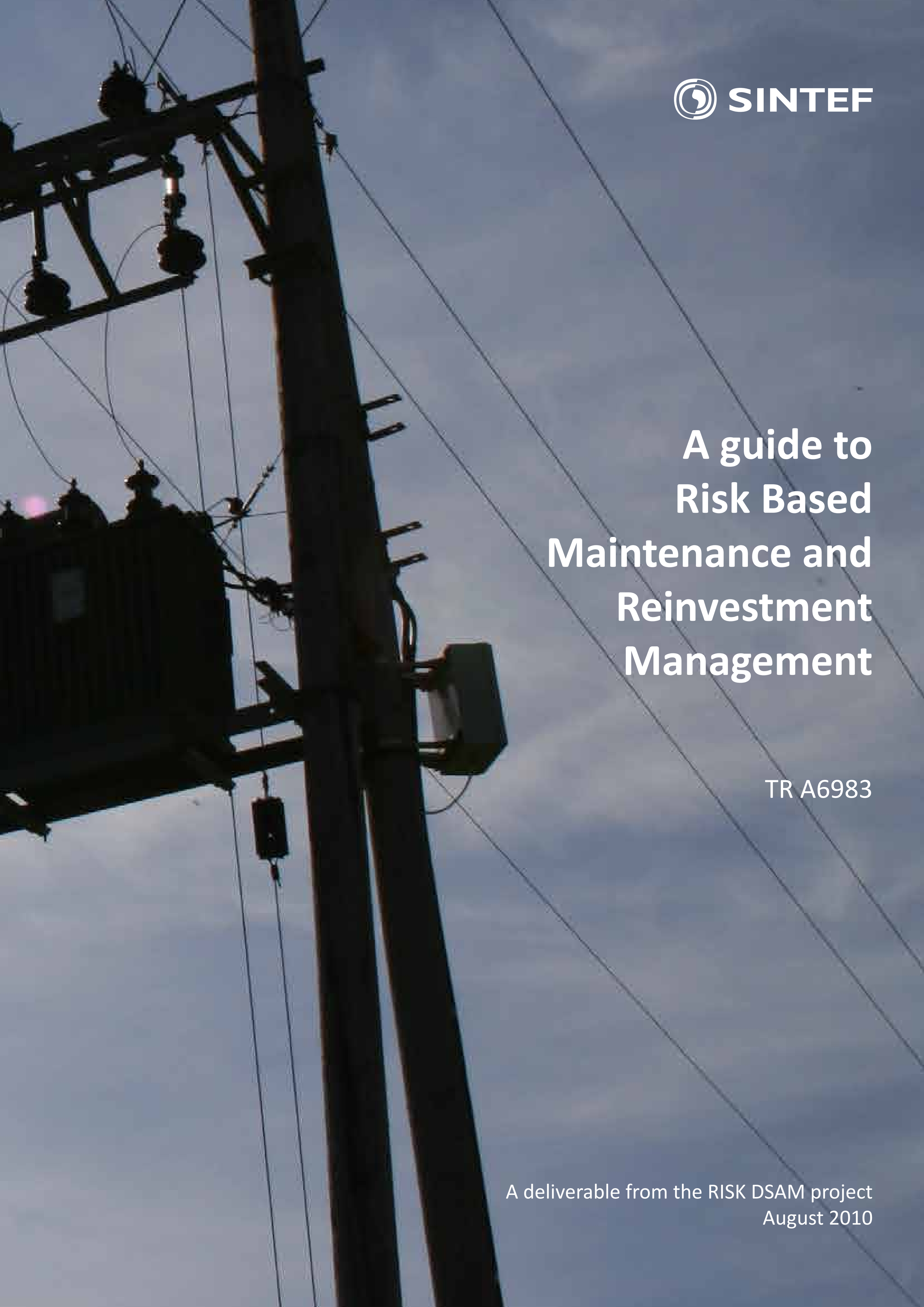

SINTEF

A guide to Risk Based Maintenance and Reinvestment Management

TR A6983

A deliverable from the RISK DSAM project
August 2010

TECHNICAL REPORT

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A guide to Risk Based Maintenance and Reinvestment Management

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RESULT (summary)

This report gives guidelines for risk based maintenance and reinvestment management of electricity distribution assets. The report is one of the deliverables from the RISK DSAM project, and presents a summary of important results from the project.

The aim of the report is to provide insight in risk based maintenance and reinvestments management and decision support to distribution network companies, by suggesting answers to the following questions:

- How to incorporate risk analysis in maintenance and reinvestment management?
- How to develop risk based maintenance strategies?
- When and how to perform reinvestment analysis?

Maintenance and reinvestment management are two closely related processes, and should be governed by the same philosophies and overall objectives, preferably coordinated by one asset management group within the electricity distribution companies.

Throughout this report we recommend two main principles for maintenance and reinvestment management:

- Risk differentiation; permitting the distribution network companies to focus their efforts where they are needed the most. The differentiation should be based on risk analysis results for all relevant risk consequence categories, for example economy, safety, etc.
- Continual improvement; both the maintenance and the reinvestment processes must be subject to continual improvement, using gathered experience and updated knowledge to learn and make the processes better.

KEYWORDS

SELECTED BY AUTHOR(S)	Risk Based Asset Management	Electricity Distribution
	Maintenance and Reinvestments	

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Setting the scene
Summary of recommendations

I Preface

This report gives guidelines for risk based maintenance and reinvestment management of electricity distribution assets, based on a structured and pragmatic approach. The report is one of the deliverables from the RISK DSAM project[1], and presents a summary of important results from the project.

The aim of the report is to provide insight in risk based maintenance and reinvestments management and decision support to distribution network companies, by suggesting answers to the following questions:

- How to incorporate risk analysis in maintenance and reinvestment management?
- How to develop risk based maintenance strategies?
- When and how to perform reinvestment analysis?

The report also discusses the need for data, and how to provide this through the use of expert judgment and condition monitoring activities.

The focus of the RISK DSAM project and of this report is preventive maintenance, and reinvestments triggered by deterioration of assets. Further, the focus is on the maintenance and reinvestment management of medium voltage[2] (MV) distribution networks. However, the presented methods and recommendations are also relevant for maintenance and reinvestments in general.

[1] RISK DSAM (Risk-based distribution system asset management) is a Competence Building project sponsored by the Norwegian Research Council, and companies within electricity distribution in Norway, France and Sweden. The project was launched in January 2006 and will end in 2010. SINTEF Energy Research is the executing partner.

[2] 1 – 36 kV

II The structure of the report

This report is divided into three main parts:

- Setting the scene and summary of recommendations
- Main report
- References and recommended literature

Setting the scene and summary of recommendations

Chapter III gives a summary of the main recommendations. These are elaborated in more detail in the main report.

Chapter IV provides a 'check-list' for distribution network companies on how to implement risk based maintenance and reinvestment management (focusing on aspects covered by this report), while Chapter V contains a list of important definitions.

Main report

Chapter 1 gives an introduction to risk based maintenance and reinvestment management and briefly describes maintenance and reinvestment of distribution system assets, deterioration of assets, and risk and risk differentiation.

Chapter 2 describes an approach for how to use risk assessment to establish maintenance strategies for asset groups.

Chapter 3 describes a structured approach to reinvestment analysis, including when to trigger such analyses, which reinvestment alternatives that exist, and how to evaluate different alternatives.

Chapter 4 describes different aspects regarding how to implement maintenance strategies and trigger reinvestment analysis. The chapter also address the need for data and the importance of condition monitoring. Finally, the principle of continual improvement is described.

Use of examples

Examples are provided throughout the report to illustrate important aspects and applications of risk based maintenance and reinvestment management. The examples are constructed for the purpose of this report, but are based on information and cases from distribution companies and hence correspond to 'real-life' applications.

References and recommended literature

References and recommended literature are provided at the end of the report, including complementary reading for the interested.

III Summary of recommendations

Overall principles

Maintenance and reinvestment management are two closely related processes, governed by the same philosophies and objectives, preferably coordinated by one asset management group within the electricity distribution companies.

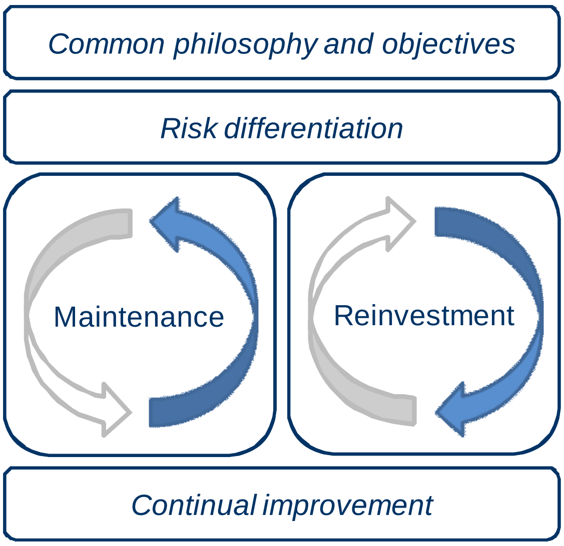

Figure III.1 Maintenance and reinvestment management as two integrated processes (Nybø and Nordgård, 2010)

Throughout this report we recommend two main principles for maintenance and reinvestment management:

- Risk differentiation
  - o Risk differentiation will permit the distribution network companies to focus their efforts where they are needed the most. The differentiation should be based on risk analysis results for all relevant risk consequence categories, for example economy, safety, etc.

- Continual improvement
    - Both the maintenance and the reinvestment processes must be subject to continual improvement, using gathered experience and updated knowledge to learn and make the processes better.

In addition, we stress the need for a structured approach, for documentation and reporting, and last but not least the importance of good information. Condition monitoring is hence a key activity in risk based maintenance and reinvestment management.

This report deals with three main topic areas:

- Maintenance management - *how to establish maintenance strategies*
- Reinvestment management - *how to perform reinvestment analyses for assets*
- Implementation and improvement

In the following, key recommendations to each of these areas are listed.

Maintenance management - *How to establish maintenance strategies*

Chapter 2 describes an approach for how to use risk assessment to establish maintenance strategies for asset groups. The main objective is to use a structured approach to identify groups of assets which can be prescribed the same maintenance, and to use risk analysis in this process. Key recommendations include:

Divide your assets into system units and establish maintenance strategies based on risk differentiation

- Identify groups of assets which can be prescribed the same maintenance
- Assets associated with high risk should be subjected to more comprehensive maintenance and be considered for reinvestment earlier compared to low-risk assets

Maintenance strategies must describe:

- The maintenance actions to be done and how often (or when) they should be performed
- When to trigger a reinvestment analysis

Reinvestment management - *How to perform reinvestment analysis for assets*

Chapter 3 describes a structured approach to reinvestment analysis, from triggering of an analysis to making the decision. Key recommendations include:

Identify the right assets to analyse:

- Define *triggering criteria (events etc*) which define when to perform reinvestments analyses, reflecting the risk that the assets represent

Establish company standards for performing and documenting reinvestment analysis, considering costs, risk and uncertainty

Beware of your alternatives:

- *Should we reinvest during the period of analysis or not?*
- Maintenance is often an alternative to reinvestment (but not forever)
- Establish standard solutions to 'known' problems concerning groups of assets

Implementation and improvement – *How to set up maintenance and reinvestment plans, gather relevant data, and ensure continual improvement*

Chapter 4 describes different aspects on how to implement risk based maintenance strategies and trigger reinvestment analysis. The need for data and the importance of condition monitoring and continual improvement in this context is also emphasised.

Key recommendations include:

Identify information needed in order to implement maintenance strategies and trigger reinvestment analysis

- What data is needed and what data is missing? How valuable is this information? How difficult is it to obtain? If necessary; How shall we obtain it?
- Systematically register and update necessary information

Create an overview of your assets and allocate them to the corresponding maintenance strategy

- Set up maintenance plans, also addressing need for reinvestments

Use condition monitoring results as input to maintenance and reinvestment management

- Different needs require different condition monitoring. Cost versus benefits of condition monitoring must be considered.

Evaluate strategies, processes, and results on a regular basis – and use this knowledge to improve.

IV Checklist for distribution system companies

Based on the findings presented in this report, some checkpoints can be formulated for the implementation of risk based maintenance and reinvestment management.

- ☑ Establish a common philosophy and objectives regarding maintenance and reinvestment

- ☑ Establish an asset management group responsible to enforce maintenance and reinvestment management

- ☑ Develop risk differentiated maintenance strategies for different system units (overhead lines, substations, cables etc), where more attention is given to the most risky assets, and less attention is given to the least risky assets

- ☑ Define criteria which trigger reinvestment analysis

- ☑ Establish a standardised procedure regarding how to perform reinvestment analyses and how to document them

- ☑ Establish a procedure regarding how to get the data required to implement and improve strategies

- ☑ Establish dedicated condition monitoring and reporting in order to meet different needs
  - Find and correct deviations
  - Reveal need for reinvestment / comprehensive maintenance
  - Gather other relevant data

- ☑ Establish a procedure for continual improvement of maintenance and reinvestment management, including meeting arenas, key questions to be addressed and the follow-up of selected indicators

V Important definitions

Risk	Combination of the probability of an event and its consequence. Note 1: The term 'risk' is generally used only when there is at least the possibility of negative consequences. Note 2: In some situations, risk arises from the possibility of deviation from the expected outcome or event.	*Source:* *ISO/IEC Guide 73*[3]
Maintenance	The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.	*Source:* *IEC©60050-191-01-01*
Corrective maintenance	The maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.	*Source:* *IEC©60050-191-01-08* *EN 13306:2001*
Preventive maintenance	The maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.	*Source:* *IEC©60050-191-01-07* *EN 13306:2001*
Reinvestment	Replacement of an existing item with a new one with the same capacity. Note: May include modification	*Source:* *The project 'Value adding maintenance in power production' (SINTEF)*

[3] ISO/IEC Guide 73 Risk Management – Vocabulary – Guidelines for use in standards.

Main report

1 Introduction to risk based maintenance and reinvestment management

This chapter gives an introduction to maintenance and reinvestments in electricity distribution systems, and to the role of risk assessment in this context.

Asset management deals with the complex balancing of cost, performance and risk – making strategies and procedures for balancing preventive and corrective maintenance actions and reinvestments.

The motivation for using risk methodologies in maintenance and reinvestment management is for the distribution companies to obtain a better allocation of resources (money and manpower). This can be achieved by prioritising and directing their efforts where there is the most to gain; spending fewer resources on low risk assets and more on high risk assets.

Maintenance and reinvestment management should be governed by a common philosophy stating principles and objectives which are important in the company's asset management. The process of formulating the overall philosophy is not further elaborated in this report.

1.1 Maintenance and reinvestments

The purpose of maintenance and reinvestment can be summarised as:

- Restore, maintain or improve an asset's condition
- Provide information about assets and their condition
- Replace and/or modify assets (reinvestments)

Electricity distribution assets typically have long life spans and will for most of their life be subjected to some sort of maintenance. New assets will in general require little maintenance. The need for maintenance increases as the asset deteriorates with time. Reinvestment becomes an increasingly relevant option as the asset deteriorates, or if maintenance is difficult to perform or disproportionately resource-demanding (e.g. through lack of spare parts). This is illustrated in Figure 1.1.

Condition monitoring is a vital part of maintenance as it provides information about assets, which can be used to prescribe maintenance or reinvestment actions. Most assets are subjected to different kinds of condition monitoring throughout their life, and as they approach their end of life, the need for information is growing, for example in order to identify reinvestment needs.

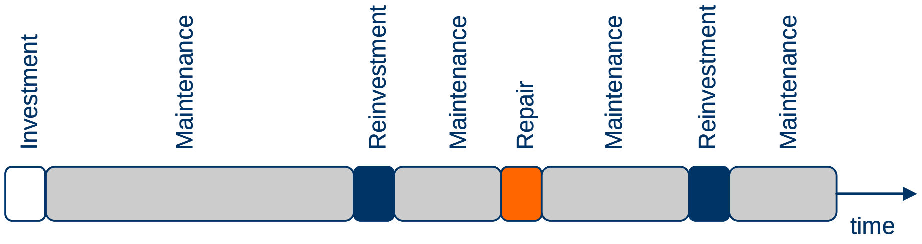

Figure 1.1 Example of maintenance and reinvestment actions throughout the life of a given asset

1.2 Deterioration of assets

Network components are designed to withstand a certain level of stress, and this ability will deteriorate with time. The components' reliability will be a function of their condition and the stress they experience, the latter for which the random contribution can be substantial (e.g. large wind / ice loads). Maintenance and reinvestment actions influence the components condition, and hence the expected probability of failure.

Figure 1.2 illustrates how the condition (strength) of a given component deteriorates with time. The normal operating stress and the random stress the component is exposed to are also illustrated. In this case failure occurs at time T due to normal operating stress[4].

[4] It is important to keep in mind that both strength and stress are stochastic, and requires a probabilistic approach.

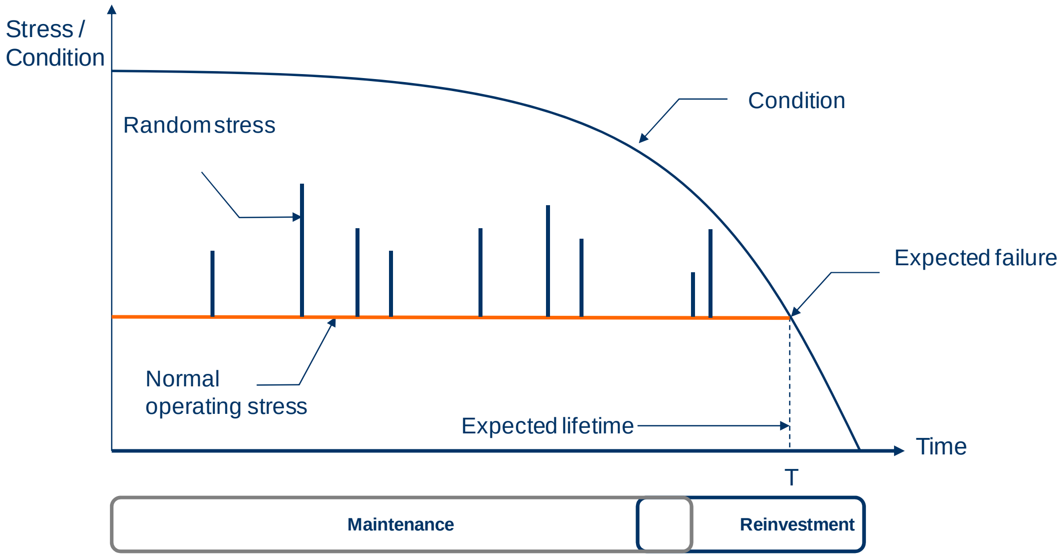

Figure 1.2 Strength and stress for a component as a function of time (Heggset et al., 2007b)

As illustrated, the component's condition deteriorates over time. As previously noted (and illustrated in Figure 1.2), reinvestments are often considered when the components (or assets) in question are approaching their end-of-life. Condition monitoring is vital in order to assess the condition and the associated failure probability and remaining life of assets.

1.2.1 Condition states and deterioration model

SINTEF has developed a failure model[5] where the technical condition of a component can be characterised on a scale from 1 to 4, and a 5th state which implies fault (Table 1.1). Further, deterioration over time can be modelled by the transition through the different condition states.

[5] The method was originally constructed for hydro power plants, but is currently being adapted for network components, (Heggset et al., 2007a),(Heggset et al., 2007b).

Table 1.1 Different condition states

State	Description
1	No indication of degradation. 'As good as new'.
2	Some indication of degradation. Condition noticeably worse than 'as good as new'.
3	Serious degradation. Condition considerably worse than 'as good as new'.
4	The condition is critical.
5	Fault

Figure 1.3 shows how an asset deteriorates with time, including the different states. The duration of each state *k* (T_k) may vary from several years to only a few years or months, depending on the asset and the stresses the assets are exposed to. As indicated in Figure 1.3, failure is defined to occur in the transition from state 4 to state 5.

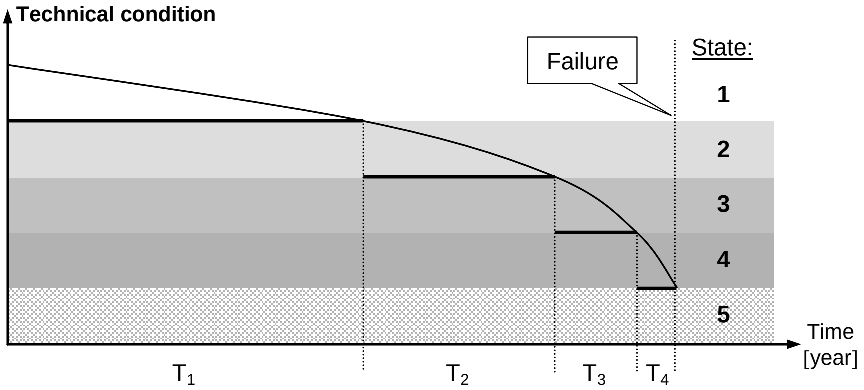

Figure 1.3 Technical condition (state 1-5) and life curve (Heggset et al., 2007b)[6]

By modelling the transitions through the states 1-5 it is possible to calculate the annual failure probability based on the technical condition of a component (Heggset et al., 2007b). Such an approach is based on life-curve models and the use of expert judgement in assessing the duration of the different condition states. This is a good alternative / complement to methods based on statistical fault data, which often is scarce (and biased since the link to component condition often is missing).

[6] The figure corresponds to the general deterioration model depicted in Figure 1.2.

1.3 Risk

Risk can be defined as the combination of probability of an event and its consequence, (ISO/IEC, 2002). The term risk is generally associated with the possibility of negative outcomes of future events.

The risk for a given asset, process or activity can be addressed by answering a triplet of questions (Kaplan, 1991):

- *What can go wrong?*
- *How likely is that to happen?*
- *If it does happen, what are the consequences*?

The answers to these questions will give a picture of the risks, where the answer to the first question describes some kind of undesired event; the answer to the second is a probability statement, while the answer to the third question is a description of potential consequences – which typically will be multi-dimensional. For example, if a specified undesired event occurs, it may have economic, reputational and safety consequences.

Even though the questions may look simple, to provide good answers can be challenging, both in terms of identifying undesired events and estimating probabilities and consequences.

1.3.1 Probability estimates

When establishing probability estimates, one try to state how likely it is for an undesired event to occur in the future. It lies in the nature of the problem that there will be large uncertainties related to this task.

For the analysis of risks related to distribution system maintenance it will be most relevant to rely on the opinions of experts, in addition to historical experience as revealed in e.g. failure and interruption statistics. Experience indicates that there are limited amounts of relevant information which can be provided by statistical sources (Nordgård et al., 2007, Nordgård and Samdal, 2010), hence expert judgment is a very important source of information in this process.

Results from condition monitoring (together with life-curve models illustrated in Figure 1.3) will be an important input to estimate probabilities – at least to identify assets with relatively high probability of failure compared to the average asset.

1.3.2 Consequence estimates

Distribution companies face risk of different kinds, which can be grouped into the following categories (Sand et al., 2007):

- Economic risk,
- Safety risk,
- Environmental risk,
- Quality of supply risk,
- Reputational risk,
- Vulnerability risk, and
- Regulatory risk.

Several of the consequence categories can be related and overlapping. For example, both safety and environmental issues may have a significant impact on company reputation.

The consequences of potential undesired events can be estimated through several methods; e.g. reliability simulations and safety risk models, but also historical records of previous experience and the knowledge of experts familiar with the components and their problems.

1.3.3 Risk matrix

The risk matrix is a useful tool to visualise risk. It shows the consequence of an event on one axis and the probability on the other. Depending on the combination of its probability and consequence, an event can be classified as more or less acceptable (as indicated in Figure 1.4).

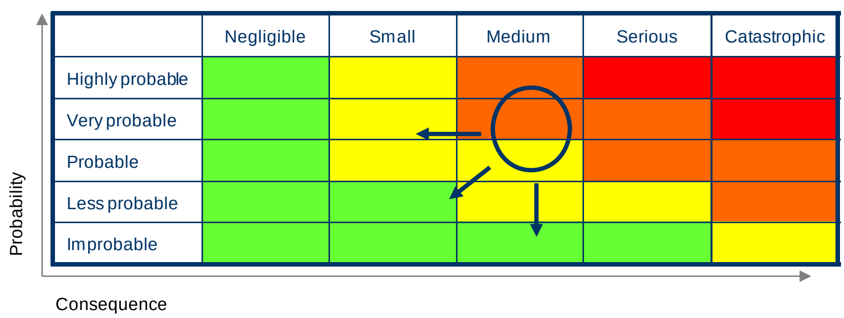

Figure 1.4 A risk matrix

It is important to bear in mind that the risk changes with time, typically due to deterioration of assets. Decisions and actions concerning investment, reinvestments, maintenance and operation, and external factors such as load development and climatic change will also influence the risk.

Risk matrixes can be used to visualise the expected impact of measures to reduce risk. With reference to Figure 1.4, measures to reduce the probability of an unwanted event will shift the associated risk downwards in the matrix, whilst measures to reduce the consequence will shift the risk leftwards. A combination of the two is also possible. This is indicated by the arrows in Figure 1.4, which show how risk can change as a result of different risk reducing measures.

1.3.4 Risk differentiation

A key concept in risk based maintenance and reinvestment management is *risk differentiation*. The rationale for risk differentiation can be expressed quite simply: to give assets with high risk more attention (and spending) compared to assets with lower risk – i.e. to spend the companies' resources where it is needed the most.

In practice risk differentiation will imply to give 'risky' assets more often and / or more comprehensive maintenance, and to consider reinvestment earlier compared to other assets.

Figure 1.5 illustrates how a group of assets are divided into different subcategories (A-D) depending on their associated risk. The aim is to use risk analysis to identify groups of assets which represent similar risk and therefore can be prescribed the same maintenance. This represent a concentration of efforts: Rather than to prescribe the same maintenance to all MV/LV substations or all MV overhead lines, the maintenance strategies are different depending on the risk the assets represent.

Figure 1.5 Risk differentiation, an illustration

Maintenance management

Establishing risk based strategies

2 Maintenance management

2.1 Introduction

Maintenance activities are an important part of the management of distribution system assets, covering a large percentage of operation costs, and triggering a majority of the reinvestments in the grid. In addition maintenance is vital for the safety of the distribution company's own personnel and third parties, and it has a potential significant impact on the company's reputation. In such a perspective it is obvious that maintenance is a key activity in asset management.

Maintenance can be divided into two main categories:

1. Preventive maintenance
   - Condition monitoring
   - Actions to improve a components condition
2. Corrective maintenance
   - Correction of minor deviations
   - Restoration after fault

A challenge for distribution system companies is to find a good balance between preventive maintenance (and reinvestments) and corrective maintenance. The costs of preventive maintenance must be compared to expected benefits related to e.g.:

- Increased (expected) component lifetime
- Reduced costs of interruptions
- Reduced costs, corrective maintenance
- Improved data concerning components

The focus of this report is on strategies for preventive maintenance, and the following chapter describes how to develop risk based maintenance strategies.

Implementation and improvement of strategies and processes are discussed in chapter 4, where we also highlight how important information from condition monitoring is in order to make good maintenance and reinvestment decisions.

2.2 Maintenance strategies

A maintenance strategy specifies what maintenance actions to do and how often (or when) they should be performed for a given asset or group of assets.

Due to the vast amount of distribution system assets, there is a need to establish maintenance strategies which cover groups of assets, instead of a specific strategy for each asset. In the strategy, when to perform maintenance can be stated as a function of technical condition, time, operation, or to be done after special events, such as failures, major storms or heavy snowfall.

Maintenance actions cover a variety of tasks with different degrees of complexity: from simple visual inspections, via more advanced condition monitoring; to minor routine maintenance and major revisions.

How often or when different maintenance actions are performed should be decided based on risk differentiation: Assets associated with high risk should be subject to more frequent and more comprehensive maintenance actions than low-risk assets.

When to make an asset or a group of assets undergo a reinvestment analysis should also be subjected to risk differentiation. We recommend that the maintenance strategies include criteria which trigger a reinvestment analysis. This is further described in chapter 3.2.

EXAMPLE 1 Excerpts from a maintenance strategy for MV overhead lines

Condition monitoring
- Inspection of MV overhead lines shall be performed annually.
- A thorough inspection of MV overhead lines should be performed every 5 years for particularly important lines, and every 10 for other lines.

Vegetation management
- Vegetation management of MV overhead lines shall be performed every 5 years, or when inspections state that it is necessary.

Reinvestment analysis
- MV overhead lines shall be evaluated with regards to potential reinvestment after 35 years of operation, or when observations from condition monitoring or other information indicate such a need.

Work process

The process of establishing maintenance strategies should be carried out in teams, utilising the knowledge of various experts. The teams can for example consist of:

- The overall responsible for the maintenance strategies
- Workers having experience with operating and maintaining the various assets
- External experts if needed and/or available
- People having knowledge and experience with risk assessment
- Facilitator(s). The facilitator is the person responsible for driving the process forward. The facilitator can both be internal or external to the company.

2.3 How to establish maintenance strategies

A suggested process to establish maintenance strategies for different system units is illustrated in Figure 2.1. The different steps are further elaborated in the subsequent sub-chapters.

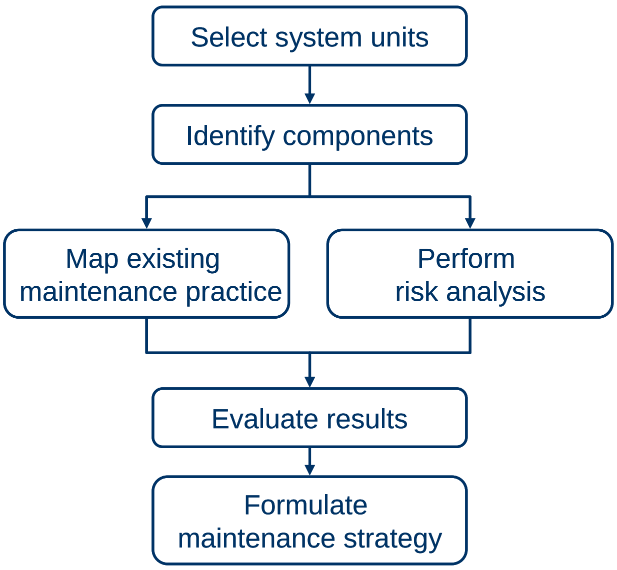

Figure 2.1 Process for establishing maintenance strategies. Based on (Nordgård and Samdal, 2010)

2.3.1 Divide the system into system units

The term *System units* is used to denote a group of components which naturally belong together. For MV distribution systems, a natural selection of system units can be:

- MV overhead lines
- MV / LV substations
- MV cables.

The aim the process is to establish a maintenance strategy for selected system unit at the time. It can be advisable to start with the system unit where the expected gain from implementing a risk based strategy is expected to be the highest (relatively to the expected efforts needed).

When all identified system units have been through the process, the company will have maintenance strategies which cover all assets, based on the same overall principles.

2.3.2 Identify system unit components

Each system unit must further be divided into its components.

EXAMPLE 2 System units and components

For the system units MV overhead lines and MV/LV substations the following components are identified:

System unit: MV overhead lines
Components:
- Wooden poles (incl. traverse, insulators, etc.)
- Phase conductors
- Line trace
- Pole-mounted switches
- Cable terminations
- Pole-mounted MV/LV substations

System unit: MV/LV substations
Components:
- MV / LV transformer
- Switch disconnectors
- Cable terminations
- LV distribution board
- Substation building

2.3.3 Map existing practice

The majority of the maintenance actions performed today have their origin in judgments and experience from decades of operating the grid. It may not at the time of origin have been called 'risk analysis', but the results will in many cases be in accordance with the principles of such.

An important first step in the work of establishing maintenance strategies is to look closely into today's practice and previous experience from maintaining the network. In addition, it is equally important to clarify if there exist any recommendations, rules or regulations concerning how and how often various maintenance actions should be performed.

The mapping should be focused on what is done of maintenance activities on each of the system unit components or at the system unit as a whole (which typically applies to condition monitoring). It is important to reveal if maintenance is differentiated in some way and why.

EXAMPLE 3 Excerpts of mapping of existing practice for MV overhead lines

For the system units MV overhead lines the following existing practice is identified:

- Inspections of MV overhead lines are performed annually. These inspections are performed using a helicopter.
- Thorough inspections of MV overhead lines are performed every 8 years. The thorough inspections are performed on the ground, following a specified checklist.

The mapping of existing practice can also provide information about specific problem areas in the systems, pinpointing assets which are believed to be more exposed to risk and how their potential failures influence the system.

One important aspect of mapping existing practice is also to clarify and agree on terminology. Experience shows that there can be many words describing the same action, or that the same word is used with different meanings. Hence there is a potential for misunderstandings and misconceptions, making communication difficult.

2.3.4 Perform risk analysis for components

The next step in the process is to perform risk analyses for different components – aiming to obtain an informative risk picture as a basis for further evaluation.

The risk analyses should be performed on component level – i.e. on the 'natural' level of resolution. The analyses of the different components will together constitute a risk analysis for the whole system unit.

We recommend the approach presented in chapter 1.3 (Kaplan, 1991), where risk is described by answering a triplet of questions:

- *What can go wrong?*
- *How likely is that to happen?*
- *If it does happen, what are the consequences?*

Guided brainstorming sessions is a good way to answer these questions, and thereby performing the risk analysis. Focus should be on events that affect consequence categories which have been found relevant in the maintenance and reinvestment philosophy. It is highly relevant to identify factors which can influence risk; i.e. factors which can influence the probability of occurrence and/or the consequences of undesired events. Such factors can be different types of operating conditions, variations in design, etc.

The risk analysis process can identify a need for a higher resolution of the asset groups. As an example it may be revealed a need to differentiate between various types of switch disconnectors. This step thus provides further detail to the grouping of assets that presumably are exposed to similar risk and hence should receive the same maintenance.

EXAMPLE 4 Differentiation of MV switch disconnectors

Concerning MV/LV substations, MV switch disconnectors should be divided into the following categories:

- Air-insulated switch disconnectors
- SF_6 insulated switch disconnectors
- Epoxy insulated switch disconnectors

What can go wrong?

The answers to the question *'What can go wrong?'* will provide a list of potential undesired events.

One major source of information to answer this will be the opinions of experts having experience from working with the components in question. The expert judgments can be supported with input from accident statistics, fault and interruption statistics and so forth, when applicable.

EXAMPLE 5 **Identification of undesired events for the component 'Wooden poles (including traverse, insulators, etc.)'**

Though brainstorming and discussions in expert groups the following undesired events have been identified:

1. Pole breakage
2. Pole askew
3. Fire damage of pole
4. Insulator flashover
5. Conductor falls on traverse / burnt traverse
6. Broken traverse
7. Flashover/discharge of insulator chain
8. Displaced traverse
9. (Partially) defect discharger
10. Person falling down from (and / or with) pole
11. Person touching MV parts (from climbing the pole or nearby trees)
12. Poor earthing connections
13. Insulators destroyed by vandalism
14. Impregnation run-off to water and/or soil

How likely is that to happen?

The answer to this question is some kind of probability statement concerning the potential occurrence of specific undesired event.

Probability estimates can be formulated in terms of verbal descriptions (*improbable, very probable, etc.*) or in terms of semi-quantitative statements, e.g. value intervals.

EXAMPLE 6 Probability scales

P5 – Highly Probable	More often than once a year
P4 – Very Probable	Once every 1-10 years
P3 – Probable	Once every 10-100 years
P2 – Less probable	Once every 100-1 000 years
P1 – Improbable	Less than once every 1 000 years

For the analysis of risks related to distribution system maintenance, potential sources of information will be the opinions of experts, in addition to historical experience as revealed in e.g. failure and interruption statistics. Experience indicate that there are limited amounts of relevant information which can be provided from statistical sources (Nordgård et al., 2007, Nordgård and Samdal, 2010), hence expert judgment is a very important source of information in this process.

However, it is still important to work towards having better statistical foundations to complement and validate expert judgment – e.g. through maintenance management systems, the fault and interruption statistics, injury reporting systems etc.

If it does happen, what are the consequences?

The answer to the third question will be an estimate of consequences of the identified undesired events. The consequences will typically be multi-dimensional, i.e. the undesired event will have impact on more than one consequence category, e.g. through having:

- Safety impact
- Environmental impact
- Reputational impact
- Economic impact.

As for the probability estimates, expert judgement will also be an important input to estimate the consequences for various undesired events. Consequences can be 'local' (related with specific assets - typically safety) or at system level (economy, reputation). In some cases – e.g. with regards to estimation of extent of interruptions – simulation tools (load flow analyses, reliability analyses, etc.) are recommended to get a better foundation to estimate the consequences of various undesired events.

EXAMPLE 7 Consequence scales

For the consequence category *safety* the following intervals may be used:

C5 – Catastrophic	One or more deaths – many serious injuries
C4 – Serious	More than one person with serious injury
C3 – Medium	Medium to serious injuries
C2 – Small	Minor injuries
C1 – Negligible	No injuries

2.3.5 Presentation and visualisation of results in risk matrices

Results from risk analyses can be plotted in risk matrixes to visualise the risks – providing a risk picture for each of the components for each of the chosen consequence categories.

There are no universal rules for how to model the risk matrixes, and different designs are seen; most often ranging from 3x3 to 5x5 matrixes. For the purpose of analysing risk in order to establish risk-based maintenance strategies, it is necessary to use matrixes with sufficient degree of resolution. The motivation for this is to enable differentiation of risk. Experience indicates that a 5x5 matrix can provide such resolution.

EXAMPLE 8 Using a the risk matrix to visualise risk

Figure 2.2 shows the result of a risk analysis for the undesired events listed in section 2.3.4 plotted for the consequence category *safety*.

Probability \ Consequence	Negligible	Small	Medium	Serious	Catastrophic
Highly probable					
Very probable					
Probable					
Less probable					
Improbable			8, 12	1, 6	10, 11

Figure 2.2 Example: Risk matrix for safety for the undesired events for wooden poles (Nordgård et al., 2007)

From Figure 2.2 it can be seen that events 10 and 11 are identified as being the most critical with regards to *safety* in this risk mapping:

- Person falling down from (and / or with) pole
- Person climbing in pole and touching live MV parts

Not all of the initial 14 unwanted events (identified in Example 5) are placed in the risk matrix for safety, because some of them are regarded not to be relevant for this consequence category.

The results from the risk analysis plotted in Figure 2.2 motivates e.g. for having maintenance activities related to monitoring the occurrence of rot in wooden poles (to avoid event 10) and for having sufficient vegetation management activities to avoid climbing in trees (event 11).

A low level of maintenance can influence the probability of occurrence for various undesired events, and hence move the probability estimate upwards in the figure. For undesired events with serious consequences it is therefore relevant to prescribe maintenance activities which can control the probability of occurrence to a sufficient low level.

2.3.6 Evaluate results and formulate strategies

Based on risk analysis and mapping of existing practise, improved strategies can be formulated. The result of risk analysis for different components must be subject to evaluation and discussions among the experts, concerning whether they give an intuitively right picture for risks related to the different components; and how this risk can be controlled through prescribing maintenance actions.

Experience shows that risk matrices are very useful tool for focused discussions within the expert groups. In the discussions, possible risk mitigating actions must be addressed, with basis in the companies existing practice. An important part of the evaluation is to judge whether there are maintenance activities well suited to mitigate the risks, and how maintenance activities should be differentiated according to identified risks.

It shall be noted that the risk mapping does not prepare for a computation of the "right maintenance" – but rather serve as a basis for a qualitative evaluation of what is needed of maintenance activities to control the identified risks.

EXAMPLE 9 Maintenance strategy

Table 2.1 shows an extracts of a maintenance strategy for a group of MV overhead lines, where the maintenance and trigger criteria for reinvestment are different for lines representing low CENS (Cost of energy not supplied) compared to lines with high CENS.

Table 2.1 Maintenance strategy for a group of MV overhead lines (adapted from (Catrinu et al., 2009))

Action	Category A: Low economic risk (CENS)	Category B: High economic risk (CENS)
Preventive maintenance	Annual inspections Thorough inspections every 10 years Vegetation management every 6 years or at explicit findings at inspections	Annual inspections Thorough inspections every 5 years Vegetation management every 3 years or at explicit findings at inspections
Triggering of reinvestment analysis when	age > 30 years <u>or</u> if condition monitoring results indicate a need	age > 20 years <u>or</u> if condition monitoring results indicate a need

2.4 Summary

This chapter has described and exemplified the main principles of a structured approach to establishing risk based maintenance strategies for distribution system assets.

The principles support the development maintenance strategies which prescribe maintenance actions which address the identified risks – and allow for differentiation of maintenance efforts based on risk analysis results.

Key recommendations include:

- Divide your assets into system units and establish maintenance strategies based on risk differentiation
  - Identify groups of assets which can be prescribed the same maintenance
  - Assets associated with high risk should be subjected to more often and more comprehensive maintenance actions and be considered for reinvestment earlier compared to low-risk assets

Maintenance strategies must describe maintenance actions to be done and how often (or when) they should be performed. The maintenance strategies should also include triggering events for when to commence a reinvestment analysis.

Reinvestment analysis

From triggering of an analysis to making the decision

3 Reinvestment analysis

3.1 Introduction

Reinvestments involve replacing or modifying existing system units or components. Reinvestments are often considered when an asset is approaching its end of life, and one of the distribution companies' challenges is that they have a large amount of such assets.

We advocate the need for a structured approach regarding when to perform reinvestment analysis by defining what we refer to as 'triggering events.' Such events are circumstances which make an asset or a group of assets undergo reinvestment analysis. It is the analysis which is triggered, and not the reinvestment itself. The decision of whether to reinvest or not, will be a result of the analysis.

Once a reinvestment analysis has been initiated, the fundamental question is:

Should the asset(s) in question be replaced and /or modified during the period of analysis or not?

We here recommend a method for reinvestment analysis, highlighting the path from triggering an analysis to decision, see Figure 3.1. In addition, important aspects regarding implementation and improvement are addressed. Different aspects of Figure 3.1 are explained in the following sections.

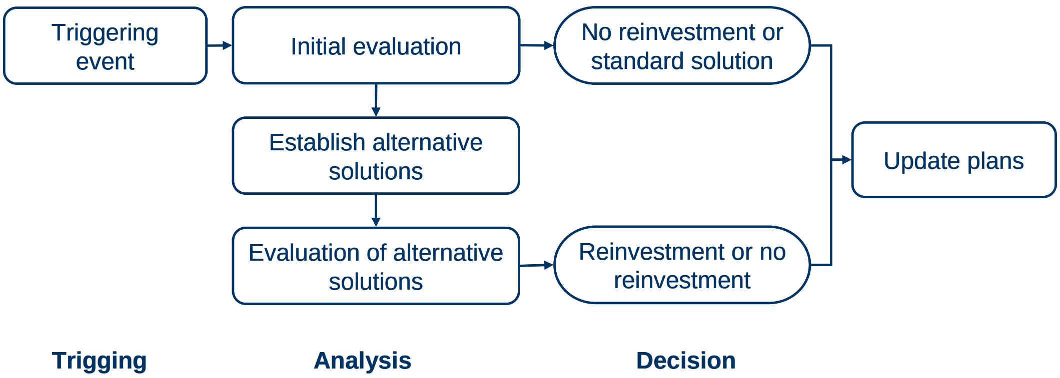

Figure 3.1 Recommended work process for reinvestment analysis

Some key recommendations, which are highlighted throughout the subsequent chapters include:

- Identify the right assets to analyse at the right time: Define triggering events
- Beware of your alternatives:
  - *Should we reinvest in the coming x years or not?*
  - Maintenance is often an alternative to reinvestment (but not forever and neither for 'maintenance free' assets)
  - Establish standard solutions to typical problems concerning group of assets
- Establish company standards for performing and reporting
  - Condition monitoring focusing on revealing reinvestment needs
  - Initial evaluation of reinvestment need
  - Evaluation of different reinvestment alternatives
- Document the reinvestment analysis even if reinvestment is postponed.

3.2 Triggering event

- Identifying the right assets to analyse

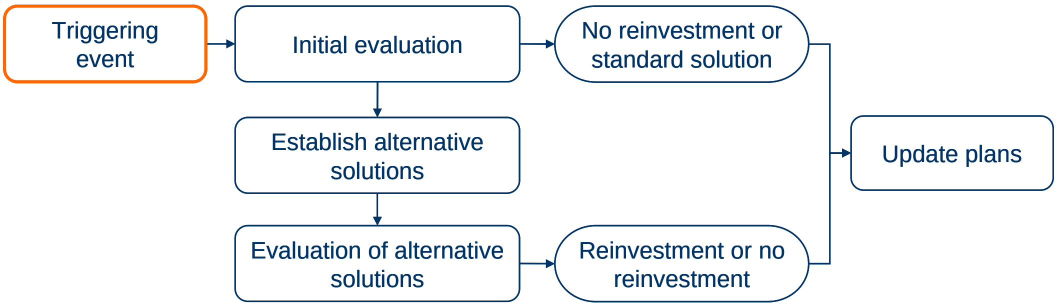

Figure 3.2 Triggering events initiates a reinvestment analysis

Network companies should define what we have called 'triggering events,' which are circumstances which make an asset or a group of assets undergo reinvestment analysis. Examples of such triggering events include:

- Results from condition monitoring
- Expected residual life (age)
- Failures and other history (e.g. overload, voltage deviations)
- Unfortunate / Unwanted design
- Regulatory intervention / requirements
- The risk associated with the asset / asset group has been questioned.
- Opportunity window (Construction activity etc.)
- High maintenance cost, interruption costs, costs of losses etc.

When defining triggering events, it is recommended to include risk differentiation, i.e. focusing on the assets associated with the highest risk and giving them a 'shorter way' to the reinvestment analysis. A description of triggering events may be included in the companies' maintenance strategies (Chapter 2.2).

In many cases a reinvestment analysis may be triggered by observation during maintenance activities, e.g. if the condition monitoring reveals that replacement may be necessary due to extensive deterioration, or if the estimated costs or other resources spent on maintenance are substantial.

EXAMPLE 10 Using input from condition monitoring to trigger reinvestment analysis

Figure 3.3 shows an overview of rot development of wooden poles on the overhead line. The scale 1-4 is used where 4 indicates substantial rot and 1 indicates that the pole is as good as new (no indications of rot), see chapter1.2.1.

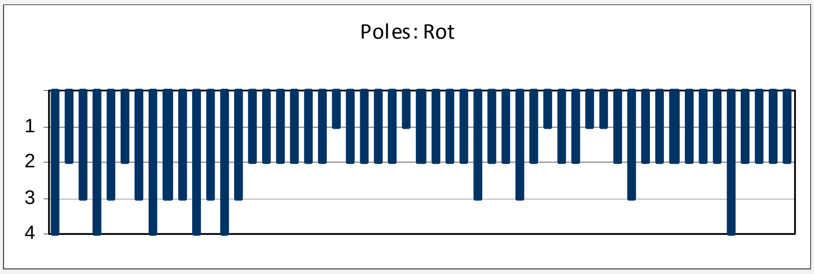

Figure 3.3 Condition information for an overhead line: rot development, poles

Information such as depicted in Figure 3.3, provides good information on whether assets should be considered for reinvestments. It is also possible to have dedicated 'check points' during condition monitoring addressing the need for reinvestment:

- *Is there a need to consider reinvestment?*
- *Should the asset be prioritised for more thorough condition monitoring in order to reveal reinvestment needs?*

3.2.1 Trigging an analysis of a group of assets

Some groups of assets call for special attention as they represent higher risk compared to other assets, due to their type and design. Such assets are often identified based on expert opinion and failure history. In some cases, public regulations might trigger replacement or modification of groups of assets, usually due to inadequate design regarding safety.

Some examples of groups of assets that might be eligible for reinvestment analysis are:

- 1st generation XLPE cables	Experience: These have a high failure probability
- Pole mounted substations operated from platform	Regulatory requirement (in Norway) to modify design
- Open low voltage systems in MV/LV substations	Safety / regulatory concern
- MV switch disconnectors with wire fence encapsulation	Safety concern
- OH-lines of types Fe-wire, cobber or cobber weld	Experience / observation: Old and brittle

Such groups should be identified during the process of establishing and / or updating maintenance strategies (chapter 2.2). Triggering criteria should be defined and included in the maintenance strategies, for example:

- All first generation XLPE cables should be considered for reinvestment within 10 years
- All substations with non-encapsulated low voltage systems should be considered for reinvestment within 5 years

If a company has large group of assets that is considered for reinvestment, they should do reinvestment analysis for these groups and try to identify standard solutions (see chapter 3.3.3).

3.3 Beware of your alternatives

As mentioned in Chapter 3.1, a reinvestment analysis must provide an answer to the following question:
Should the asset(s) in question be replaced and /or modified during the period of analysis or not?

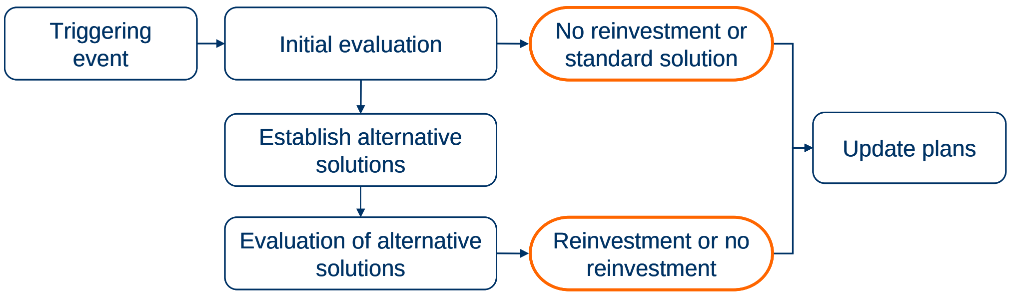

Figure 3.4 Alternatives include reinvestment (including standard solution) or no reinvestment

For a given asset or a group of assets, the distribution company has several choices that should be considered:

- No reinvestment
  - Postpone the reinvestment. Keep the asset in service some more years
- Reinvest now
  - Total / Partial reinvestment. The reinvestment can be a solution dedicated to the problem at hand or a standard solution applied to previously analysed problem.

In addition, to remove the asset might be an eligible option. The different alternatives will represent different risk (and costs) for the company.

Postponing the reinvestment should always be one of the alternatives for the analysis, if necessary including minor measures to reduce risk such as increased maintenance, restrictions in operation or minor replacements or modifications. This alternative can be referred to as the 'reference alternative', and will work as a basis of comparison for other alternatives.

When considering postponing the reinvestment, it is necessary to have the time perspective in mind; i.e. considering for how long this is a viable option:

For how long is it possible to postpone the reinvestment and does this require some specific effort (e.g. increased maintenance or operating restrictions)?

3.3.1 Identifying possible reinvestment alternatives

Before starting to evaluate the different reinvestment alternatives one should consider their overall properties and check whether they are eligible options or not. If it is clear that certain alternatives will not represent a preferred solution, these can be ruled out without further analysis. Alternatives which are regarded unacceptable in terms of risk must be modified to include measures which render them acceptable.

Considering the alternatives listed previously, the answers to the following questions will provide a good overview of which alternatives should be further evaluated:

- *Is reinvestment now a possible and good alternative? Why would we like to reinvest now?*
- *Is a standard solution applicable? (see chapter 3.3.3)*
- *Is partial reinvestment a possible and good alternative? Why?*
- *Is to 'remove' the asset a possible and good alternative? Why?*
- *Is it possible to postpone the reinvestment? For how long? Are immediate measures needed?*

The answer to the questions above will of course vary depending on the asset(s) at hand, but some general characteristics can be stated.

The main objective to postpone reinvestment is to exploit the assets lifetime, hence reducing cost by incurring them later on. This has to be weighted against the positive effects of reinvestment; mainly associated with the improvement of condition, better design or more appropriate capacity and /or network configuration. Simply put, the main drivers for the different alternatives could be summarised as:

Main drivers for reinvestment now (total or partial)

- Improvement of condition, design, capacity, placement
- Reduced costs / use of resources: interruption costs, maintenance, cost of losses

Main drivers for postponement

- Reducing short-term investment cost

Main drivers for removal

- Simplifying the network; reducing costs. Asset no longer 'necessary.'

EXAMPLE 11 Reinvestment alternatives for a MV/LV substation

For a MV/LV substation the reinvestment alternatives could roughly be described as follows:

- Reinvest
  - Rebuild the entire substation; including replacement of all components inside – consider placement, capacity and possibility to remove the substation
  - Renovate the building; replace all components inside

- Partial reinvestment
  - Renovate the building and / or replace or modify some of the components inside; switch disconnectors, cable terminations, transformer, low voltage system

- Remove the substation and transfer the customers to another station

- Postpone the reinvestment. Keep the substation in service
  Some relevant measures might be:
  - Put restrictions on the operation of switch disconnectors
  - Reduce the maintenance intervals; perform maintenance more often and use more comprehensive maintenance activities
  - Consider reinvestment again after 5 years

EXAMPLE 12 First screening of alternatives

For a MV/LV substation the answers to 'the first screening questions' presented in chapter 3.3.1 could be:

Reinvestment now?
Yes, it will improve the condition, resulting in reduced probability of unwanted events which will improve safety and quality of supply. It will give a long-term solution.

Partial reinvestment?
Yes, the switch disconnectors and cable terminations are in worse condition than the rest of the station. It is an alternative to replace only the switch disconnectors and cable terminations. This is less costly than to reinvest the entire substation; but will extend the substations lifetime shorter than is the case for 'full' reinvestment.

Removal?
No, this is not considered to be a viable alternative. Nearby substations does not have the capacity to take over the supply.

Postponement?
Yes, it is an alternative to postpone the reinvestment for 5-10 years. We can 'save money' by reinvesting later. The risk is considered to be acceptable given condition monitoring each fifth year to reveal further degradation

3.3.2 Reference alternative and time horizon

When comparing reinvestment alternatives, it important to keep in mind:

- *What is the reference alternative?*
- *What is the period of analysis (time horizon)?*

This is important both when estimating risk and performing cost-benefit analysis. Answer to questions such as *'What is the risk?'* and *'What are the costs?'* will of course depend on what time horizon is used. The risk associated with an asset may be acceptable at the moment, but expected to evolve into an unacceptable level during the next 10 years.

We here emphasise the need to define a reference alternative (often referred to as *alternative 0*), which will work as a basis of comparison of the other alternatives. It is important that this is a viable alternative for the whole period of analysis. If necessary, the reference alternative must include minor measures in order to be acceptable in terms of risk.

We recommend to use '*Postponing the reinvestment*' as the reference alternative for all reinvestment analysis.

EXAMPLE 13 Reference alternative and period of analysis

The table below shows two different choices of period of analysis (for the same reinvestment) and corresponding reference alternatives and their associated cost.

Period of analysis	Reference alternative	Investment cost
5 years	Postpone the reinvestment (keep asset in service).	0
20 years	Postpone the reinvestment. Expected need to replace most deteriorated components in year 10.	20 000 Euros in year 10

As we can see from the example, the choice of reference alternative must be consistent with the period of analysis. In this case, to postpone the reinvestment entirely (investment cost 0) is not a viable option if the period of analysis is 20 years, thus the reference alternative must include some reinvestments costs.

In many cases it can be advantageous to use a short period of analysis (5-10 years) for the reinvestment analysis. The advantages include:

- For a short period of analysis to postpone the reinvestment is a viable alternative
- Assumptions regarding risk, failure probabilities etc. is based on observations from condition monitoring, and updated information is typically gathered every 5 or 10 years (in some cases even more often)
- The most important question to answer is whether to reinvest in the coming few years or not. If reinvestment can be postponed even further, only a rough estimate of when is needed (as a new analysis will be performed when reinvestment is considered again)

3.3.3 Standard solutions and standard analysis

Due to the vast amount of assets in the distribution system, it is advantageous to define reinvestment strategies which resolve typical worries for groups of assets. This can be done by identifying standard reinvestment solutions, for example based on expert opinion, and estimated years on reinvestment for the company's different assets.

The question to be asked is:
What are typical reinvestment projects in our area the next 5 years? Further ahead?

The answer to the first question may for example be:

- OH-lines with many rotten poles
- Pole mounted substations operated from platform
- Substations with switch disconnectors of a certain type and condition
- Underground cables assumingly approaching their end of life (based on their age)

Once typical reinvestment projects are identified, one should seek to find standard solutions.

- *What are typical worries with the existing solution?*
- *Can simple measures resolve these worries?*
- *What are typical reinvestment alternatives and their associated effects?*

The answer to these questions is a basis to define preferred solutions to identified problems, i.e. define reinvestment strategy for groups of asset.

It will also be profitable to use such a 'standard reinvestment' analysis as a basis to do an analysis for a specific asset or group of assets, even if a standard solution doesn't apply.

3.4 Evaluation of alternatives

Evaluation of reinvestment alternatives comprises three main steps: Initial evaluation, establish alternative solutions, and evaluation of alternatives.

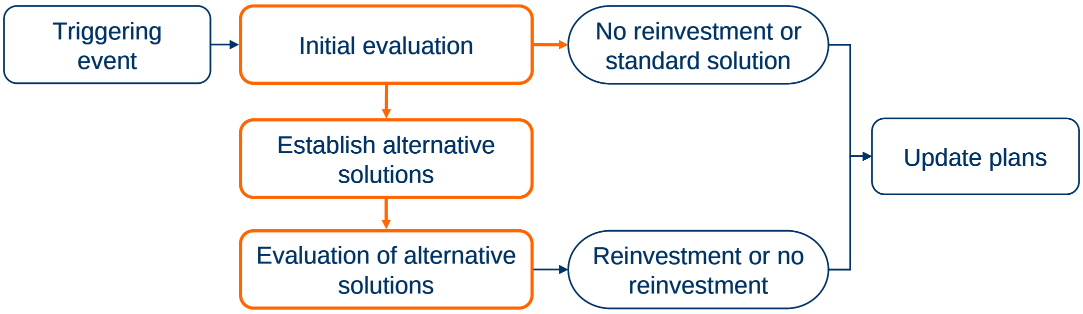

Figure 3.5 Initial evaluation, establish solutions and evaluation of solutions

The initial evaluation is a coarse analysis of the asset or assets at hand (in order to decide if further analysis is necessary), while evaluation of different alternatives requires a more detailed approach.

Proposed methods include risk analysis and cost-benefit analysis; the latter can be given less emphasis in the initial evaluation. Uncertainty is an important aspect when evaluating both the existing solution and different reinvestment alternatives, and we advocate that this must be addressed both in the risk analysis and the cost-benefit analysis.

In some cases there is a need for technical analyses, e.g. of power flow and voltage to ensure that the alternatives represent technically good solutions, but this is not further discussed here.

3.4.1 Initial evaluation

The purpose of the initial evaluation of the asset(s) is to determine whether reinvestment can be postponed, or if there is a need for further analysis. Risk analysis, based on information about the assets' condition is a vital part of the initial evaluation.

The initial evaluation of the asset or group of assets at hand will lead to one of two main conclusions, as indicated in Figure 3.5.

1) No reinvestment or standard solution
    a. Reinvestment can be postponed. May include simple measures[7]
    b. A standard solution is applicable

2) There is a need for further analysis
    - Alternative solutions must be established and evaluated

In some cases, especially if the reinvestment analysis is triggered due to age, one can relatively easily determine whether reinvestment can be postponed or further analysis are required. This presupposes good and updated information about the object considered for reinvestment.

EXAMPLE 14 Desk-top evaluation

Consider a MV/LV substation, where the building has reached the age of 60 years, triggering a reinvestment analysis. Reports from condition monitoring and other relevant information show no indication of circumstances that call for action. The reinvestment can be postponed without further analysis, but a thorough control of the building by a construction engineer should be performed as a part of the next scheduled maintenance (in 3 years).

In addition to information about condition, design etc, other relevant circumstances witch affect the need for reinvestment may include:

- Complaints from the general public (placement, aesthetics, quality of supply)
- Negative publicity in the press
- Registered / expected deviations regarded quality of supply (interruptions, voltage problems etc)
- Removal or replacement of asset should be considered
    - Obstruction of traffic / new or planned constructions
    - Redundant asset
    - Other circumstances
- Need for increased capacity / reinforcements.
- Window of opportunity (possibility to coordinate reinvestments with other projects in the area)

We suggest a list of questions that should be addressed in order to reach one of these two conclusions, see chapter 3.4.2. The importance of good and updated information

[7] Simple measures may for example include minor modifications, replacement of non-costly components and / or increased preventive maintenance.

about the asset(s) condition is emphasised, and it might be necessary to do an 'in field' evaluation in order to acquire this information.

3.4.2 Suggested process for initial evaluation

We here recommend some key questions that should be addressed during the initial evaluation.
The answers to these questions will reveal if there is a need for further analysis, and identify possible reinvestment alternatives.

1) Trigging — *What triggered the reinvestment analysis?*

2) Existing plans — *Do we have existing plans concerning the asset?*

3) Standard solution — *Is a standard solution applicable?*

4) Mapping of the asset condition
What are the condition of the asset and its main components?
Summary of relevant condition information

5) Economy and other relevant reasons to consider reinvestments
Are there any economic reasons to consider reinvestment?
High maintenance costs? High CENS? High losses?
Are there other circumstances which influence the need for reinvestments?

6) Summary of risk
What are the main identified risks and what are possible measures?

7) Is there a need for further analysis?

No — *No need for reinvestment*
Simple measures are sufficient

If no: *What measures are needed?*
When should reinvestment be reconsidered?

Yes

If yes: *Which alternatives should be further analysed?*

EXAMPLE 15 Initial evaluation

The following example shows an initial evaluation of a MV/LV substation. The numbering corresponds to the suggested process presented in chapter 3.4.2.

1) *What triggered the reinvestment analysis?*

- Results from condition monitoring: Oil leakage on cable termination
- Expected year of reinvestment: Based on age and type of the switch disconnectors
- Unfortunate / unwanted design: Old switch disconnectors of type RB NEBB. Operation of such switch disconnectors represent a certain safety risk

2) *Do we have existing plans concerning the asset?*

3) *Is a standard solution applicable?*

None existing plans or standard solutions

4) *What is the condition of the asset and its main components?*

Condition indicator[8]		**Comment**
Building	2: some indication of degradation	*Some graffiti and minor 'wear and tear'.*
Switch disconnectors	2: some indication of degradation	*Switch disconnectors not tested.*
Cable terminations	4: critical	*Substantial leakage / perspiration one of the oil-filled cable terminations*
Low voltage system	1: 'as good as new'	
Transformer	1: 'as good as new'	

Summary: The condition of the cable terminations is not acceptable (minimum one cell must be replaced). The rest of the substation is in good condition, except from the roofing paper which must be redone.

5) *Are there any economic reasons to consider reinvestment?*
High maintenance costs? High CENS? High losses?
Are there other circumstances which influence the need for reinvestments?

No particular circumstances.

[8] The numbers 1-4 correspond to the condition index developed by SINTEF Energy Research. The index also includes a 5th state which implies fault (see chapter 1.2.1).

6) *What are the main identified risks and what are possible measures?*

Risk				Comment	Measures
Safety			x	Condition, cable terminations	Replace one or all cable terminations
Quality of supply		x		Condition, cable terminations: Increased failure probability (low CENS)	
Safety			x	Old switch disconnectors without encapsulation. Open bus bars. Uncertainty concerning operation of switch disconnectors	New switch disconnectors Functional test / revision Restrictions on operation
Safety		x		Open low voltage system	Shielding of LV system
Reputation	x			Graffiti on door, signs, building	Remove graffiti

7) *Is there a need for further analysis?*

Yes: Wish to look further into the following alternatives:

- A0: Postpone reinvestment

  Necessary measures include replacement of cable termination with leakage and increased maintenance of the switch disconnectors. Restrictions on operation must be considered.
- A1: New switch disconnectors and cable terminations

For both alternatives: Shielding of LV system and removal of graffiti.

3.4.3 Evaluation of alternative solutions

Once alternative reinvestment solutions are identified (based on the initial evaluation; see also chapter 3.3.1), the expected effects of these must be estimated and compared to the reference alternative 'postpone reinvestment'.

The evaluation of alternative solutions shall follow the same approach and use the same methods and criteria as the initial evaluation. Keep in mind what triggered the analysis in the first place, and the results of the initial evaluation.

Risk analysis

The risk analysis performed in the initial evaluation, is the basis to evaluate how alternative solutions affect the risk.

For each alterative one must determine whether and how it affects the risk compared to today's solution:

- *What unwanted events are affected?*
- *Does the probability change?*
- *Does the consequence change? What type of consequence?*

It can be useful to use illustrations such as in the following example to visualise the effect of different alternatives.

EXAMPLE 16 Illustrating changes in risk for different reinvestment alternatives

This example shows how changes in risk can be illustrated graphically. The analysis corresponds to the initial evaluation of the MV/LV substation described in example 15, and considers the following alternatives:

- A0: Postpone reinvestment
- A1: New switch disconnectors and cable terminations

A0 includes minor measures to reduce the risk, but as we can see, the risk reduction is less than for A1.

Risk	Now	A0	A1	Comment
Safety				A0: Replacement of cable termination with leakage A1: New cable terminations
Quality of supply				
Safety				A0: Functional test of switch disconnectors. Revision/restrictions if needed
Safety				A0 / A1: Shielding of LV system
Reputation				A0 / A1: Removal of graffiti

Cost-benefit analysis

In a cost benefit analysis, different alternatives are compared in economic terms. The following elements must be considered:

- Investment cost and remaining value
- Maintenance costs
- Cost of losses
- Interruption costs; Cost of energy not supplied.

Reinvestment decisions will in general consist of a trade-off between immediate cost (investment) and potential future benefits (reduction in risk, future maintenance costs, future interruption costs etc). To adjust for the fact that the cost elements occur at different points of time, the concept of present value is used (Brealey and Myers, 2003)[9]. Some general recommendations regarding cost-benefit analysis for reinvestments are listed in (Nybø et al., 2009) and include:

- Evaluate economical effects of alternative reinvestment solutions by performing cost-benefit analysis.
    - Use the principle of present value
    - Compare different alternatives with the reference alternative ('postpone the reinvestment')
- Establish a company standard for cost-benefit calculations including:
    - General parameters such as time horizon, discount rate
    - How to calculate and document cost elements
    - How to perform sensitivity analysis
    - How comprehensive the analysis should be; this can differ depending on the project
    - Whether and how to include effects such as regulation and taxes
- Beware of the fact that not all effects of reinvestment can be expressed in economical terms, and that a cost-benefit analysis must be supplemented by an analysis of unwanted events (risk analysis)
- Incorporate simple sensitivity analysis[10] in the cost-benefit analysis: Highlight the parameters which are the most uncertain and will influence the net present values of reinvestment alternatives the most. In many cases this will be the failure rate.

Key questions to be asked include:

- How much can we gain by postponing the reinvestment costs?
- Given postponement: How much higher are the interruption costs, maintenance costs and cost of losses compared to reinvestment now?
- Given postponement: How much higher is the risk compared to reinvestment now?

[9] Norwegian readers can read about present value in 'Planleggingsbok for kraftnett,' *www.planbok.no*

[10] Norwegian readers can read about sensitivity analysis in 'Planleggingsbok for kraftnett,' *www.planbok.no.*

EXAMPLE 17 Presenting results from a cost-benefit analysis

Figure 3.6 shows how main results from a cost benefit analysis can be illustrated. A0 (postponement) requires some minor measures, but the investment cost is much less than for A1 (reinvestment now). On the other hand, A0 will give higher maintenance costs and interruption costs. In this example, the costs of losses are not affected by the reinvestment.

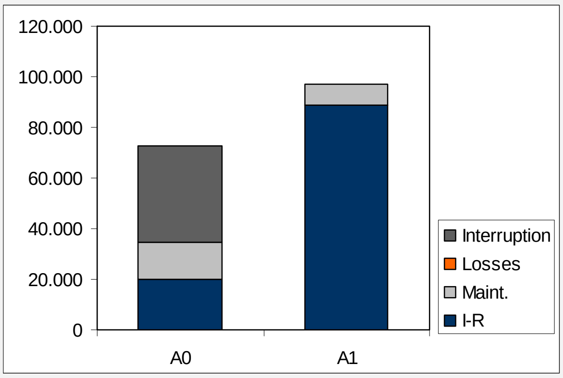

Figure 3.6 Present value of cost the next 5 years for the reinvestment alternatives A0 (postponement) and A1 (reinvestment now). I-R is the investment cost corrected for remaining value.

If the decision maker's only criterion is net present value, A0 will be preferred. But risks and uncertainties not included in this calculation must also be considered. In general, postponement of reinvestment will imply higher risk and uncertainty (about the assets actual condition, failure rate etc) than reinvestment now, and these are factors which might lead the decision maker to prefer A1 in this example.

Uncertainty

There will always be uncertainty associated with the estimated effect of different solutions, and it is important to describe this in the analysis.

Examples include:

- Uncertainty concerning the estimation of asset's condition and the estimation of effects on safety, reputation, quality of supply etc.
- Uncertainty concerning the estimation of future interruption costs, maintenance costs, cost of losses and investment costs.
- Uncertainty concerning load development or other factors which are relevant for the reinvestment decision

Such uncertainties should be described, highlighting factors with large impact on the estimated risks and costs. Uncertainty concerning the present value of alternative solutions can be quantified and visualised through sensitivity analysis.

In some cases it may be favourable to take measures to reduce the uncertainty, e.g. to perform (a new) thorough condition monitoring if there are doubts concerning assets condition.

3.4.4 Decision making

As outlined in this chapter, reinvestments typically involve different decision criteria, and how the different alternatives scores according to these criteria (as shown in example 16) must be considered.

A summary of the existing solution and associated risk, and changes in risk as a result of different reinvestment alternatives (see example 16, page 36) and a summary of associated cost (see example 17, page 38), will be a good basis for making decisions. The different decision criteria must be considered together and the best overall alternative selected

There exist multi criteria decision making methods which can be used to aid the process of merging different criteria into comparable utility values for the alternatives. Such methods are not further elaborated in this report, but the interested reader is referred to e.g. (Catrinu et al., 2007).

3.5 Summary

This chapter has described and exemplified a structured approach to reinvestment analysis, including:

- When to trigger a reinvestment analysis
- Which reinvestment alternatives to consider
- How to evaluate different alternatives
- How to document the analysis

Key recommendations include:

- Identify the right assets to analyse
    - Define *triggering events* reflecting risk
- Beware of your alternatives
    - Should we reinvest in the coming period of analysis or not?
    - Maintenance is often an alternative to reinvestment (but not forever)
    - Establish standard solutions to 'known' problems concerning groups of assets
- Establish company standards for performing and documenting reinvestment analysis

4 Implementation and improvement

This chapter describes some important aspects regarding how to implement risk based maintenance strategies, trigger reinvestment analysis and establish a culture of continual improvement. The need for data, in particularly from condition monitoring is given special attention.

Recommendations include:

- Create an overview over what kind of assets you have and allocate them to their corresponding maintenance strategy and plan
  - Systematically register and update necessary information about your assets
  - Set up maintenance plans, also addressing need for reinvestments
- Use condition monitoring data as input to maintenance and reinvestment management
- Evaluate and improve strategies and processes

Chapter 4.1 address the first bullet point, while chapter 4.2 promotes the importance of condition monitoring and chapter 4.3 describes how to continually improve strategies and processes.

4.1 From maintenance strategies to plans

In order to allocate the different assets to their appropriate maintenance strategy (see chapter 2), information about selected parameters must be registered. E.g. if age, condition, type and CENS/h is decisive for the maintenance of MV cables, these parameters must be found in the assets database in order to allocate the cables to their appropriate strategy and set up maintenance plans (as illustrated in Figure 4.1).

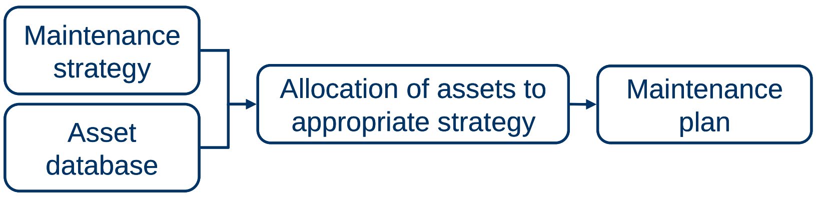

Figure 4.1 From maintenance strategy to maintenance plan

Once assets are allocated to their appropriate maintenance strategy, maintenance plans can be derived, both for individual assets and for groups of assets.

As illustrated in Figure 4.2, the planning horizon typically varies between short (typically one budget year), medium (5 - 10 years), and long (20-30 years). The level of detail will be quite high for the short / medium term plans, while more rough for the long term plan.

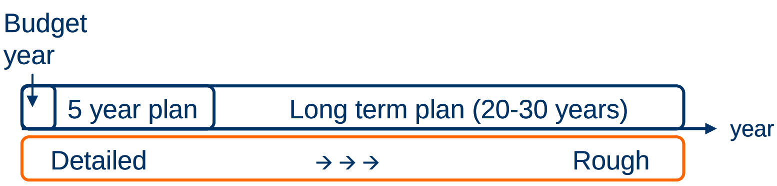

Figure 4.2 Planning horizon

Typically, many of the same parameters used to differentiate maintenance are also used to trigger reinvestment analysis. In order to implement the concept of triggering criteria in practice, the network companies have to define a routine for how to compare assets' properties against triggering criteria.

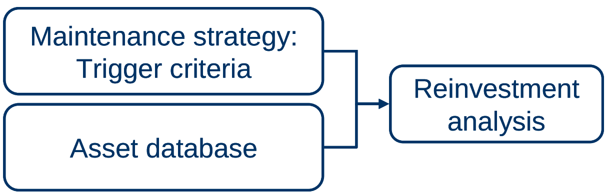

Figure 4.3 Trigging a reinvestment analysis

4.1.1 Acquiring necessary information

In many cases, information needed to differentiate maintenance and trigger reinvestment analysis, is lacking, and in this case, one should start with what is available and begin to systematically collect the missing data, for example as part of the next scheduled inspection.

A first step will be to:

- Identify information needed in order to implement maintenance strategies for different system units[11]
    - *What data is needed and what data is missing? How valuable is this information? How difficult is it to obtain?*
- Create a preliminary overview (categorisation) of your assets and their associated maintenance strategy based on available information

The most important is to identify the 'high risk' assets, to ensure that they get appropriate maintenance and reinvestment attention. In addition, assets which represent very 'low risk' should be identified in order to prevent to over-spend resources here.

The level of detail can be gradually refined as better information is gathered, and therefore should not the lack of data prevent the implementation of strategies.

4.1.2 Examples

The following examples highlight important aspects regarding the implementation of maintenance and reinvestment strategies:

- Necessary information in order to differentiate maintenance and get an overview of your assets
- Trigger reinvestment analysis and addressing future reinvestment needs
- Setting up maintenance plans

[11] This should also be kept in mind when defining the maintenance strategies.

EXAMPLE 18 Necessary information in order to differentiate the maintenance of MV/LV substations

A group of network companies has developed a risk differentiated maintenance strategy for their MV/LV substations where the intervals between different maintenance activities depend on the following parameters:

- Switch disconnector type and voltage level
- Environment, switch disconnectors
- Encapsulation, switch disconnectors
- Age, switch disconnectors

Table 4.1 summarises key properties for a MV /LV substation. Based on information about the switch disconnectors, which in this case is decisive for the maintenance, the substation can be assigned to its appropriate maintenance programme and time for next condition monitoring and so forth can be derived. A rough estimate regarding reinvestment need is also included, which is useful in order to trigger reinvestment analysis and for the long term planning. The term 'estimated year of reinvestment' is described on page 46.

Table 4.1 Summary of key properties for a substation.

Substation nr 5012		
Switch disconnector type	NAL - 12 kV	
Encapsulation	Fully	
Environment	Clean	
Installation year	1980	
Maintenance programme	**A2 – Low risk**	
Scheduled inspection (last / next)	2009	2010
Scheduled 'thorough inspection' (last / next)	2007	2012
Scheduled functional test (last / next)	2000	2020
Estimated year of reinvestment	**2030** First estimate (age)	
Factors influencing reinvestment needs	None known	

EXAMPLE 19 Creating an overview of assets

Based on their maintenance strategy (referred to in the previous example) and a population of their substations with air insulated switch disconnectors, a distribution network company has performed a mapping of the number of substations within each category (Figure 4.4).

The overview shows that a large portion of their substations are associated with low risk and require little maintenance attention (indicated by shades of green), whereas a small number of substations will be subjected to more comprehensive maintenance (indicated by shades of orange / red). In other words, the company has a substantial potential to reduce risk by giving just a small number of stations extra maintenance attention. In addition, there is a substantial saving potential in terms of reducing maintenance for low risk substations.

Environment	Age	Encapsulation		
		Fully	Semi	Open
Exposed	> 24 years	11	14	1
Exposed	≤ 24 years	36	1	0
Clean	> 24 years	161	252	1
Clean	≤ 24 years	337	15	0

Figure 4.4 Overview of number of substations within each category. Age is here used as one of the factors for risk differentiation. When good condition information exists, this will provide better information about risk than age.

EXAMPLE 20 Addressing reinvestment needs: Estimated year of reinvestment

A group of network companies has defined 'estimated year of reinvestment' as 'the year it's most likely that a component must be replaced.' The idea is to use this to trigger reinvestment analyses.

The estimated years of reinvestment are assigned to different assets. E.g. for a MV/LV substation the estimated year of reinvestment[12] is assigned to the different objects building, switch disconnectors, low voltage system etc. When one or more objects in a substation approach their estimated year of reinvestment, a reinvestment analysis of the station is trigged.

A first estimate of the year of renewal can be established based on age, type / design, and environment. As time passes, the estimated year of renewal must be updated based on results from condition monitoring and other relevant information. An example is shown in Figure 4.5. For assets close to their estimated year of reinvestment, technical condition and load development are decisive for the estimated year of reinvestment. Further ahead, it's ok to use an initial (rougher) estimate based on age.

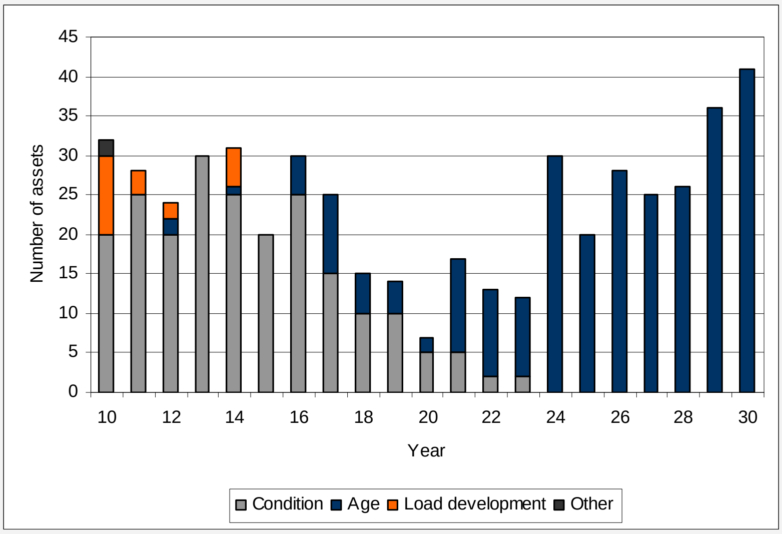

Figure 4.5 Estimated year of renewal for a number of assets

In addition to triggering reinvestment analysis, the concept of estimated year of renewal is also useful in order to develop a long term reinvestment plan and to trigger condition monitoring. The latter can be done by prioritising assets which approaches their estimated time of renewal for thorough condition monitoring.

[12] The year of renewal may be different for different objects in the substation, e.g. the switch disconnectors might have estimated year of renewal 2015, while the estimated year of renewal for the building is 2025.

EXAMPLE 21 Maintenance plans

Figure 4.6 shows planned maintenance activities (condition monitoring) for two selected substations. Plans (and some history) regarding inspection, thorough inspection and reinvestment need assessment is shown. The plans for condition monitoring may change as a result of the reinvestment need assessment, and is therefore not illustrated after this point in time.

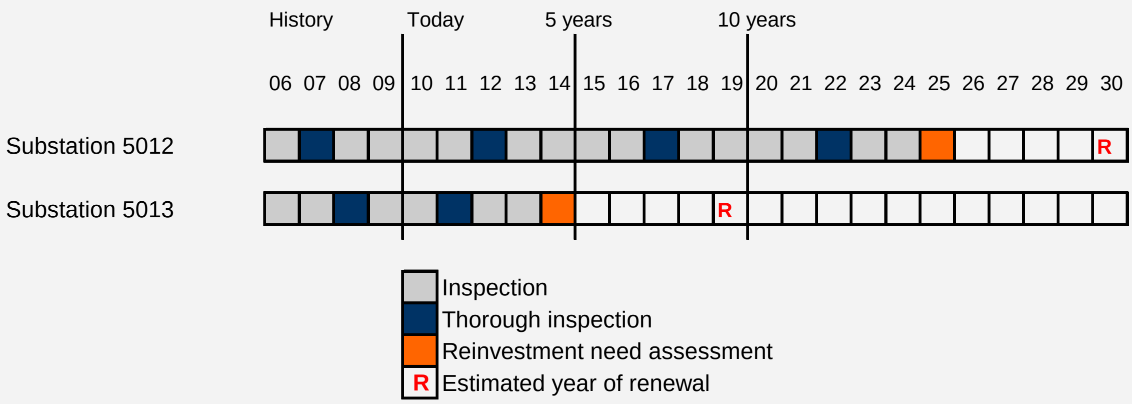

Figure 4.6 Maintenance plan for two selected substations

Based on maintenance plans for individual assets (as shown above), more aggregated plans for groups of assets or the whole asset base can be generated. Such plans can be useful input to resource allocating, budgeting etc.

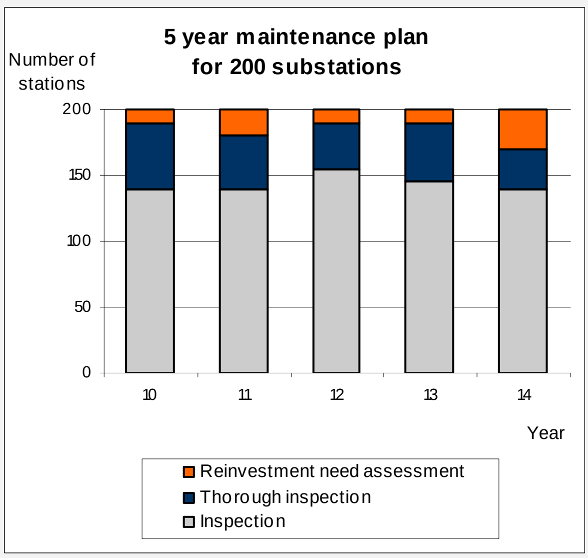

Figure 4.7 5 year maintenance plan (condition monitoring) for a population of 200 substations

4.2 The value of condition monitoring

We have previously emphasised how important it is to have good information about the condition of assets in order to do sound decisions about maintenance and reinvestments. As an asset deteriorates it represents a higher risk in terms of an increased probability of failure, and information about assets' condition is the main reason to perform maintenance and / or trigger reinvestment analysis.

Condition monitoring represent a large part of the network companies maintenance activities, and serves several purposes:

- Find and correct deviations
- Assess the condition of components. Reveal need for reinvestment / comprehensive maintenance.
- Gather other relevant data

Depending on the purpose, there is a need for different kinds of condition monitoring. In general, there is need for a rather thorough condition monitoring in order to identify reinvestment needs.

Assets assumingly approaching their end-of-life can be prioritised for thorough condition monitoring based on available information on condition, failure history, age etc.

EXAMPLE 22 Condition monitoring triggered due to failure

The underground cable networks in cities are a main concern for many distribution network companies for several reasons:

- Many of the cables are old
- Missing documentation: Both age, type and condition is in many cases unknown
- 'Unavailability': Digging imply large costs and much administration

After several failures in an urban area, the distribution network company decided to prioritise several cables in this area for thorough condition monitoring in order to reveal the need for reinvestment. Such condition monitoring is relatively costly, but on the other hand, more information about the cables' condition will help the company make a better decision and avoid reinvesting too early.

EXAMPLE 23 Detecting rot in poles

Rot development in wooden poles is a challenge, and many poles are replaced because their strength is reduced due to rot. Several methods exist to detect and measure rot, from simple screening techniques using a hammer or a special train dog, to more sophisticated methods to measure the extent of rot.

For lines assumingly approaching reinvestment, sophisticated methods to measure rot (and also other methods to assess the condition of the line as a whole) are needed. In other cases, screening techniques may be sufficient. Where the screening indicates rot, the pole can be more thoroughly controlled

4.3 Continual improvement

The principle of continual improvement is advocated as a fundamental part of asset management in numerous disciplines – see e.g. (Deming, 2000, ISO, 2005, British Standards Institution, 2008a).

The goal of continual improvement is to ensure that the organisation learns over time and uses this new knowledge to improve their asset management practice[13]. This is done through accumulating knowledge, learning and adopting to change, and includes e.g.:

- Acquiring and adapting new knowledge about 'best practice'
- Adapting to new recommendations and demands
- Updating risk assessments based on new knowledge, information or priorities
- Identifying and implementing standard solutions to recurring maintenance and reinvestment challenges

To make it practically applicable, it is important to start the process of continual improvement with a relatively simple approach, e.g. to:

- Establish an asset management team which is responsible for implementation and follow up (continual improvement) of maintenance and reinvestment management
- Create meeting areas for this group. They should gather at least 1-2 times a year with the purpose of identifying areas of improvement
    - Go through a list of questions that is regarded as important in order to reach company goals regarding maintenance and reinvestments
    - Compliment with simple analysis of selected indicators.

[13] This section is heavily based on (Nybø and Nordgård, 2010).

A potential pitfall is to make the follow-up too complex and time demanding. It is hence important to start with simple questions and analysis, and to link these with the companies' objectives and focus areas.

EXAMPLE 24 Follow-up questions related to maintenance and reinvestment goals

Table 4.2 provides examples of follow-up questions related to specific goals regarding maintenance and reinvestments (the list is by no means exhaustive). Such follow-up questions should be asked regularly. Indicators may be used to monitor trends and goal achievement.

Table 4.2 Goals and follow-up questions

Goal	Follow-up questions
Implement maintenance strategies	Have we implemented our maintenance strategies? - If not, why? How can they be implemented? - If yes, have we identified any improvement potential?
Compliance with rules and regulations	Are there any new rules and regulations affecting our strategies? Do we know about deviations from current rules and regulations?
Achieve a high level of safety for our personnel and 3. party	Have there been any accidents or near accidents? Have we any other indications concerning safety? - Have this revealed unaddressed safety concerns?
Increased security of supply: Improved vegetation management in certain areas	Have vegetation management been performed according to plan? (if not, why?) Do we have any indications of reduced failure rate? (e.g. limited damage from last storm, positive trend in failure statistics)

4.3.1 Indicators

Continual improvement is closely related to the term 'indicator'. By combining different indicators one can create a simplified description of the distribution system and assess past and future performance. Some aspects concerning risk indicators (indicators providing information about risk) and their use in distribution system asset management is discussed in (Sand, 2009). This includes results from a survey among distribution network companies in Norway, Finland and France on which indicators are used today.

Using indicators to measure the effects of maintenance and reinvestments can be a challenging task, because the costs incur now, while the benefits incur in the future and are less visible (often in terms of a failure or accident *not happening*).

One way to meet this challenge is to distinguish between two groups of indicators (based on (OECD, 2003)):

- Activities indicators
  - Designed to help identify whether actions believed to lower risks are taken
- Outcome indicators
  - Designed to help measure whether such actions are, in fact, leading to less probability and / or less consequences of unwanted events.

In other words; outcome indicators tell you *whether* or not you have achieved a desired result, while activities indicators they you *why* the result was achieved or why it was not.

EXAMPLE 25 Indicators 'measuring' the effects of reinvestments

Table 4.3 illustrates different indicators related to specific goals and activities. Note that the activity indicator is easy to observe and connect to goals / activities, while the outcome indicators will be observed over a longer period of time and will usually be a result of many different activities (as well as stochastic factors such as weather).

Table 4.3 Activities indicators and outcome indicators

Goal	Activity	Activities indicator	Outcome indicator
Increased security of supply	Replace first generation XLPE cables	Km replaced Costs	Quality of supply index Focus on cable failures and areas where cables are replaced
Increased security of supply	Improved vegetation management	Areas / km with improved vegetation management Costs	Quality of supply index Focus on failures related to vegetation and areas where vegetation management is improved
Improved safety for personnel	Improve encapsulation for switch disconnectors in MV/LV substations	Numbers of improved encapsulations / Costs	Safety index

Quality of supply indexes are normally based on failure statistics, while safety indexes are normally based on accidents statistics.

There exist models trying to describe the relationship between activities and outcomes, for example level of maintenance and reinvestments, the condition of grid components, and quality of supply indexes.

EXAMPLE 26 Indicator describing the need for reinvestments

The British regulator OFGEM has defined a health index and uses this to describe the condition of selected components in the UK power system, including for example transformers, switch gear and overhead lines. The health index uses a 1-5 scale to describe assets' condition, see Table 4.4.[14]

Table 4.4 Health Index Definitions

ID	Description
HI1	New or as new
HI2	Good or serviceable condition
HI3	Deterioration requires assessment and monitoring
HI4	Material deterioration, intervention requires consideration
HI5	End of serviceable life, intervention required

The use of such indexes can be fruitful in order to get an overview of the network and assets that require maintenance, reinvestment or investments on an aggregated level. It may also be used to illustrate the expected benefits from reinvestment (represented by improved health or slower deterioration).

In order to say more about risk, the health index may be combined with other indexes, for example an index reflecting the components importance for the system[15].

Figure 4.8 shows an example of the use of the health index for a group of High Voltage switchgear. A group of such assets are categorised in three groups according to their condition:

- Health index 3 or better (HI1-HI3)
- Health index 4 (HI4)
- Health index 5 (HI5)

The pie to the left shows the current situation (Year 0), the pie in the middle shows the situation in year 5 without intervention, and the pie to the right shows the situation in year 5 given that certain actions are undertaken. As we can see, with no actions taken, the health of the population deteriorates with time; a higher percentage is classified

[14] This index is closely related to the condition index described in chapter 1.2.1.

[15] OFGEM has also defined an index which describes the degree of utilisation for selected components (using a scale ranging from 'Significant spare capacity' to 'Fully utilised, mitigation required'), see www.ofgem.gov.uk.

HI5 ('End of serviceable life'). With investments, the health of the population improves.

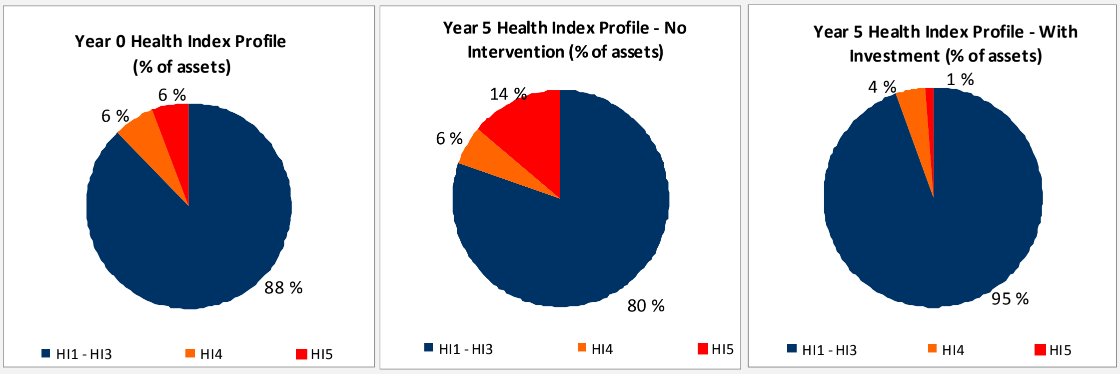

Figure 4.8 Health index distribution for a group of High Voltage switchgear

4.4 Summary

This chapter has described and exemplified different aspects regarding:

- How to implement maintenance strategies and to trigger reinvestment analysis
- The need for data and the importance of condition monitoring.
- Continual improvement and use of indicators.

Key recommendations include:

- Identify information needed in order to implement maintenance strategies and trigger reinvestment analysis
  - o *What data is needed and what data is missing? How valuable is this information? How difficult is it to obtain? If necessary; how shall we obtain it?*
  - o Systematically register and update necessary information
- Create an overview of your assets and allocate them to their corresponding maintenance strategy
  - o Set up maintenance plans, also addressing need for reinvestment analyses
- Use condition monitoring data as valuable input to maintenance and reinvestment management
  - o Different needs require different condition monitoring results
- Evaluate strategies, processes, and results - and use this knowledge to achieve continual improvement

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