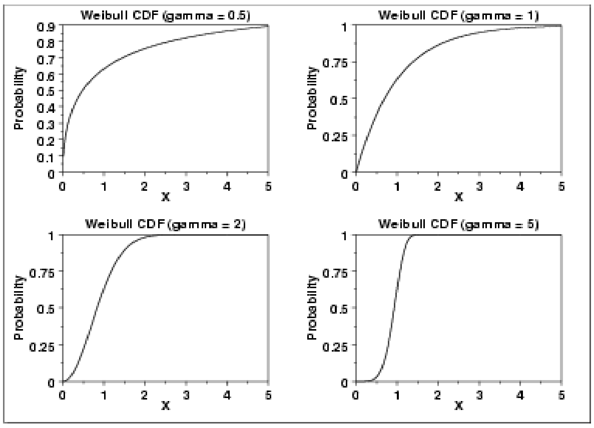


Figure n°8 : Weibull cumulative distribution function

The formula for the hazard function h(x) of the Weibull distribution are :

h(x) = $\gamma \cdot x^{(\gamma-1)}$

$x \geq 0; \gamma > 0$

The following figures n°9 give the plot of the Weibull hazard function for the values of γ : 0.5, 1, 2 and 5.

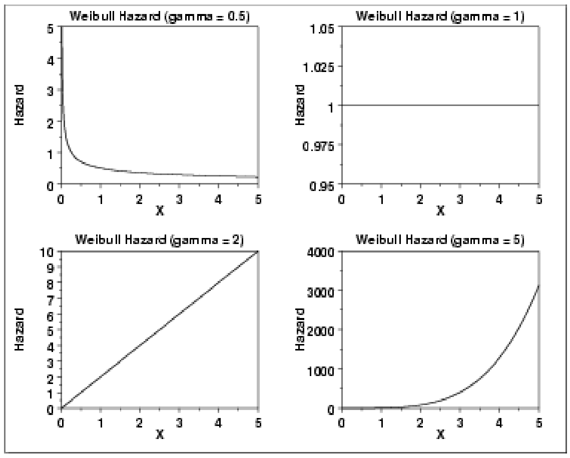


Figure n°9 : Weibull hazard function

H.3 life expectancy

H.3.1 DEFINITION

Demographic studies also use another concept : the life expectancy.

Life expectancy is a statistical measure of the average for the life span of a population.

This value is precisely the average of age for death of a group of members and is not the probability to die at a specific age.

Below an example of life expectancy calculation is given, for a better understanding.

H.3.2 EXAMPLE OF LIFE EXPECTANCY CALCULATION

The example is about the calculation of the age of death for a first group of 100 members, given in the following table.

Age for death	0	10	20	30	40	50	60	70	80	90	100
Population size	5	2	2	2	4	8	12	15	25	15	10

Life expectancy for this group 1 is E_1 :

$$E_1 = \frac{5x0+2x10+2x20+2x30+4x40+8x50+12x60+15x70+25x80+15x90+10x100}{100}$$

E_1 = 83,8 y.

The same calculation for another group of 100 members.

Age for death	0	10	20	30	40	50	60	70	80	90	100
Population size	10	2	2	1	2	3	10	10	25	20	15

Life expectancy for this second group is E_2 :

$$E_2 = \frac{10x0+2x10+2x20+1x30+2x40+3x50+10x60+10x70+25x80+20x90+15x100}{100}$$

E_2 = 69,2 y.

In this second case, life expectancy is much lower than for the first group, even if the number of members reaching age of 90y of more is greater : in the first group, 25 members live more than 90y, compared with 35 people in the second group.

H.3.3 SYNTHESIS OF DIFFERENT CALCULATIONS

These two examples of the §3.2 show that life expectancy is an average of death and not a risk of death at specific age. The method used in these cases supposes to wait until the death of the last members, situation not simple. So demographic studies use another method for life expectancy calculation.

The right method uses the death rate at each year, otherwise called age-specific death rates of a population.

For example, if 10% of a group of members die at 80 years, then the age-specific death rate is 10% at age 80. These rates are then used to build the life table, from which one can calculate the probability of surviving to each age.

To assess this death rate, an easy method is to subtract the number of members at the beginning of a period to the number at the end of the same period, the total divided by the number of members at the beginning of the period.

Using the following notation :

- d_x = death rate at age x years,
- N_x = number of members still alive at the age x,
- N_{x+1} = number of members still alive at the age x+1.

$$d_x = (N_x - N_{x+1})/N_x$$

The probability of surviving from age x to x+1 is :

$$S_x = 1 - d_x = N_{x+1}/N_x$$

The probability to be alive until the age of x years is :

$$U_x = S_1 \times S_2 \times S_3 \times \ldots\ldots S_{x-1} = N_x/N_1$$

The following table gives the death rate for a population (data from INSEE organization upon French population).

age	<1	1-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	>90
death rate (/1000)	3,1	0,3	0,1	0,1	0,4	0,6	0,6	0,8	1,1	1,7	2,9	4,5	6,1	8,4	12,1	24,5	40	67	100	205

Table n°1

Using the data of the table n°1, e following curves can be drawn

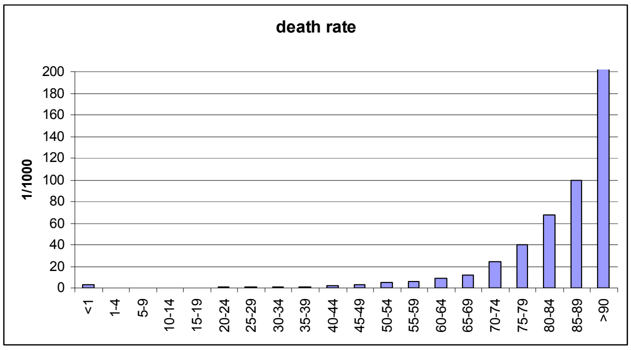


Figure n°10

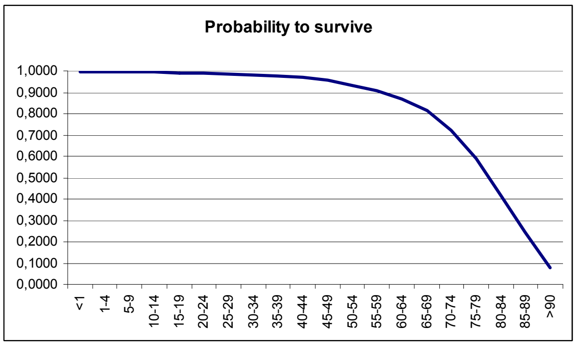


Figure n°11

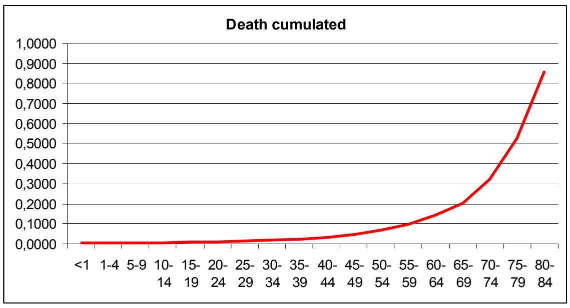


Figure n°12

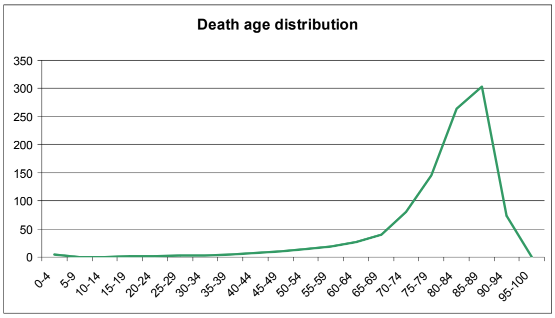


Figure n°13

Figure n°10 represents the death rate at each range of age. With the concepts of the paragraph 4.2, it represents the hazard function.

Figure n°11 represents the probability to survive at a specific age. With the concepts of §4.2, it is the survival function.

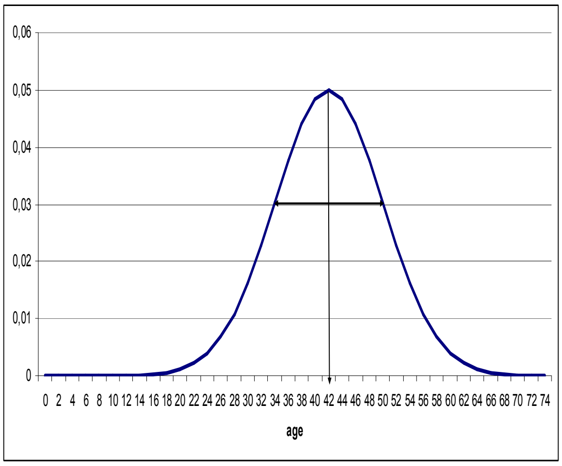
Figure n°12 represents the cumulated number of deaths. Figure n°13 represents the death age distribution.

H.4 Risk of confusion

There is sometimes a confusion between death rate and death age distribution.

To illustrate this confusion, we present hereafter an example.

The figure n°14 represents the normal distribution of "death" for a population with 42 years as mean value and 8 years as standard deviation.



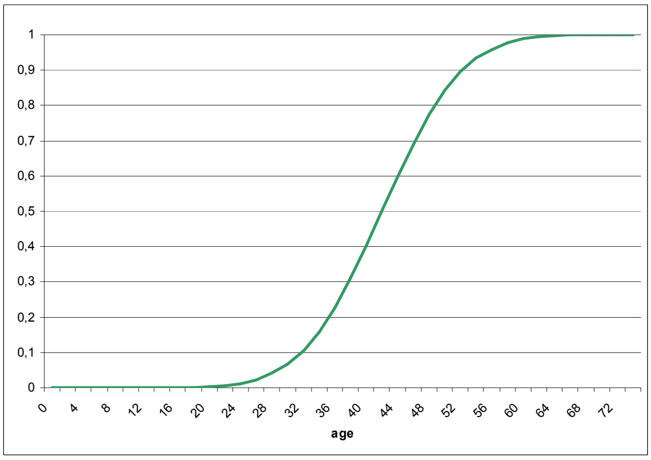
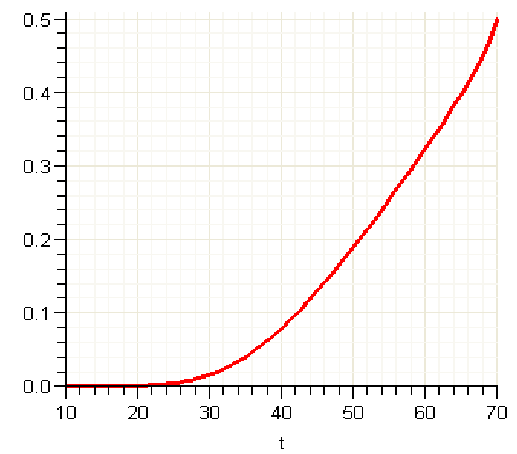


Figure n°14 : normal distribution

figure n°15 : normal cumulative distribution

mean value = 42y, standard deviation = 8y

The figure n°15, represents the normal cumulative distribution associated. The figure n°16 represents the hazard function for this normal distribution with the parameters 42 years as mean value and 8 years as standard deviation.



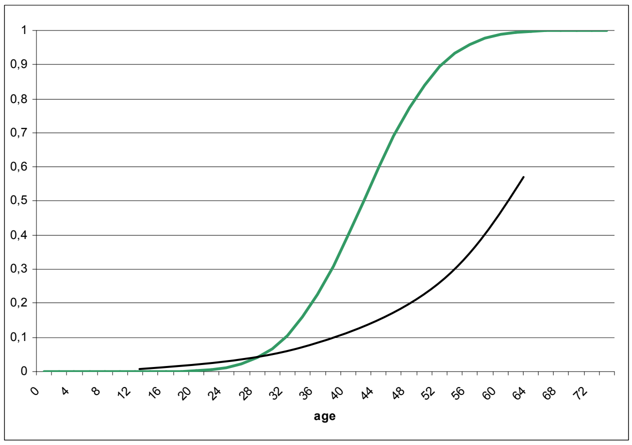


Figure n°16 : hazard function

Figure n°17 : normal cumulative distribution + hazard function

The figure n°17 presents normal cumulative distribution and hazard function, in the same figure. It shows the difference between the two curves and the risk of error if the normal cumulative distribution is used to get the death rate.

Thereby if, for example, we look at the death rate at 50 years, it is 20% according the hazard function. If we use the normal cumulative function to get the death rate, instead of hazard function, the value would be 80%, much higher than the right one.

H.5 Conclusion

The demographic studies commonly use statistical models to handle data on ages. This appendix presents the models more often used. It emphasizes on the use of each parameters and on the risk of misunderstanding for "end-of life" issue.

Therefore, the most important parameters to use are :

- Life expectancy,
- Death rate or failure rate according age.

The life expectancy is the average age for death, but not the age limit. It also do not represent the risk to die. Nevertheless, this value is useful for comparison of populations. In human demographic studies, the life expectancy is an interesting indicator of people development.

Indeed the risk of death or of failure is represented by the death rate, also called hazard function in statistics studies.

Care must be taken with the use of statistics model. And sometimes a confusion is made between distribution of death-age and death rates.

CIGRE Study Committee N° C1

PROPOSAL FOR CREATION OF A NEW WORKING GROUP *

WG C1.16	**Name of Convenor : Eric Rijks**
Title of the Group : Transmission Asset Risk Management	

Background : Many transmission networks contain assets that are approaching their design life. Some groups of assets may have increasing failure rates due to ageing and may show an impact on supply reliability. Determination of failure rates, condition monitoring of assets and forecasting end-of-life have become key activities for network companies to enable their asset managers to make timely decisions on measures to be taken such as maintenance, replacement, refurbishment etc.

Expenditure in a network through either CAPEX or OPEX to maintain or improve reliability performance will be limited to some budgeted/regulated level and it is paramount for a network company to target this investment to achieve maximum benefit.

The objective of this WG is to provide an insight into the application of asset management in electricity transmission companies, the risks due to an ageing asset base and how these are managed.

Deliverables
The WG aims to deliver:

1. A number of case studies of risk management applied by electricity transmission companies, describing the general approach taken and the decision making process adopted.
2. An overview of the methods adopted for classifying and establishing asset condition.
3. Identify the key indicators used for classifying and establishing asset condition.
4. How results from an asset condition review process will impact on other parts of a network business activity.
5. Establish the key business reasons that underpin the investment profile over the whole asset lifecycle.
6. Identify the data (type and format) that asset managers need from asset specialists.
7. Publish the results in a Technical Brochure with Executive Summary in ELECTRA.

Time Schedule : Start February 2007 Final Report : March 2009

Comments from Chairmen of SCs concerned :

Approval by Technical Committee Chairman : Klaus Fröhlich **Date** : Dec. 20, 2006